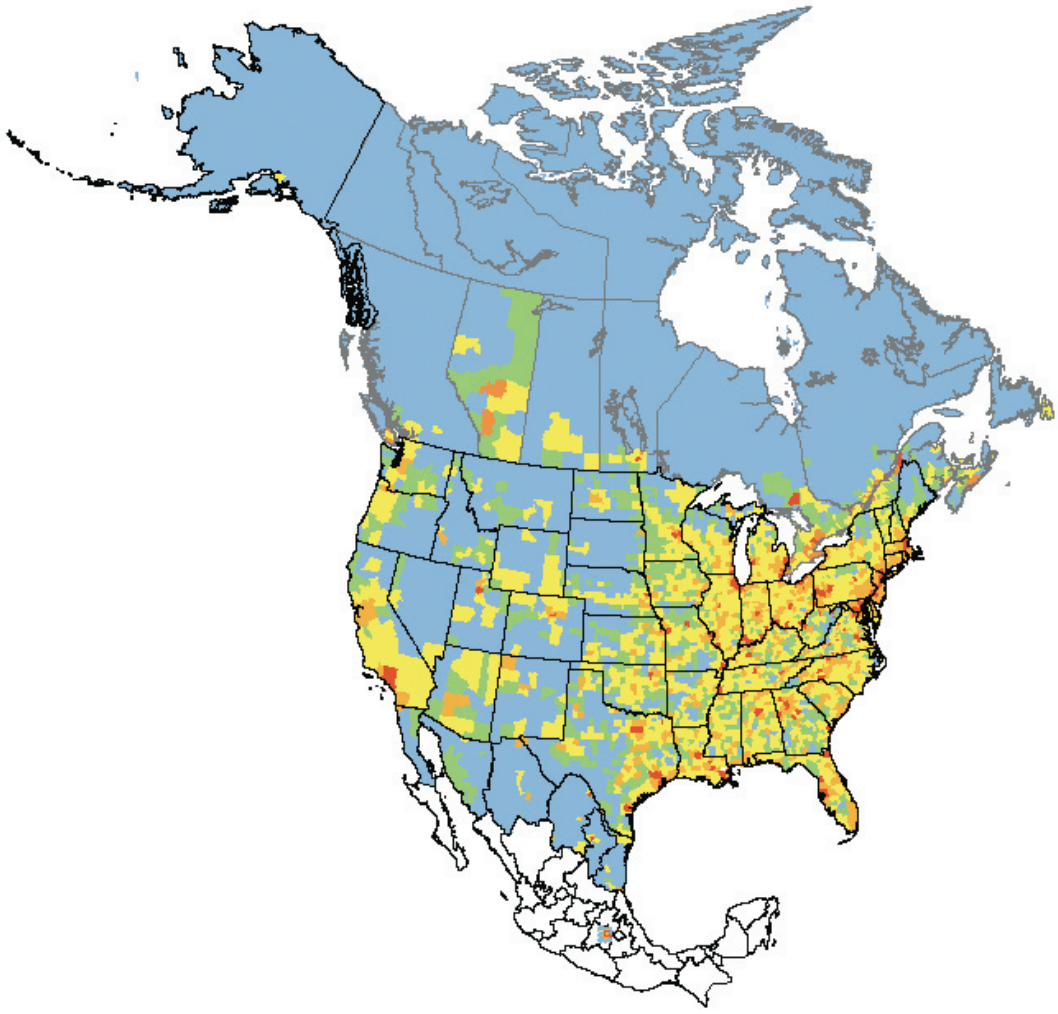
NARSTO-05-001

Improving Emission Inventories for Effective Air Quality Management Across North America



A NARSTO Assessment

Prepared by:

The NARSTO Emission Inventory Assessment Team

ABOUT THE COVER

The map on the cover of this Assessment shows nitrogen oxide emissions (in tonnes/yr/km^2) for Canada, the United States, and Mexico. This map was created using information from national emission inventories compiled by the respective countries. More information about this map and its data sources can be found in Chapter 3 of this Assessment.

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August 2005

NARSTO Contact Information

Further information about NARSTO and its contacts is available on the Web site www.cgenv.com/Narsto

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PREFACE

NARSTO is a public/private partnership whose membership spans government, the utilities, industry, and academia throughout Canada, the United States, and Mexico. NARSTO's primary mission is to coordinate and enhance policy-relevant scientific research and assessment of tropospheric pollution behavior; its activities provide input for science-based decision-making and determination of workable, efficient, and effective strategies for local and regional air-pollution management. NARSTO was formerly an acronym for "North American Research Strategy for Tropospheric Ozone." However, the term NARSTO has become a wordmark signifying this tri-national, public-private partnership for dealing with multiple features of tropospheric pollution, including ozone and suspended particulate matter. More information on NARSTO can be found at http://www.cgenv.com/narsto/.

NARSTO conducted and released two previous Assessments on ozone and particulate matter (***An Assessment of Tropospheric Ozone Pollution: A North American Perspective*** – 2000 and ***Particulate Matter Science for Policy Makers*** – 2004). Both of these Assessments recommended improvements in emission inventory programs. To investigate and pursue these recommendations, NARSTO supported an Emission Inventory Workshop in October 2003 in Austin, Texas. Based on the results of the two previous Assessments and the Workshop (reference the NARSTO website for additional information), NARSTO decided to conduct an Assessment of Emission Inventories to identify actions needed to enhance these programs. This document is the result of that Assessment.

This NARSTO Emission Inventory Assessment was prepared by the NARSTO Emission Inventory Steering Committee. The project was initiated in October 2003. The first draft of this document was reviewed by the NARSTO members and interested public parties in October 2004. A second draft, prepared in response to comments received from that review, was reviewed by an external scientific review panel in February 2005. The third draft was prepared in response to comments received from that panel. The third draft was presented to the NARSTO Executive Assembly in April 2005 and approved for publication following technical edit. This is the final report of the Assessment.

NOTE ON URLS

This document contains a number of universal resource locators (URL) and hyperlinks to web addresses. At the time of document preparation, these were all checked and verified for proper functionality. URLs may change over time; therefore, NARSTO does not guarantee their future functionality for users wishing to access specific web sites.

DISCLAIMER

The views expressed in this Assessment are those of the authors and do not necessarily reflect the views or policies of any organization within or outside the NARSTO community. Further, any policy implications derived from the material herein cannot be considered to be endorsed by NARSTO or its member organizations.

ACKNOWLEDGMENTS

NARSTO would like to thank and acknowledge the many people and agencies who made this report possible. This includes the NARSTO leadership, the Emission Inventory Steering Committee and Co-Chairs, chapter authors and contributors, and funding organizations.

The Co-Chairs of the NARSTO Emission Inventory Assessment were: Marc Deslauriers (Environment Canada), Howard Feldman (American Petroleum Institute), Christopher Frey (North Carolina State University), David Mobley (U.S. Environmental Protection Agency), Leonora Rojas-Bracho (National Institute of Ecology of Mexico), and Susan Wierman (Mid-Atlantic Regional Air Management Association).

The NARSTO leadership who also contributed significantly to the planning and preparation of the document included: Steven Cadle, Co-Chair, NARSTO Emission Team (General Motors); Jeremy Hales, NARSTO Management Coordinator (Envair); George Hidy, Co-Chair, NARSTO Assessment Team (Envair); David Mobley, Co-Chair, NARSTO Emission Team (U.S. EPA); Jeffrey West, NARSTO Associate Management Coordinator (NOAA); and Susan Wierman, Co-Chair, NARSTO Assessment Team (Mid-Atlantic Regional Air Management Association).

NARSTO would also like to thank the lead and contributing authors of the nine chapters of this Assessment:

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Chapter 8 – *Methods for Assessment of Uncertainty and Sensitivity in Inventories*: Lead Author: Christopher Frey (NCSU). Contributing Author: Junyu (Allen) Zheng (NCSU).

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The External Scientific Peer Review Panel's comments and suggestions were an important contributor to the final document. The Panel was chaired by Donald C. McKay of Canadian ORTECH Environmental. Other panel members were: Lyle R. Chinkin, Sonoma Technology, Inc.; Robert Harley, University of California, Berkeley; Wick Havens, Pennsylvania Department of Environmental Protection; Luis R. Sánchez Cataño, independent environmental consultant in Mexico City; John G. Watson, Desert Research Institute; and Stephen Ziman, ChevronTexaco Energy Technology Company.

Funding for this Assessment was provided by the following sources: California Air Resources Board; Commission for Environmental Cooperation; Environment Canada; U.S. Department of Transportation, Federal Highway Administration; Mid-Atlantic Regional Air Management Association; National Oceanic and Atmospheric Administration, Aeronomy Laboratory; Southern Company Services; New York State Energy Research and Development Authority; U.S. Department of Energy, Office of Science; U.S. Environmental

Protection Agency, National Exposure Research Laboratory; U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards; and the U.S. EPA/STAPPA-ALAPCO Emissions Inventory Improvement Program.

NARSTO would like to thank all the authors and reviewers whose generous contribution of time and effort in reviewing this Assessment made its timely compilation possible.

Finally, a special acknowledgment is given to David Mobley of the U.S. EPA for coordinating the overall planning and preparation of this NARSTO Emission Inventory Assessment.

EXECUTIVE SUMMARY

Improving Emission Inventories for Effective Air Quality Management Across North America: A NARSTO Assessment examines the current state of emission inventories for Canada, the United States, and Mexico, and offers suggestions for improvement. Prepared to address the needs of a broad user base composed of decision makers as well as developers and users of emission inventories, the Assessment begins with a vision statement that sets the goal for future inventory development: **the ultimate emission inventory is one that includes all significant emissions from all sources, time periods and areas, with quantified uncertainties, and timely accessibility**. The Assessment concludes with prioritized recommendations and an action plan for achieving that vision.

The Assessment has four functions; it:

- Identifies many national, state or provincial, regional, local and specialty inventories and provides information for accessing them.
- Describes the methods used to generate emission inventories and discusses the strengths and weaknesses of these methods as well as of the resulting inventories.
- Directs considerable attention to methods for determining uncertainties in emission estimates, and provides comparisons between emission estimates and independent measurements for key emission sectors.
- Suggests ways to improve future inventories, characterize their uncertainty, and improve the delivery of emission data to users.

The motivation for the Assessment, the strengths and weaknesses of current emission inventories and emission models, and the recommendations and action plan for resolving these shortcomings are summarized below.

MOTIVATION FOR THE ASSESSMENT

Emission inventories are the foundation of air quality management. Although current inventories capably support many emission management and regulatory activities, they have shortcomings that could be reduced by application of improved inventory development, analysis, and dissemination techniques. In the past, most air quality management goals have focused on emissions from major, and relatively well characterized, source categories. As recently implemented regulatory programs take effect, however, emissions from these sources will decline substantially. The remaining emissions will be more evenly distributed over source categories that are much more difficult to measure or model. In this situation, errors in emission estimates from smaller individual sources will have greater consequences. These consequences could range from wrongly identifying a pollutant that should be controlled to overlooking source categories whose control could result in more cost-effective emission reductions.

The following text box illustrates this problem. It shows that the cost consequences of unreliable or incomplete emission information can be considerable. Incomplete or inaccurate information also limits the development of effective policies. Unreliable or incomplete information on sources of toxic air pollutants, for example, can lead to inaccurate assessments of exposure. Likewise, incomplete information on the chemical composition of fine particulate matter limits the characterization of the health effects of airborne particles and the development of more effective control measures. The policy consequences of poor information on emissions, therefore, are actions that may be misplaced or ineffective in achieving the goal of protecting human health and welfare.

Consequences of Incomplete Information

Incomplete or unreliable emission information can have serious consequences in terms of the cost and effectiveness of air pollution control strategies. The case in Houston, Texas is a good example. Houston is currently in noncompliance with federal air quality standards for ozone. The state had to devise a strategy that would result in compliance with the Clean Air Act ozone standards or face federal sanctions. Based on existing emission inventories, the state concluded that reducing NO_x emissions by 90 percent would be effective in meeting the standards. In 2000, a field experiment was conducted in Houston to examine the atmospheric chemistry of the Houston area and the emissions driving this chemistry. The study discovered sources of highly reactive volatile organic compounds that were not included in the existing inventory. Revised emission estimates and new modeling showed that achieving the desired air quality improvements would require reductions in these volatile organic compounds but only an 80 percent reduction in NO_x emissions. A NO_x-only strategy would not have been as effective as expected. It would also have been costly. Interest groups active in the decision process have asserted that ten years after implementation, a 90 percent reduction in NO_x emissions would result in 65,000 fewer jobs and a $9 billion smaller regional economy compared to a 79 percent NO_x reduction strategy that allowed emissions trading. While this analysis did not account for the costs of VOC controls, even when they are included the revised control strategy results in substantial annual cost savings. Clearly, obtaining accurate and complete emission estimates is very important.

STRENGTHS AND WEAKNESSES OF CURRENT INVENTORIES

Over the past 40 years, emission inventories in all three countries of North America have improved dramatically in terms of accuracy and completeness. Today, air quality managers have a good understanding of the emissions from major point sources, and they have used this knowledge in developing effective actions for reducing them. Models for estimating emissions from mobile sources have been continuously improved. The importance of natural, biogenic emissions has been recognized, and this knowledge has affected the design of air quality management strategies in regions where these emissions are significant. In Canada and the United States, emission inventories and models can provide quantitative estimates of emissions at national, state or provincial, and county (or their equivalent) levels for many source categories, and there is an improved understanding of the relative importance of various source categories to specific air quality problems. Air quality managers can use these inventories to track emission trends and to evaluate the effectiveness of measures designed to reduce these emissions. In Mexico, emission inventories have been completed for the Valley of Mexico and the states bordering the United States. The first national inventory will be released in the near future.

In spite of this progress, emission inventories in all three countries of North America have significant weaknesses or shortcomings that will become increasingly important for future air quality management problems. Addressing these problems is the focus of the findings and recommendations of this Assessment, and it is worthwhile summarizing them here:

- Quality assurance and quality control procedures are not strictly applied in the development of most emission models and inventories, and the documentation of uncertainties and data sources in emission inventories is not adequate.
- There are significant uncertainties in mobile source inventories particularly regarding the speciation of volatile organic compounds, the magnitude of carbon monoxide emissions, and the temporal trend of nitrogen oxide emissions.
- Emissions for many important categories such as fine particulates and their precursors, biogenic emissions, toxic air pollutants, ammonia, fugitive emissions, open biomass burning, and many other area sources are uncertain and inadequately characterized.

- Emission estimates are frequently based on a small number of emission measurements that may not be representative of real-world activity, either because the samples do not appropriately cover the range of real-world activity patterns or because the measurement methods are not intended to capture such patterns. Thus, the precision and accuracy of estimates developed from such measurements are limited.
- The process for developing information on emissions with the kinds of spatial and temporal resolution needed for location-specific air quality modeling is problematic and a source of unquantified uncertainty in model results.
- Methods used to estimate emissions of individual chemical species in many emission models are out of date and produce estimates that are not reliable.
- Current emission inventories are not developed and updated in a timely manner.
- Differences in current emission inventories in the three countries create difficulties for jointly managing air quality.

FINDINGS AND RECOMMENDATIONS

The Assessment culminates in eight principal findings and recommendations, applicable in all three countries of North America. The first of these is the most critical one. The remaining findings and recommendations are of roughly equal priority. This second tier can be divided into recommendations dealing with emission data (items 2, 3, 4 and 8) and with emission data processing (items 5, 6 and 7).

1. Reduce Uncertainties Associated with Emissions from Key Undercharacterized Sources

Finding

Comparisons of national emission inventories with ambient measurements and other independent measures indicate that emission inventories for certain source categories and pollutants, particularly gaseous emissions from electric utilities in the United States, are well characterized and reported. Emission inventories for other source categories and pollutants are much more uncertain. Of particular concern are nonpoint sources including transportation and fugitive emissions from industrial facilities, landfills, sewage disposal systems, and feedlots, as well as sources of organic compounds, carbonaceous particulate matter, ammonia, and hazardous air pollutants.

Recommendation

Focus immediate measurement and development efforts on areas of greatest known uncertainty within current emission inventories. Systematically continue to improve emission inventories by applying sensitivity and uncertainty analyses and by comparing them to independent sources of measured data. Such comparisons will help identify subsequent improvement priorities.

Resources must be targeted to reduce the greatest sources of uncertainty and focused on those source categories whose control will be most effective in reducing costs and health risks while achieving air quality management goals. Various expert panels have proposed lists of priority emission inventory development needs along these lines. The following list of emission sources, consolidated from these recommendations, represents the highest priority needs for improving emission inventories.

- Size-segregated, speciated emissions of fine particles and their precursors, including black and organic carbon emissions
- Toxic and hazardous air pollutants
- Emissions from onroad vehicles
- Emissions of ammonia from agricultural and other area sources
- Speciated, spatially and temporally resolved organic emissions from biogenic sources
- Emissions of volatile organic compounds and organic hazardous air pollutants from petrochemical and other industrial facilities
- Emissions from offroad mobile sources, including farm and construction equipment, aircraft and

airport ground equipment, commercial marine facilities, and locomotives

- Emissions from open biomass burning, including agricultural and forest prescribed burning, wildfires, and residential backyard burning
- Residential wood combustion in woodstoves and fireplaces
- Paved and unpaved road dust.

2. Improve Speciation Estimates

Finding

Contemporary air quality issues such as particulate matter and ozone nonattainment and identification of "hot spots" of hazardous air pollutant concentrations require detailed information about the species being emitted from sources.

Recommendation

Develop new and improve existing source speciation profiles and emission factors plus the related activity data needed to more accurately estimate speciated emissions for particulate matter and its precursors, volatile organic compounds, and toxic air pollutants.

3. Improve Existing and Develop New Emission Inventory Tools

Finding

Technical advances in instrumentation and computation have allowed measurements and analyses that were not previously possible; continuing development of these and other technologies is likely to further improve emission inventory measurements and analyses. Improvements in modeling and data processing capabilities provide the basis for more detailed and more accurate emission models and processors.

Recommendation

Continue the development of new and existing measurement and analysis technologies to enable expanded measurements of emissions and ambient concentrations. Apply these technologies in developing emission model and processor capabilities to allow models to more closely approximate actual emissions in time and space.

4. Quantify and Report Uncertainty

Finding

The emission inventories, processors, and models of Canada, the United States, and Mexico are poorly documented for uncertainties; as a result, the reliability of the emission estimates cannot be quantified.

Recommendation

Develop guidance, measures, and techniques to improve uncertainty quantification, and include measures of uncertainty (including variability) as a standard part of reported emission inventory data.

5. Increase Inventory Compatibility and Comparability

Finding

Numerous emission inventories have been developed by different organizations for different purposes and covering different spatial domains. Although there have been substantial improvements in reporting national emission inventories in a mutually consistent way by categories, estimation methods, and chemical constituents, further efforts are needed to make these diverse emission inventories more comparable across organizations, purposes, geographies, and time periods.

Recommendation

Define and implement standards for emission inventory structure, data documentation, and data reporting for North American emission inventories.

6. Improve User Accessibility

Finding

The accessibility of emission inventories or emission models is presently limited because of the sheer size of the databases and the cumbersome manner in which the data have been reported and archived. Improved accessibility to emission data is critical to meet the diverse needs of the user community.

Recommendation

Improve user accessibility to emission inventory data, documentation, and emission inventory models through the Internet or other electronic formats.

7. Improve Timeliness

Finding

Timely and historically consistent emission inventories are crucial elements for stakeholders to assess current conditions and estimate progress in improving air quality.

Recommendation

Create and support a process for preparing and reporting national emission inventory data on a yearly basis.

8. Assess and Improve Emission Projections

Finding

Emission projections are critical to developing control strategies for attaining air quality standards and goals, and for evaluating future year impacts associated with regulatory development.

Recommendation

Emission projection methodologies for all emission inventory sectors in North America should be evaluated to determine the accuracy of past projections and identify areas of improvement for future projections.

STEPS FOR IMPLEMENTATION

The authors of this NARSTO Assessment maintain that implementation of the above-listed recommendations over the next 10 years is essential to approach the vision of this Assessment. Progress toward achieving this vision will require cooperation among Canada, the United States, and Mexico. It will also require individual actions by these national agencies to assist state, local, and provincial agencies in meeting their inventory development responsibilities. It will require investments in educating the next generation of emission scientists and engineers, and it will require investment in the tools needed to construct the emission inventories of the future. Country-specific implementation plans will need to take into account the increasing trend toward integrated air quality management, and they should involve continued and extensive cooperation among the involved agencies at all levels of government as well as with stakeholders in industry and the research community.

Four actions are considered to be common to Canada, the United States, and Mexico in implementing the recommendations:

- Implementation efforts should be planned, coordinated, and executed by Environment Canada, the U.S. Environmental Protection Agency, and *Secretaría de Medio Ambiente y Recursos Naturales* (SEMARNAT) over the next 10 years. Interim milestones for emission inventory improvement should be developed to support regulatory deadlines in each country.
- Federal support for regional, state, and provincial emission inventory development and improvement needs to be on-going to ensure that emission inventories are able to provide the required quality of information.
- Interaction and collaboration among and across Canada, the United States, and Mexico should be maintained and enhanced.
- Increased training of agency staff at federal, state and provincial, and local levels and industrial stakeholders will be required to effectively implement these recommendations.

Development of complete implementation plans for Canada, the United States, and Mexico is beyond the scope of this Assessment. However, country-specific action plans with approximate estimated costs for taking the first steps towards full implementation of the recommendations of this Assessment are briefly outlined below.

INITIAL ACTION PLAN FOR CANADA

- Improve the emission inventory for $PM_{2.5}$ and its precursors.
- Improve speciation profiles for fine particulate matter and volatile organic compounds.

- Improve point source emission estimates.
- Update the national emission inventory database system.
- Improve the timeliness for the dissemination of the national emission inventory trends and projections.
- Engage appropriate stakeholder groups to develop a national strategy to implement the eight recommendations of this Assessment.

INITIAL ACTION PLAN FOR THE UNITED STATES

- Enhance the emission inventories and associated tools (such as SPECIATE) for $PM_{2.5}$ and its precursors, especially for carbonaceous particles.
- Establish emission inventory reporting requirements for hazardous air pollutants and integrate data into the National Emission Inventory.
- Improve the capacity of state, local, and tribal agencies to develop inventories to meet State and Tribal Implementation Plan and other regulatory requirements.
- Engage appropriate stakeholder groups to develop action plans to implement the full range of recommendations.
- Increase support of research to develop and improve emission inventories.

INITIAL ACTION PLAN FOR MEXICO

- Complete the National Emission Inventory for Mexico.
- Develop and implement a communication strategy to disseminate the results of the National Emission Inventory.
- Develop and fulfill requirements at the national level to enable emission inventory updates on a 3-year cycle.
- Build emission inventory development capacity among state environmental agencies.
- Expand capabilities among Mexican agencies.
- Continue to improve the capabilities to develop emission inventories through interactions with the United States.
- Improve programs to conduct direct emission measurements by identifying sources needed to develop Mexico-specific emission factors and by developing vehicle fleet characterization data for mobile sources.
- Develop a national emission data system.
- Increase human resources available for emission inventory compilation, maintenance and update.

The costs of implementing these initial steps, in $US, are estimated to be approximately $6 million per year for Canada, $35 million per year for the United States, and $7 million per year for Mexico over 3 to 5 years. These expenditures would be in addition to current investments in emission inventory development.

Current spending on emission inventories is roughly $40 million per year across North America. This is obviously a substantial sum. To put this sum into perspective, it has been estimated that the United States spent about $19 billion in 1999 to meet the requirements of the *Clean Air Act*. Thus, for every $1,000 spent to meet the *Clean Air Act* requirements, about $2 is spent to characterize emissions. Doubling this investment would significantly improve knowledge of emissions and the ability to design better-targeted air quality management strategies. Better-targeted strategies, in turn, should reduce the cost of regulatory compliance. A modest increase in expenditures on inventories should lead to far more cost-effective protection of our health and ecosystems.

CONCLUSION

Emission inventories, essential to achieving air quality improvements, face challenging requirements in the next 10 years. The findings, recommendations, and action plans included in this Assessment provide specific direction for future development and begin to identify the resources necessary to achieve these

improvements. The priorities and resources available for implementing this Assessment's recommendations and action plans will differ among Canada, the United States, and Mexico, but continued coordination and collaboration will enhance the effectiveness of individual efforts. Significant public and private expenditures will be needed to address priority and long-term needs.

CHAPTER 1

INTRODUCTION

Chapter 1 Objective: ***To define the rationale, objectives, scope, and audience for this Assessment, as well as to describe the logical progression of its primary chapters.***

Modern emission inventories have evolved to become a cornerstone of air pollution management practice. Providing consolidated information to quantify pollutant emission rates associated with specific sources and time periods, such inventories have been – and will continue to be – critical resources for air quality modeling, local and regional regulatory planning, and international cooperation. Resulting in large part from the efforts of scientists and engineers working in this field, emission inventory sophistication and complexity have increased significantly during the past several decades, to a point where it is difficult to imagine how North American pollution management strategies could operate in the absence of this important information resource.

This fundamental and critical importance provides an increasingly strong incentive to continue emission inventory improvement. In response to this need, this Assessment addresses the status of current North American emission inventories as well as projected future progress in inventory applications and research. This Assessment's primary goal is

. . . to guide the development of future inventories, as well as to facilitate the use of inventories for atmospheric process evaluation and air pollution management.

In addressing this goal this Assessment takes a critical and in-depth view of existing inventories, and suggests a number of areas for their future improvement. It does so, however, acknowledging the efforts and contributions of those who have developed the field to its present state.

The development and application of emission inventories is a particularly timely subject for several reasons. The previous NARSTO Assessments of ozone and airborne particulate matter (PM) (NARSTO, 2000; NARSTO, 2004) identify a number of desired inventory improvements that are essential for development of more efficient and reliable ozone- and PM-management strategies in the future.[1] Moreover, the recent U.S. National Research Council reports *Air Quality Management in the United States* (NRC, 2004a) and *Research Priorities for Airborne Particulate Matter* (NRC, 2004b) spotlight several areas where substantial enhancements are needed, including new emission monitoring techniques, regularly updated and field-evaluated inventories, organic PM precursor speciation, and the characterization of physiologically important PM components. The first of these NRC reports notes that, while continuous in-stack monitoring allows direct and reliable quantification of emissions from most large stationary sources, substantial future progress will be necessary to provide a corresponding level of confidence for most other source categories. These reported recommendations reflect relatively recent findings regarding health impacts of PM and other pollutants. They also recognize that emission inventories remain an essential component of air-pollution modeling and management.

Four additional features further emphasize the need for an emission inventory assessment. The first of these is the evolving recognition that traditional

[1] The emission inventory chapters of these two Assessments tabulate annually averaged national North American inventory data for primary PM emissions as well as for emissions of gaseous PM and ozone precursors. As a partial response to actions recommended in these Assessments, NARSTO hosted a technical conference in October 2003, entitled Innovative Methods for Emission Inventory Development and Evaluation (Hidy, Mobley and Cadle, 2004). Presentations from this workshop form an important technical basis for the current Assessment, and can be viewed on the NARSTO website: www.cgenv.com/narsto.

emission inventories contain substantial (and largely unspecified) levels of uncertainty, which can severely limit the reliability of associated pollution-management strategies.[2] Systematic identification and quantification of these uncertainties are essential to further progress in the field. Second, past successes in reducing emissions from many traditional sources have led to a situation wherein substantial emission fractions originate from malfunctioning and/or previously uncharacterized sources. Characterization of many of these emission categories requires new methodologies.

A third feature reflects recent scientific advances suggesting innovative techniques that are potentially applicable for future emission inventory development and verification. It is probable that application of these methods, in conjunction with the more established approaches, will be highly beneficial to the overall inventory development and verification process. There is no doubt that current emission inventory activities provide information that has been, and will continue to be, invaluable for modeling and management efforts. However, simply increasing these traditional activities is unlikely to reduce associated uncertainties in an efficient or cost-effective manner. Thus, a systematic and serious consideration of new and innovative methods to augment traditional methodologies is in order.

Fourth, inventory-related needs among Canada, the United States, and Mexico are diverse. Stemming from geographical and industrial differences as well as from varying states of inventory development, this diversity suggests that Canada, the United States, and Mexico will emphasize different priorities for immediate development efforts. At the same time, there is considerable benefit in maximizing consistency and transparency among Canadian, U.S., and Mexican inventories.

In recognition of these considerations, this Assessment takes a decidedly forward-looking perspective, which is reflected by the following sub-objectives to its primary goal:

1. **Promote Efficient and Effective Use of Current Emission Inventories and Identify Critical Uncertainty Areas in these Inventories.**

- Provide a comprehensive resource for locating and acquiring current North American inventories.
- Provide a comprehensive guide to emission inventory application tools, including emission models and emission processors.
- Assess the strengths and weaknesses associated with emission inventories in general as well as with selected specific inventories.
- Provide guidelines for efficient and appropriate application of existing inventories.

2. **Guide the Development of Future Emission Inventories.**

- Itemize advanced and potential future techniques for emission inventory development, including their potential applications, their prospects for enhancing inventory development, and their implementation requirements and timelines.
- Encourage the systematic incorporation of uncertainty analysis in inventory preparation, and promote the routine inclusion of uncertainty information in published inventories.
- Discuss possible future archival methods for emission inventory data, which will ensure greater accessibility and more reliable application.
- Encourage the further development of instrumentation, interpretive methodologies, and archival/retrieval systems.
- Encourage the development of user-friendly interfaces for emission inventory databases, to provide improved methods of data retrieval and interpretation.
- Encourage harmonization of emission inventories prepared for different and adjoining areas within national boundaries and especially across international borders.

[2] Although several relatively recent developments can be cited, the Texas 2000 field study's discovery of major underestimates in volatile organic compounds (VOCs) in Houston's emission inventory provides a key example to illustrate this point (see Section 7.3).

3. **Establish Inventory Development Guidelines for the Future.**

- Recommend actions to enhance the timeliness, quality, and cost-effectiveness of current emission inventory approaches.
- Recommend action items for development and deployment of the advanced methods discussed in this document.

1.1 AUDIENCE AND SCOPE

To fulfill the above objectives, this Assessment is directed to a diverse audience. In particular, it focuses on a variety of decision analysts, scientists, and stakeholders, including

- **Decision makers responsible for funding and setting the priorities for emission inventory development and for research needed to improve the procedures and technologies used to produce these inventories.**
- **Users of emission inventories**
  - Policy analysts, planners, and regulators
  - Air quality modelers
  - Field campaign designers and practitioners
  - Community interest groups
  - Negotiators and implementers of international agreements.
- **Developers of emission inventories**
  - Developers in organizations at all levels in Canada, the United States, and Mexico
  - Developers of tools to derive emissions from process information
  - Developers of tools to measure emissions.

In addressing its audience, this Assessment confines its scope mainly to North American emissions and to criteria pollutants and their precursors, although some discussion of non-criteria pollutants such as greenhouse gases and toxic air pollutants is naturally included owing to commonality of measurement, characterization, and data-archiving technologies.

This Assessment does not duplicate currently available documents in the emission inventory field. It is not a methods manual and, although it provides a valuable user's guide to locating current emission inventory data, it is not a compendium of these data. Rather, this Assessment provides an examination of uncertainties in current emission inventories, identifies critically important aspects of these uncertainties, and indicates future pathways for improvement. Important aspects of this improvement process include the application of evolving and anticipated future technology, as well as measurement and database quality.

1.2 REPORT STRUCTURE

The chapters of this Assessment follow a progression that closely reflects the objectives and scope noted above. Chapter 2 responds to sub-objectives 2 and 3 by providing a summary vision statement which, from the authors' viewpoint, sets forth a desired yet technologically feasible state of future North American emission inventories and emission inventory research. Chapters 3 and 4 address sub-objective 1 by presenting an overview of current North American emission inventories, emission processors, and emission models, including techniques for their development. This is followed by Chapter 5, which examines strengths and weaknesses of the current inventories and their associated uncertainties. These chapters are intended to set a basis for subsequent discussion and to serve as a location resource for those seeking current inventory information. As noted above, this Assessment is not intended to be a data compendium but rather to serve as a convenient "signpost" for information.

Chapter 6 takes a more forward-looking perspective, addressing sub-objectives 2 and 3 by providing an overview of future and evolving emission measurement technology, interpretive techniques, and data management practices. Individual methods described here are accompanied by discussions of potential feasibility and projected future applications. Chapter 7 discusses several "reality checks" of specific emission inventories using a variety of independent

measurements and back-checking techniques, and provides further indications of inventory reliability and uncertainty levels.

Uncertainty is a particularly challenging issue owing to the multitude of potential uncertainty sources, the lack of quantitative treatment in most past efforts, and the technical difficulty of grounding the multifaceted uncertainty issue on a sound mathematical basis. Chapter 8, which is rooted in basic statistical theory, addresses the issue of setting a consistent framework for interpreting inventory uncertainties. It presents an ambitious objective of providing quantitative uncertainty analysis in future inventory studies.

Chapter 9 synthesizes the previous seven chapters to construct a series of findings and recommendations for moving from the present state of emission inventory science to the advanced state anticipated in Chapter 2. Because Canada, the United States, and Mexico have different development issues and priorities, this chapter lists individual action plans for the three countries, which include specific items for primary focus in achieving the noted recommendations. While establishing specific blueprints for action is beyond the scope of this document, these action plans are intended to assist the individual countries in their subsequent, more definitive planning processes. Because the anticipated cost of improving emission inventories is an element of the planning process, the action plans address anticipated costs in general terms; refer to sections 3.5 and 9.2.1, 9.2.2, and 9.2.3.

Despite this document's chapter sequence and logical flow, it need not be read cover-to-cover. Rather, each chapter is designed as a stand-alone unit and is intended for direct reader access without necessarily studying the preceding material: for example, readers seeking information on emission inventory sources can go directly to Chapter 3, while those interested in basic statistical methods for analyzing uncertainty can proceed immediately to Chapter 8. In this manner, the document can treat its variety of subjects in sufficient detail to convey salient information without unduly burdening the reader pursuing a specific subject area.

With its stated objectives, its audience, and its presentation, this Assessment is intended to stimulate creative thinking and future activity by instrument and methodology developers, decision makers, policy analysts, and inventory developers and users. As is noted in Chapters 2 and 9, significant advancements in emission inventory science are anticipated during the coming decade as a consequence of combined efforts of members of these communities. This Assessment is intended to serve as a first step in that direction.

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CHAPTER 2

VISION FOR FUTURE NORTH AMERICAN EMISSION INVENTORY PROGRAMS

Chapter 2 Objective: ***To describe the parameters that will guide the development and application of future emission inventories.***

Emission inventories are a critical foundation of air quality management activities. Future inventories must meet growing demands for ever more detailed chemical speciation, temporal and spatial resolution, data quality, data accessibility, and affordability. This chapter defines a "vision" for future emission inventory programs that is designed to achieve the goal of this Assessment: to guide the development of future inventories and to facilitate their use in atmospheric process evaluation and air pollution management. The vision follows from an understanding of emission inventory applications, the air quality management framework within which emission inventories are developed and implemented, and the issues emission inventories will need to address in the future.

Both anthropogenic activities and natural processes emit gases and particles into the atmosphere. Most pollutants emitted by anthropogenic activities, such as automobiles, electric utilities, and industrial plants, can be controlled. Natural sources such as wildfires and dust storms are usually not manageable. Anthropogenic sources are generally characterized as point, nonpoint or area, and mobile. Point sources (chemical plants, incinerators, industrial boilers, and power plants) are emitters located at fixed geographical coordinates that are large enough to be enumerated individually. A large facility, such as a chemical manufacturing plant, may have many individual point sources. Stationary sources, such as such as dry cleaners, wood stoves, and home furnaces, whose individual emissions are too small to be considered as emission points in most analyses and uses are usually treated as nonpoint sources. Agricultural tilling, controlled burning, construction activities, and dust from mining also fall into this category. Some facilities such as refineries contain both point sources and nonpoint sources. The mobile-source category includes both onroad vehicle emissions and offroad sources such as construction equipment, farm tractors, airplanes, railroads, and ships. Natural emissions include forest fire smoke, volcanic particles and gases, nitrogen oxides (NO_x) from lightning, volatile compounds from vegetation, sea salt particles, and wind-blown dust.

Emission inventories are developed to characterize these sources and to provide air quality managers, modelers, and other users with information on the sources of air pollutants and their precursors. Inventories are also essential for assessing whether or not air quality regulations are having the intended effect, a process often termed "accountability." Emission inventories were originally based on annual equivalent emission estimates and were developed on spatial and temporal scales generally relevant to addressing near-source, urban emissions. Early inventories supported the design and evaluation of local air pollution control programs. Later emission inventories served a much broader set of applications, ranging from identification and location of primary pollutant sources to provision of detailed, gridded emission data for air quality modeling (see Box 2.1). As even larger spatial-scale issues emerged, involving regional to global impacts (e.g., acid rain, regional haze, ground-level ozone, stratospheric ozone depletion and climate change), emission inventories were extended to cover very large areas.

Box 2.1. Emission Inventory Applications

- Implementation Plan or Control Strategy Development
- Compliance Determination
- Emission Cap and Trade Activities
- Early Reduction Program Design
- Emission Trends Analysis and Projections
- Permit Limit Determination
- Toxic Release Inventory Reporting
- Information for Public
- Excess Emission Reporting
- Emission Statement/Fee Collection
- Environmental Impact Modeling and Assessment
- International Treaty Reporting
- Field Study Design
- Real-time Air Quality Forecasting
- Conformity Analysis
- Accountability Assessments

Table 2.1 summarizes the temporal, spatial, species, and process-level data needed for the representative applications listed in Box 2.1. The diversity of these applications, and the differing levels of detail demanded in association with them, highlight the difficulty developers and users face in harmonizing emission data.

Calls for improving emission inventories are not new. In the United States, two recent reports issued by the U.S. NRC have highlighted the need for continued improvement in emission inventories (NRC, 2004a,b). In addition, the U.S. *Clean Air Act* Advisory Committee's (CAAAC's) Air Quality Management Working Group is working with the U.S. Environmental Protection Agency (U.S. EPA) to develop a response to the U.S. NRC's recommendations on air quality management (CAAAC, 2004). This NARSTO Assessment addresses the recommendations in the two NRC reports as they pertain to emission inventories and is intended to coordinate with the CAAAC in developing their recommendations.

The atmospheric chemistry community now recognizes that air pollution is multi-scale and that efforts to systematically characterize and manage airborne pollution and its effects often requires knowledge of emission fluxes over a wide range of spatial scales. For example, photochemical oxidant and PM pollution are significantly influenced by emissions and transport on local to continental (or greater) scales. This knowledge motivates our vision for high-quality emission inventories for North America: that they have sufficient resolution to deal with pollution issues on neighborhood to hemispheric scales.

In addition to covering a variety of spatial scales, future emission inventories will need to be more current and better able to address problems requiring higher temporal resolution. Current emission inventories are often based on information that may be several years old. Emission inventories and projections need to be dynamic and regularly and consistently updated to represent the conditions in changing population, transportation, energy, manufacturing and other important emission sectors. New types of air quality models and new uses for their output will, as discussed below, require emission inventories with both high spatial and temporal resolution.

Accurate emission inventories are necessary for characterizing and assessing current air quality and global change issues. More importantly, they are critical to the design and evaluation of cost-effective control strategies to address these problems. This includes the necessity to determine progress towards air quality goals, and make any necessary mid-course corrections in control levels. Any vision for future North American emission inventory activities

Table 2.1. Summary of Emission Inventory Resolution by Application.

Emission Inventory Application	Temporal	Spatial	Species	Process-Level Data
Control strategy development including mid-course correction	Hourly up to annual, and projections	Gridded source and county	Criteria pollutants,[1] precursors,[2] and hazardous air pollutants (HAPs)	Detailed stack and process parameters
Compliance determination	Hourly up to annual	Source	Criteria pollutants & HAPs	Limited
Emission cap and trade activities	Hourly up to annual	Source	Criteria pollutants, mercury, and greenhouse gases (GHGs)[3]	Limited
Early reduction program design	Hourly up to annual	Source	Criteria pollutants and GHGs	Limited
Emission trend analysis and projections	Annual	Source categories at state/provincial/ national level	Criteria pollutants and GHGs	Generally none
Permit limit development	Hourly up to annual	Source	Criteria pollutants	Detailed process data
Toxic release inventory reporting	Annual	Source	Toxic species, HAPs, and GHGs	None
Information for public	Annual and projections	Source to state	Criteria pollutants, HAPs, and GHGs	None
Excess emission reporting	Hourly	Source	Criteria pollutants	Detailed
Emission statement/ fee collection	Hourly up to annual	Source	Criteria pollutants	Limited
Environmental impact modeling and assessment	Hourly up to annual and projections	Source	Criteria pollutants, HAPs, and GHGs	Limited
International treaty reporting	Annual and projections	National	Criteria pollutants, GHGs, and HAPs	None
Field study design	Episodic or long term	Regional	Criteria pollutants, HAPs, and GHGs	Limited
Real-time air quality forecasting	Hourly	Gridded source and county	Criteria pollutants and precursors	Detailed stack and process parameters
Conformity analysis	Hourly	Gridded source and county	Ozone, PM, and precursors	Detailed stack and process parameters
Accountability assessment	Hourly up to annual	Gridded source and county	Criteria pollutants, HAPs & GHGs	Detailed stack and process parameters

[1] U.S. criteria pollutants for which national ambient air quality standards have been set: carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), PM, ozone, and lead. As explained in Chapter 3, Canada and Mexico have similar designations.
[2] Precursors are VOCs, size-segregated PM, and ammonia (NH_3).
[3] The primary greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

must recognize that the development of accurate, comprehensive, and timely emission inventory data will be driven by the requirement that they support effective air quality management decisions both now and in the future. Based on this recognition, the vision for future North American emission inventories is one that

… includes all significant emissions from all sources, time periods and areas, with quantified uncertainties, and timely accessibility. From this vision, the overall goal is to make inventories complete, accurate, timely, transparent, and affordable.

The following sections of this chapter summarize the current emission inventory process, the societal issues that drive it, challenges in inventory development and maintenance, and the attributes of a comprehensive emission inventory.

2.1 CURRENT EMISSION INVENTORY PRACTICE: A BRIEF OVERVIEW

An emission inventory is a collection of emission data from specified sources over a specified geographic area for a specified time period. Figure 2.1 is a flowchart of the general process employed for compiling emission inventories in Canada, the United States, and Mexico. It illustrates the complex myriad of steps in inventory development, compilation, and quality assurance. The boxes on the left of the chart list the information inputs for constructing emission inventories, while the center boxes indicate the procedural steps required for inventory construction, review, quality assurance, and completion. The right-hand side of the figure indicates some of the more important emission inventory enhancements to support their application. Feedback loops, as indicated along the bottom of the figure, involve tests, evaluations, and reviews of existing inventories which are crucial for uncertainty identification and reduction.

It is desirable to measure emissions directly for incorporation into emission inventories. However, this is not always possible. In standard practice, most emissions associated with individual sources are estimated using the following equation:

Emission rate = emission factor x

activity factor x control factor **(2.1)**

An *emission rate* is an amount of emission per unit time, e.g., kilograms of NO_x per year. An *emission factor* is a representative value that relates the amount of pollutant emitted to the atmosphere to an activity associated with that source (e.g., kilograms of NO_x emitted per unit of fuel burned). An *activity factor* is a measure of the driving force for the operation that produces emissions (e.g., kilograms of fuel burned per month or time period of interest). The *control factor* is the fraction of emission reduction in that source achieved by an add-on control device (e.g., selective catalytic reduction of NO_x) or process modification (e.g., installation of low-NO_x burners). In many cases, control factors are included within the emission factor.

Emission models are tools that apply the paradigm of Equation (2.1) to source categories with complex emission factors, activity data, and control factors. As explained in Chapter 4, emission models are used for onroad and offroad mobile sources, natural/biogenic emissions, and other sources. Models also allocate emissions by time, location, and chemical or physical pollutant species. Current-year inventories for some source categories are estimated by applying growth factors to previous inventories to reflect up-to-date or projected activity levels.

For development of an emission inventory, emissions are calculated or reported from the information sources on the left-hand side of Figure 2.1. These data can be developed and submitted by any stakeholder in the emission inventory process. Most of the basic emission inventory information is developed by the authority or governmental entity most familiar with the emission characteristics of the source or source category. Once the data are compiled, they are typically sent to national, state, provincial, tribal, or local agencies for review, incorporation of updates, and insertion of additional locally generated data. After local improvements and updates are applied, a revised emission inventory with the best information available is produced. After additional quality assurance, the inventory is released to the public.

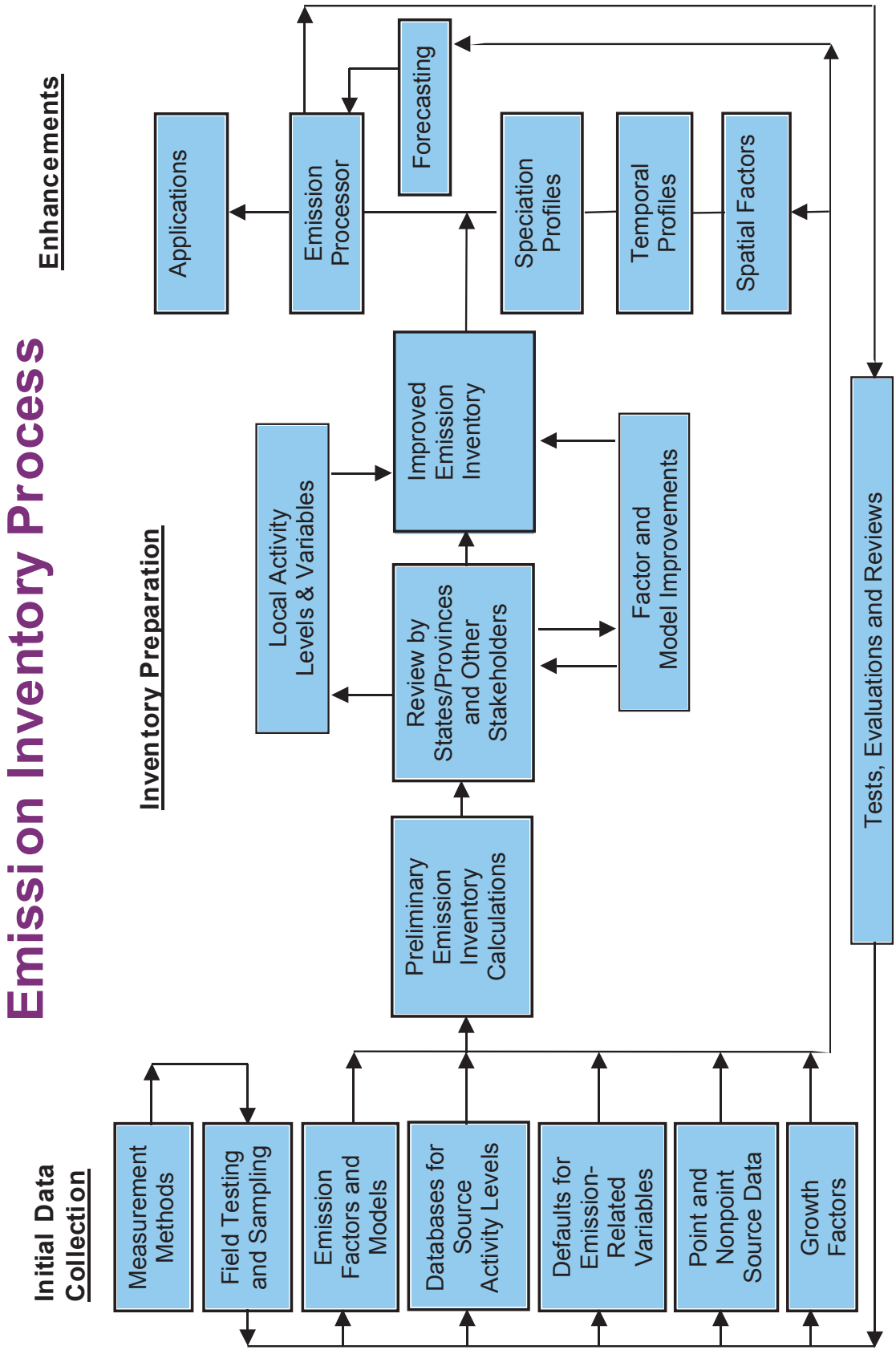

Figure 2.1. Emission Inventory Development

The new emission inventory can be applied by policy makers, atmospheric and economic modelers, regulators, and planners for their respective needs.

The enhancements on the right-hand side of Figure 2.1 illustrate how atmospheric modelers may apply temporal, spatial, and speciation allocation factors to the inventory to create appropriate inputs for detailed studies and other applications of emission inventories. As described in Chapter 4, *emission processors* are used to combine emission estimates and related data (e.g., chemical speciation profiles, temporal profiles, or spatial factors) for input into air quality simulation models. Forecasting future inventories is an important and complex step necessary for air quality management.

As discussed in Chapters 3 and 4, emission inventories and models are currently available for a variety of criteria and other pollutants, with various levels of temporal and spatial resolution. Acknowledged deficiencies in these inventories as well as emerging societal needs, however, provide a strong impetus for future improvement. Section 2.2 summarizes "societal drivers," which are defined in this context as important motivations for emission inventory applications.

2.2 SOCIETAL DRIVERS FOR FUTURE NORTH AMERICAN EMISSION INVENTORIES

The need for emission inventories derives from continuing efforts to manage air quality across North America. The issues that drive these efforts are the protection of human health, the promotion of human welfare, and the protection of natural ecosystems. This final issue – protection of ecosystems – may expand to include protection of the Earth's climate system. This section reviews the principal technical issues that are most critical to achieving these broad societal goals.

2.2.1 Photochemical Oxidants

The range of problems attributed to airborne pollutants has grown steadily over the last 50 years. After the pioneering work of Haagen-Smit and co-workers (Haagen-Smit, 1970) identified photochemical production of oxidants, especially ozone, as the cause of air quality degradation and vegetation damage in the Los Angeles basin in the 1950s, knowledge of both the spatial scale and the undesirable effects of photochemical smog have expanded significantly. Motivated primarily by evidence of the detrimental impacts of airborne oxidants on human health, the U.S. *Clean Air Act* Amendments of 1970 initiated efforts to reduce ozone and related oxidants in major cities across the United States. Similar efforts soon followed in Canada and Mexico (NARSTO, 2000). By the early 1990s, the U.S. NRC was able to demonstrate both that simple control of precursor anthropogenic VOCs would not be sufficient to control photochemical oxidant production in many areas and that long-range transport of photochemical oxidants and their precursors endowed the problem with a regional to semi-continental length scale (NRC, 1991). NARSTO's assessment of tropospheric ozone pollution in North America confirmed the multi-spatial scale nature of photochemical oxidant pollution episodes and raised the issue of a rising background level of ozone on the continental scale, motivating a continental perspective for the problem (NARSTO, 2000). Further, increasing evidence of the detrimental human and ecosystem health impacts of ground-level ozone and related oxidants have resulted in a more stringent national ambient air quality standards (NAAQS) for ozone in the United States, a review of the Canadian air quality standard for ozone, and an enhanced effort to enforce Mexico's ozone standard, particularly in the key Mexico City and Guadalajara metropolitan areas (Molina and Molina, 2004; Molina et al., 2004; NARSTO, 2000).

2.2.2 Airborne Particulate Matter (PM)

The detrimental health effects of airborne particles were recognized early in the twentieth century and were dramatically demonstrated by London's 1952 "killer fog" episode that resulted in over 4000 deaths. More recently, studies have shown that adverse health effects continue to be linked with exposure to particles, even at levels previously considered "safe" (U.S. EPA, 2004). This concern has prompted the establishment of air quality standards for airborne

PM in all three North American countries. Mexico enacted standards for particles with aerodynamic diameter less than or equal to 10 μm (PM_{10}) in 1993, and a proposal for a new standard to regulate particles with aerodymanic diameter less than 2.5 μm ($PM_{2.5}$) was published for public comment in the *Diario Oficial* (a publication similar to the U.S. Federal Register) on October 2002, but has not yet been enacted. Canada regulates $PM_{2.5}$. The United States originally established standards for total suspended particulates (TSP) and subsequently set both PM_{10} and $PM_{2.5}$ NAAQS values in response to epidemiological evidence that higher ambient airborne PM levels correlate with premature deaths from both lung and cardiovascular diseases (NARSTO, 2004; U.S. EPA, 2004). The close tie between photochemical oxidant production and secondary PM formation through SO_2, NO_x, NH_3, and VOC emissions has been recognized and discussed in previous NARSTO assessments (NARSTO, 2000; NARSTO, 2004).

2.2.3 Toxic and Hazardous Air Pollutants

In addition to criteria air pollutants, the atmosphere in urban and industrial areas is often burdened with a range of hazardous substances that can be detrimental to both human health and ecosystem viability. Under the U.S. *Clean Air Act*, the U.S. EPA has established a program to characterize emission sources and ambient concentrations of a wide range of HAPs, currently recognizing 188 chemical species or species classes believed to be threats to human health (U.S. EPA, 2003a). Particular attention has been paid to mercury and several compounds emitted by motor vehicles that are known or suspected human carcinogens, including benzene, formaldehyde, acetaldehyde, acrolein, and 1,3 butadiene. In Canada, air pollutants such as PM_{10}, NO_x, SO_2, VOC, and NH_3 have been recently been declared toxic under the Canadian Environmental Protection Act (CEPA, 1999). Since 2002, these substances along with total PM, $PM_{2.5}$, and CO are required to be reported by the Canadian industries to the National Pollutant Release Inventory (NPRI) on an annual basis. Emission reporting requirements are also being implemented in Mexico and will likely include selected toxic air pollutants. Future emission inventories will need to track emissions of the many organic HAPs out of direct concern for their health impacts as well as for their role as precursor species for criteria air pollutants like ozone and PM. The air quality modeling of toxic and hazardous air pollutants places challenging requirements on emission inventories. In addition to the difficulty of characterizing the numerous species of interest, the temporal and spatial scales may need to be very detailed to capture the urban hot spots and community analyses that are typically of concern. Toxic air pollutant issues are also likely targets for environmental justice concerns, which represent additional challenges for the analyses including the underlying emission inventory.

2.2.4 Regional Haze and Visibility

Both primary and secondary PM can contribute to the formation of persistent haze conditions that degrade visibility in both urban and rural locations. Impaired visibility is often thought of as a safety issue for aircraft or an aesthetic problem that degrades the local quality of life by obscuring vistas and casting a pall on outdoor activities. The U.S. NRC has reviewed the challenge of reducing haze levels that impair visibility at major of U.S. national parks and wilderness areas (NRC, 1993). The United States has adopted regulatory requirements to restore visibility conditions in major national parks and wilderness areas (Class I areas) to "natural conditions" by 2064 (U.S. EPA, 1999). Incremental progress toward this goal is required. The U.S. EPA has established five Regional Planning Organizations (RPOs) to develop strategies to ensure progress toward this goal. To support regional haze and visibility programs, emission inventories will need to address the precursor pollutants which are generally the same as would be needed for photochemical oxidants and PM. However, due to the long term nature of the U.S. regulatory requirements, emission inventory trends must be tracked, necessitating consistency of methodologies over time and access to and potential recalculation of archival emission data.

2.2.5 Regional Ecosystem Effects

Acid deposition (acid rain) was the first widely recognized regional scale ecosystem impact produced

by urban and industrial emissions. The process is driven by atmospheric oxidation of NO_x and SO_2, emissions to ambient nitric and sulfuric acid (HNO_3 and H_2SO_4). Problems arise when these acid gases and the secondary sulfate/nitrate PM they form are deposited downwind on poorly buffered surface waters or soils. A range of detrimental impacts on sensitive lakes, streams, and forests as well as materials damage has been documented (NAPAP, 1990).

A closely related problem involves fertilization effects caused by the deposition of airborne fixed nitrogen species (ammonium - NH_4^+ - and nitrate PM and their gas-phase precursors) to buffered soils and fresh or marine surface waters that are not susceptible to acidification. Combined with fixed nitrogen and phosphorus from fertilizer, animal waste and human sewage sources, atmospheric deposition of fixed nitrogen may contribute to fertilization of soils, lakes, streams, and estuaries leading to changes in primary productivity and, potentially, to eutrophication. This problem has been documented in the Gulf of Mexico, Chesapeake Bay and other major water bodies (U.S. EPA, 2001). Atmospheric nitrogen deposition may even have impacts on the open ocean, including the stimulation of phytoplankton blooms (Molina and Molina, 2004; Molina et al., 2004). More recently, it has been documented that high levels of fixed nitrogen deposition can have significant effects on ecosystem diversity, even when deposition receptor areas are not heavily acidified (Stevens et al., 2004).

High regional emissions of fine primary PM and PM precursors may also lead to high levels of ambient fine PM with absorption and scattering properties that significantly influence both the direct and diffuse components of photosynthetically active radiation (PAR) (Bergin et al., 2001; Cohan et al., 2002). It has been suggested that attenuation of PAR by both atmospheric PM and PM deposited on plant leaves may significantly impact solar radiation available for photosynthesis in important agricultural regions in China (Chameides et al., 1999).

Finally, as noted above, it has been recognized that photochemical oxidant production increasingly becomes a regional problem as urbanization spreads (NARSTO, 2000; NRC, 1991; NAPAP, 1990). Photochemically produced oxidants and their precursors flowing out of major cities frequently produce high levels of ozone and other oxidants all the way to the next major city, subjecting the intervening towns, forests, and agricultural areas to high oxidant exposures. Exposure to ozone and related photochemical oxidants is known to damage both native and agricultural vegetation (NRC, 1991). Thus, emission inventory requirements for regional ecosystem effects are similar to the requirements for the regional pollutants of photochemical oxidants and PM.

2.2.6 Regional Climate Change

Radiative forcing results from an imbalance in solar radiative energy coming into the atmosphere and thermal radiation going out. A positive radiative forcing tends on average to warm the surface of the Earth, and negative forcing tends on average to cool the surface. The positive radiative forcing of greenhouse gases (CO_2, CH_4, N_2O, and long-lived halogenated gases like perfluorocarbons, chlorofluorocarbons, and SF_6) in driving climate change on a global scale is widely recognized and global scale emission inventories for these species are being actively pursued (IPCC, 2001). Less widely appreciated are the important roles of several largely secondary pollutants on climate change at a regional scale. These include tropospheric ozone, a potent greenhouse gas over and downwind of large sources of precursor emissions. They also include fine particles, usually with diameters less than 1 μm, which often can be transported over regional to hemispheric scales (Menon et al., 2002). Some of these particles absorb solar radiation and warm the atmosphere. Others cool it either by reflecting solar energy back into space or by affecting the radiative properties or the lifetimes of clouds (IPCC, 2001).

A review of regional to continental impacts of PM pollution from megacities has documented several recent studies that demonstrate depression of sunshine duration and maximum daily surface temperatures in and downwind of major urbanized areas in China and India (Molina and Molina, 2004; Molina et al., 2004). Unfortunately, the uncertainties in both the regional atmospheric PM burdens, which depend on

both meteorology and precursor emission levels, and the magnitude of both direct and indirect radiative effects for PM, which depend on their composition, combine to make quantitative evaluation of their climate forcing highly uncertain (IPCC, 2001).

Characterizing the impacts of greenhouse gases and aerosols, including tropospheric ozone and PM, on regional climate change in North America will likely require emission inventories defined over different spatial and temporal scales than those needed to assess ground-level health effects from these same species. Further, emission inventories over time will be needed to address the international treaties, such as the Kyoto Protocol. This will also require consistency of methodologies over time, requiring accessibility of data. The utilization of trends from emission inventories to determine compliance with international treaties will place difficult demands on emission inventories.

2.2.7 Air Quality Forecasts

The need to characterize and manage each of the air quality-related issues described above will force disparate and challenging requirements on future emission-inventory activities. However, another emerging activity, the development of daily air quality forecasts for North American cities, may place even more demanding requirements on them. Air quality forecasting is currently the subject of significant research activity, including exploratory work under the auspices of the U.S. Weather Research Program (Dabberdt et al., 2004; Otte et al., 2005). Current or planned operational activities include the U.S. EPA's AIRNow program (U.S. EPA, 2003b) that provides short-term, city-specific air quality forecasts, and the U.S. National Weather Service program that is preparing to issue four-day ozone and PM forecasts for selected U.S. cities in the near future. Air quality forecasting capabilities are also being developed in Mexico and Canada. Such forecasts are generally motivated by public health concerns and are designed to provide warnings of unhealthful pollutant levels to sensitive sub-populations, as well as the general population, including those who spend much time outdoors for work or recreational activities and may need to be warned about potential exposures. The forecasts can enable sensitive individuals to alter their exposure to elevated levels of air pollutants, and concerned citizens can alter their activities which may add to pollution levels (e.g., commuting behavior). However, there is also a substantial and growing demand for air quality forecasts to inform institutional decision makers who must plan for air-quality-influenced demand changes or who might be asked to curtail emission-producing activities in an effort to manage air quality. Industrial and public sector organizations, including power generators, transportation companies, health care organizations, emergency responders, and recreation facilities, could all be heavily affected by air quality episodes (Dabberdt et al., 2004).

As air quality forecasting methods move from statistical evaluations to fully coupled, operational meteorological/atmospheric chemistry models, the demand for real-time, highly spatially resolved emission inventories will grow. Just as the physical weather cannot be reliably predicted without current data on wind, water vapor, and temperature, the chemical weather will be hard to predict accurately without current, highly spatially and temporally resolved emission fluxes of key primary pollutants and secondary pollutant precursors. Since severe air quality episodes are usually multi-day events with extreme pollution levels occurring after two to three days, their forecast will require both timely local and upwind regional emission data plus accurate meteorological prediction capabilities. It will be especially important to characterize on a near real-time basis the emissions from prescribed and wild fires, accidental chemical releases and spills, and major traffic jams.

These seven major issues will set the requirements for emission inventories in all three countries of North America for the foreseeable future. How these requirements will affect the development of emission inventories and their attributes will differ among them. Table 2.2 summarizes the more important inventory limitations that affect each country's ability to satisfy air quality management needs. The table identifies areas that need immediate emphasis, and it provides brief guidance on how these deficiencies might be resolved.

Table 2.2. Important Inventory Limitations and Associated Needs for Immediate Emphasis in the United States, Canada, and Mexico.

Attribute	Canada	United States	Mexico	Resolution	Potential for Support –New Methods
Composite Emission Inventory	Refine national inventory.	Upgrade NEI and components, with improved emission factors and models.	Complete detailed national inventory.	Use established methodologies with assistance of modeling techniques, and error identification.	Improved use of measurements combined with calculation methods open opportunities
Pollutant Species Resolution	Particular attention to carbon (VOC, OC, BC), $PM_{2.5}$, NH_3, wildfires, toxics	Particular attention to carbon (VOC, OC, BC), NH_3, fires, HAPs	Particular attention to carbon (VOC, OC, BC), $PM_{2.5}$, NH_3, Biomass, toxics	High priority for measurements and emission factors, Activity development	New measurement methods and reconciliation needed to address emerging issues
Uncertainty quantification	Quantify uncertainties in estimates, especially industrial sources, fire, and transportation	Quantify uncertainties in NEI, especially transportation and area sources	Estimate uncertainties and priorities for improvement	Difficult problem, requires combined measurements, and improved estimation techniques	Measurement uncertainties and reconciliation methods applied systematically.
Processing Tools	Air quality model support an important driver	Air quality model is an important driver with fine spatial and temporal resolution.	Air quality model support for cities an important driver	Emission models and processes continue to evolve;-attention to transportation and diffuse sources.	Modeling requirements need to be met with new emission models and focus on emerging pollutant specs.
Spatial and Temporal Resolution	Concern for O_3 and $PM_{2.5}$ broaden spatial and temporal scale concerns.	Extremes in space and time scales for models crucial for health effects and for intercontinental assessment.	Ill defined area and fugitive sources need multiscale quantification.	Seek reasonable uniformity in reporting emissions by country; attention to improved estimates by scale and time.	Modeling continues to push extremes of spatial and temporal scales for improved emission estimation.

Table 2.2. Concluded.

Attribute	Canada	United States	Mexico	Resolution	Potential for Support –New Methods
Air Quality Management Requirements	Concern for health and welfare issues including transboundary transport of pollutants.	Multiscale applications with a variety of techniques will increase with stakeholder and international needs.	Regional applications become more important for transboundary issues and megacity influence.	Model applications combined with emission models will continue to evolve with more sophistication as needed.	Expect methods reconciliation to continue improvement. Improved definition and application of uncertainty analysis.
Data Accessibility	Increase accessibility for stakeholder use within legal constraints	Increased efficient stakeholder access important	Increase accessibility for stakeholder use	Adoption of improved data management methods for user friendly access	Application of new, efficient means of data base management.
Timeliness	Provide for regular update for progress tracking	Measure of progress critical element for NEI	Provide for regular update with consistent methodology	Requirement for continued stakeholder interaction and efficient use of data management skills.	Updates require continuing stakeholder attention and support, use of new methods may help obtain data more rapidly.
Projections	Improve ability to make emission projections.	Improve ability to make projections important element of planning	Improve ability to make emission projections	Requires integration of local and regional socio-economic and technology outlooks.	Increased stakeholder input, technological and economic forecasting, and trend analysis may improve projections.

2.3 REQUIREMENTS FOR FUTURE EMISSION INVENTORIES

As discussed above, each air quality issue has intrinsic distance and time scales as well as specific pollutants that drive associated emission inventory requirements. Emission data must be provided on spatial and temporal scales that meet the requirements of the receiving model or analysis. The data must also contain the required source and chemical speciation information. As more sophisticated, high-resolution atmospheric chemistry and transport models are being used to assess air quality management options, providing these data has become more challenging. The following sections describe some of the scale, chemical speciation, uncertainty, and data compatibility issues that emission inventories will increasingly need to address.

2.3.1 Urban Neighborhood Scales

In order to obtain better characterization of human exposure to photochemical oxidants, PM, or toxic air pollutants, air quality model simulations may need to be focused on the urban neighborhood level. Air quality forecasts, for example, would be most useful if they could be prepared at the neighborhood scale. It is widely recognized that differences in meteorology and emission patterns can cause very significant gradients of pollutant concentrations on the urban scale. Thus, detailed "micro-scale inventories" of sources surrounding measurement sites may be needed in order to understand model performance or measurement issues in such locations. Harmonization of micro-scale and urban-scale emission inventories places additional challenges for emission inventory programs, but can serve as a valuable evaluation step in the development process. Urban-district-scale data are also necessary to estimate the impact of outdoor air pollutant concentrations on indoor air quality in households and workplaces. New techniques for continuous air quality measurement in combination with neighborhood-scale modeling and micro-scale inventories present opportunities to learn more about the causes and health effects of air pollution.

2.3.2 Metropolitan Area Scales

Rapid urbanization has forced the focus of urban air pollution to shift from individual municipalities to metropolitan areas. These areas can encompass high populations and very large areas. For instance, the Mexico City metropolitan area, with a population of 3 million in 1950, reached 18.7 million by 2003, and its urbanized area expanded from 118 to about 1500 km^2 from 1940 to 1995 (Molina and Molina, 2004; Molina et al., 2004). Large metropolitan areas like Mexico City, New York City, and Los Angeles typically expand over dozens of municipalities and may extend into several states or across national borders. In order for inventories to represent the frequently changing population and transportation patterns in these areas, they need to be dynamic and updated in a timely manner.

2.3.3 Regional to Continental Scales

It is increasingly clear that the effects of degraded air quality are no longer restricted to areas in or near major cities. Regional air quality modeling activities have been instrumental in pushing the development of regional emission inventories. This is evidenced by the U.S. regulatory and legislative activities regarding the acid rain program (NAPAP, 1990), Grand Canyon Visibility Transport Commission (GCVTC, 1996), Ozone Transport Assessment Group (OTAG, 1997), and the Clean Air Interstate Rule for SO_2 and NO_x (U.S. EPA, 2005a) and the mercury rule (U.S. EPA, 2005b). International agreements have also been supported by regional emission inventories and modeling activities such as the U.S.-Canada Air Quality Agreement (U.S.-Canada, 1991) and the U.S.-Mexico Border 2012 Agreement (U.S. EPA and SEMARNAT, 2003). Photochemical oxidants and secondary fine PM produced in the plumes from major cities and industrial areas cross not only state/provincial borders but also penetrate national boundaries. Photochemical episodes as well as the pollution events caused by widespread wildfires have been observed to impact large fractions of the North American continent. The evidence that many air quality problems need to be addressed on a continental scale is compelling (NARSTO, 2000;

NARSTO, 2004). This means that North American emission inventories will need to be rationalized and coordinated on the continental scale, not just at the borders. It may be necessary to take an even broader view of emissions in the future. Because of growing emission levels and long-range transport, the lines between local, regional, continental, and global regimes are becoming increasingly blurred.

2.3.4 Intercontinental/Hemispheric Scales

It is becoming clear that long-range transport of fine particles and long-lived gases is affecting air quality over the entire northern hemisphere. Similar effects have also been observed in the southern hemisphere. Evidence for a systematic increase in background pollutants due to intercontinental transport is growing.

It has been shown that African dust can be transported across the Atlantic Ocean on the trade winds to the Caribbean, Mexico, and the southern United States (Prospero, 1999; Prospero and Lamb, 2003). In a major event in April 1998 (Husar et al., 2001; Wilkening et al., 2000), Asian dust from storms originating in the Gobi desert was transported over the Pacific Ocean to the North American coast and reached as far inland as Minnesota. A similar dust event occurred in April 2001 (DeBell et al., 2004) when elevated concentrations of dust were observed from this event as far east as New England. Such events have the potential to contribute to violations of ambient air quality standards for PM.

Evidence shows that the background concentration of ozone is increasing in North America (NARSTO, 2000; Lin et al., 2000). Some of this increase may be due not just to North American emissions, but also to Asian emissions transported across the Pacific Ocean (Berntsen et al., 1999; Jacob et al., 1999). Jacob et al. (1999) have shown that by 2010 the effect of rising emissions in Asia could influence monthly mean ozone concentrations in the western United States by 2 to 6 ppbv for the April-June time period. According to Jacob et al., this increase in background levels would "more than offset the benefits of 25 percent domestic reductions in anthropogenic emissions of NO_x and hydrocarbons in the western United States."

It is broadly appreciated that increases in Asian and European emissions of NO_x and hydrocarbons can affect tropospheric ozone concentrations over a very wide area (Wild and Akimoto, 2001; Wild et al., 2004) and that increases in PM emissions can not only increase particulate concentrations in far-removed locations but also affect local radiative forcing and influence ozone chemistry (Martin et al., 2003).

Trace elements and persistent organic species also have the potential to travel for long distances. With an atmospheric lifetime of about one year, elemental mercury emissions certainly contribute to a hemispheric background that influences concentrations in North America. It is estimated that 20 to 30 percent of the mercury deposited in the United States is of Asian origin (Seigneur et al., 2004).

All of this evidence points in the same direction: North America is not an isolated "airshed." Rather, it is a collection of emitting sources situated in a background pool of air pollution encircling the entire globe (Akimoto, 2003). When studies are undertaken of ambient air quality in North America, it may be important to take into account the contributions of sources outside North America, especially fine particles and long-lived gases, which may have significant episodic or seasonal contributions. This could be especially crucial with respect to the goals of the U.S. visibility program. To ignore such contributions may cause over-optimism regarding the provision of clean air to the people or the effectiveness of local emission control measures. Not only may future domestic attempts to reduce ozone concentrations in the United States be thwarted by a rise in global background ozone, but control of global CH_4 may be an effective way to reduce ozone concentrations in North America (Fiore et al., 2002). In fact, it may be necessary to consider regulating emissions and concentrations on a hemispheric scale, along the lines of the Long Range Transport of Air Pollutants Convention under the United Nations Economic Commission for Europe (Holloway et al., 2003). These developments should lead to continental-scale models utilizing boundary conditions from global models to effectively account for these interactions, which in turn will require hemispheric or global emission inventories.

2.3.5 Time Scales

It is increasingly clear that a better characterization of the temporal and spatial distributions of emissions will be required to assess the impact of proposed air quality management strategies and to provide reliable air quality forecasts. The long-term goal should be the maintenance of a dynamic emission inventory whose content changes in response to actual activity factors and emissions. As inputs to air quality models become more demanding, the stage is set for increased temporal resolution of emissions for major source categories.

Emission inventories were initially developed on an annual average basis. This was adequate for targeting major sectors for controls. However, as air quality models became widely used to address the atmospheric reactions contributing to acid rain and ozone, it became necessary to represent emissions with higher temporal resolution. For major source categories, this requirement was initially achieved by creating seasonal and daily emission profiles. These profiles apportioned annual emissions to weekday and weekend-day by season and used average diurnal operating profiles to achieve the desired temporal resolution (NAPAP, 1990). This approach was later extended to create the emission inventories for a typical summer day that were developed to address ozone issues (OTAG, 1997).

As controls have been implemented, it has become more important to represent actual emissions on finer and finer time scales. Seasonal allocations were replaced by monthly allocations. Field studies, which were being used to evaluate air quality models, required actual episodic emission inventories and not typical summer-day estimates (ARB, 1990; CCOS, 2000; CRPAQS, 1999-2001; TexAQS, 2000). Atmospheric modeling of fine particles will present even greater challenges. The models will require hourly emissions in order to simulate seasonal differences in secondary organic aerosol formation over an annual cycle. Meeting these emission data needs will be simplest for large utility sources as these sources are equipped with continuous emission monitoring systems (CEMS) which measure actual emissions on an hour by hour basis. Providing these data from other sources will be more challenging.

Air quality measurements in urban areas consistently show time-of-day profiles that are intimately linked to daily human activity patterns. For instance, vehicle emissions have significant temporal dynamics that tend to differ substantially for various parts of a metropolitan area. Neighborhoods containing major arterial roads will typically experience much higher rush hour emissions, with the morning emissions usually concentrated into a shorter time frame than for the evening period. Some emissions will be larger, in both flux rate and duration, when accidents or weather stall traffic. Differences in weekday and weekend traffic patterns and vehicle mix may also lead to observable "weekend effects" in air quality (Marr and Harley, 2002). Further, holiday emissions, and the resulting ambient pollutant concentrations, often vary significantly from regular workdays.

At the other end of the temporal scale it is important to document emission trends over decades. This information is required to understand the efficacy of control technologies and the evolution of air quality issues. These data are also needed to evaluate the ability to model air quality trends, and to characterize North America's contribution to global emissions.

2.3.6 Expanded Gaseous Species Requirements

That more chemically complete emission inventories are required to address the photochemical production of oxidants, including speciated VOC and NO_x emissions, has long been recognized (NRC, 1991). The growing recognition that secondary fine PM production drives $PM_{2.5}$ levels in many environments also places a priority on increased knowledge of gaseous VOC emissions, especially aromatic and biogenic compounds whose oxidation products are known to form semivolatile species (NARSTO, 2004; NRC, 2004b). In the United States, this need could be met by improving the U.S. EPA's SPECIATE database and by increasing the number of related speciated VOC emission measurements (U.S. EPA, 2002). These improvements would benefit Canada and Mexico as well since the SPECIATE data base is used extensively across North America. Better emission inventories for precursors also will be required to characterize secondary fine PM formation (NARSTO, 2004; NRC, 2004b). The growing

attention paid to ambient levels of the 188 hazardous and air pollutants and related health effects will likely require better stationary and mobile source emission inventories for a variety of aromatic (e.g. benzene, toluene), carbonyl (e.g. formaldehyde, acetaldehyde, acrolein, etc.), olefinic (e.g. 1,3 butadiene), and other priority toxic air compounds.

2.3.7 Expanded PM Requirements

The unsatisfactory state of current emission inventories for PM and its precursors has recently been highlighted by a U.S. NRC committee advising the U.S. EPA on research priorities for PM (NRC, 2004b). Continued progress is required to better represent the full size distribution of primary PM emissions, including ultrafine (nanoparticle) emissions from mobile sources. An improved knowledge of primary particle composition as a function of particle size is also required not only for improved understanding of the contribution of sources to ambient concentrations, but also to better understand the possible relationships between PM composition and adverse health effects. Improved characterization of direct PM emissions as well as the precursors of secondary organic aerosol formation is needed. This includes improved quantification of ammonia emissions because they are critical to understanding the formation of ammonium sulfate and ammonium nitrate. Both the elemental and organic content of primary PM requires chemical characterization. The black carbon (BC) content of PM (closely related to elemental carbon, EC) has become an important issue in determining the impact of PM on regional climate factors, including solar radiation absorption, cloud stability, and rainfall (Molina and Molina, 2004; Molina et al., 2004; Menon et al., 2002). Organic PM is known to dominate the secondary aerosol loadings in many urban areas and thus plays a key role in scattering solar radiation (IPCC, 2001).

2.3.8 Better Quantification of Emission Inventory Uncertainty Levels

Numerical values without well-defined error limits are basically unacceptable for any scientific purpose. Future emission inventories must be assembled with careful attention to measurement and activity factor uncertainties. Measured emissions should be evaluated to determine both statistical (measurement variability) and systematic (measurement error) uncertainties. A recent U.S. NRC report addressing PM research priorities calls for characterization of emission inventory uncertainties for both primary PM and secondary PM precursors (NRC, 2004b).

2.3.9 Consistent and Harmonized Data

Emission inventories are needed to address air quality issues at a variety of geographic and temporal scales. Developing compatible inventories facilitates sharing data, and improves efficiency and quality. The multiple temporal and spatial scales of current air quality issues discussed in this section show that emission inventories must be combined to characterize and manage problems that span state/provincial and national borders, and in some cases oceans. The combination of emission inventory data from different states and countries will not be possible unless their data collection and reporting practices are reasonably consistent. A harmonization of emission inventory data acquisition and reporting practice across North America and beyond will be necessary to deal effectively with many air quality issues. This harmonization will be important not only for current emission inventories but also for future ones in order to assess trends in emissions and air quality. Harmonization also will be required in procedures used to project emissions into the future. Such projections are essential for analysis of alternative control strategies. Thus, a family of consistent and harmonized data is needed over a variety of spatial and temporal scales to support the myriad of emission inventory applications. This consistency also is needed over extended time periods to support trends analysis of emission data.

Addressing all nine requirements should be the objective of future near-term emission inventory development activities in North America. Table 2.3 lists important attributes that will be required of these inventories. These attributes serve as targets for focusing emission inventory improvement activities in the three countries.

Table 2.3. Attributes of Future Emission Inventories.	
Category or Application	**Attribute**
Criteria pollutants and their precursors	Include SO_2, NO_x, CO, size-differentiated PM, Pb, total VOCs, VOC reactive species, NH_3, elemental and organic carbon
Hazardous and toxic air pollutants	Include 188 listed HAPs plus persistent bioaccumulative and toxic chemicals (PBTs)
Greenhouse gases and aerosols	Include CO_2, CH_4, N_2O, BC, HFCs, PFCs, SF_6,
Point sources	All sources, with emphasis on sources that contribute 80 percent of the emissions of stationary-source pollutants Process-level detail (e.g., source classification code, fuel burned, fuel characteristics, boiler capacity, activity indicator, age, operating schedule) Name and location, and stack data (latitude, longitude, height, diameter, flow) Control equipment (type, efficiency, age, and regulatory driver--MACT, BART, NSPS state)
Nonpoint or area sources	Source classification codes County or local level activity, Emission factors, controls, temporal factors Census tracts for localized assessments
Mobile sources	Urban and county level vehicle miles traveled (VMT) and vehicle kilometers traveled (VKT) and fuel use, fleet characteristics, diurnal and seasonal temperature profiles, and nonroad equipment populations
Natural or biogenic sources	County or local species, daily meteorological data, emission factors, species profiles
Emission factors	Up-to-date and comprehensive factors for all pollutants and source categories
Speciation profiles	Up-to-date and comprehensive profiles for VOC species and PM size fractions with chemical composition
Temporal profiles	Up-to-date and comprehensive profiles representing hourly, daily, and seasonal emissions by major source categories over the annual cycle.
Spatial profiles	Up-to-date and comprehensive profiles for allocation of emissions by major source category to 1 km grids across the continent.
Measurement methods	Continuous methods for major sources Accurate and affordable methods for all pollutants and sources
Data collection techniques	Timely and affordable survey techniques Satellite data for ground cover and fires
Timeliness	Annual reporting of emission inventories (e.g., point sources in first quarter; mobile, area and biogenic sources in second quarter; quality assurance in third quarter; composite in fourth quarter)
Daily forecasting and recording	CEM data for the largest point sources Load forecast for the largest emitting sources. Mobile source indicators of events (major traffic events--accidents, ball games, etc) Area sources (Major upset events --i.e. fires, spills, accidental releases)
Future year predictions and forecasting	Reliable forecasts for specific years, seasons, or other periods of interest Emission forecasts for largest sources or categories linked to economic forecasts Links to transportation planning
Analysis of trends	Annual trends for criteria and hazardous air pollutant emissions Annual trends for greenhouse gases and aerosols Accurate indicators of progress in emission reductions

Table 2.3. Concluded.	
Category or Application	**Attribute**
Accessibility	Electronic reporting and data exchange among sources and governmental entities Internet-based electronic access to data and exchange of information Distributed network that facilitates sharing among inventory developers and users
Accuracy and quality control	Avoid missing sources and double entry of sources Avoid sources in wrong location Avoid sources with unreasonable flow rates from stacks Avoid missing data on key parameters Quickly recognize and correct data entry errors Uncertainty indicators for all data elements and composites Provide evaluation criteria with complementary measurements (e.g., tunnel studies, aircraft studies, source region studies)
Affordability	Software for effective data entry, data computation, data exchange, quality control, and quality assurance Optimize intensive manpower and time consuming steps Affordable emission factor characterization – keep step with technology changes
Transparency	All material documented, inventories transportable, calculations reproducible
National and international exchange	Electronic data exchange among - United States: states, tribes, localities and regional consortiums - Canada: provinces, and localities - Mexico: states, and localities - Europe and Asia

2.4 CHALLENGES FOR DEVELOPING AND MAINTAINING ENHANCED NORTH AMERICAN EMISSION INVENTORIES

Meeting the requirements for future emission inventories calls for a number of actions to be taken by the individuals and teams who develop the inventories and by the organizations that fund them. These actions range from dealing with personnel issues to embracing the new technologies that will be needed to develop the inventories and to facilitate their accessibility by users.

2.4.1 Recognizing Scientific and Professional Motivation Problems

Gathering emission and activity factor data and constructing emission inventories for air quality assessment and management have not traditionally been regarded as technically glamorous pursuits. Scientists who mount successful field measurement campaigns, conduct laboratory experiments to characterize atmospheric pollution, or construct elaborate atmospheric models to explain current observations and predict future pollution levels and impacts, are far more likely to have their efforts widely recognized. Constructing and improving emission inventories is painstaking and laborious, and many field studies of ambient air quality have utilized available information without investing in additional improvements for emission inventories.

However, there is a growing recognition that insufficient knowledge of emission quantities, chemical speciation, spatial distributions, and temporal variations are seriously hampering progress in understanding and managing a wide range of air quality issues. As air quality models and measurements become more sophisticated and comprehensive, inconsistencies due to inadequate knowledge of emissions become more frequent. For example, recent measurements in Mexico City (Arriaga-Colina et al., 2004) show that the VOC/NO_x and CO/NO_x ratios calculated from the official 1998

emission inventory for that critical metropolitan area are low by a factor of 2.5 to 3. As a result, attempts to model air quality based on the official emission inventory do not reproduce observed photochemical oxidant levels. Recommendations have been made for significantly improving Mexico City's emission inventory (Molina and Molina, 2002), and an effort to significantly improve it is now underway. Such problems are not limited to the newly developed Mexican inventories. The Texas Air Quality Study in 2000 also found that emissions of certain VOC species from stationary sources were low by factors of 10 to 100 in the Houston area (TexAQS, 2000), leading to additional efforts to improve that inventory.

Global issues such as stratospheric ozone depletion and greenhouse-gas-driven climate change have demonstrated that sustained, international efforts are required to develop improved emission inventories for forcing species (IPCC, 2001; WMO, 2002). Administration of international treaties addressing these issues such as the Montreal Protocol and the Kyoto Protocol is dependent on accurate inventories for ozone depleting and radiative forcing substances. Consequently, the creators of those high-profile emission inventories are better supported and their contributions are recognized by publication in leading journals and inclusion in international assessments (IPCC, 2001; WMO, 2002).

Improving the completeness, accuracy, and timeliness of North American emission inventories will require dedicated and talented technical professionals equipped with innovative measurement and emission modeling tools. In order for the vision of improved North American emission inventories to be realized, high quality scientists and engineers must be recruited and supported to develop and utilize innovative and effective methods to improve and expand emission inventories. This will require enhanced and sustained support for those performing emission inventory research, development, and maintenance activities. Resource needs for achieving these improvements are discussed in more detail in Chapter 3.

2.4.2 Utilizing New Tools and Techniques

Part of the challenge of increasing the accuracy, coverage, resolution, and timeliness of North American emission inventories can be met by enlisting new technologies and using them to develop new strategies. Emission inventories are information, and the general advance in information technology is both rapid and profound. Revolutionary methods for acquiring data (real-time sensors, sensor networks, remote sensing), transmitting data (internet, cell phones, wireless networks), accessing data (massive electronic storage systems, search engines, relational data bases), and assessing data (expert systems, sensor fusion algorithms, pattern recognition, image analysis) are rapidly changing they way North Americans acquire and use information in their professional and personal lives. The convenience and power of evolving information technologies, broadly defined, must be harnessed to produce comprehensive and dynamic emission inventories to replace the more limited and static versions currently available. Chapter 6 of this report presents descriptions and discussions of a number of innovative measurement systems and strategies currently used in emission research activities that might be more widely utilized to produce enhanced emission inventories.

Data-gathering systems currently being deployed for other purposes might be utilized to produce higher spatial resolution and/or dynamic emission inventories. For instance, since vehicle emissions are a major source of both primary pollutants and secondary pollutant precursors, any high temporal and spatial resolution information on vehicle activity factors or vehicle emissions would be invaluable input for air quality exposure or forecast models. In many North American metropolitan areas, a surprisingly large amount of traffic data is already being gathered each day. Many major urban areas in Canada and the United States have systems of airborne (eye-in-the-sky) and/or roadside video cameras used to relay traffic reports to the commuting public and/or city transportation officials. Video systems are sometimes supplemented by pneumatic

or magnetic vehicle counters deployed on key roads. The activity factors recorded by these systems could be routinely captured, their images/data analyzed and interpreted automatically, to inform a dynamic emission inventory.

Mexico City officials have recently deployed video cameras imaging over a hundred key traffic points in the Federal District. The main purpose of these surveillance cameras is to observe the vehicular congestion and adjust traffic lights as well as to monitor safety on the streets. Although not the main purpose of these surveillance cameras, a recent Mexico City air quality field measurement program used data from these cameras to assess time-resolved traffic intensity and vehicle mix to help interpret real-time ambient pollutant measurements near major roadways. There is no insurmountable technical barrier to capturing and processing these data in real-time on a daily basis.

There may even be opportunities to capture actual vehicle emission measurements. For instance, several U.S. states are experimenting with the routine deployment of cross-road remote sensing systems to "clean screen" onroad vehicles in non-attainment regions. If the NO, CO, and VOC emissions of individual vehicles are shown to be acceptable in a specified number of sensor encounters, the license plate image is used to identify the vehicle's owner who is excused from traditional exhaust inspection procedures for that year. Each "clean screen" sensor is evaluating and recording the real-time exhaust emissions for thousands of vehicles per day under certain limited operating conditions. The data may be useful for emission inventory improvement in the future. For instance, these data could be used to quickly recognize changes in onroad vehicle emissions due to a change in local fuel formulation or a variation in average vehicle speed caused by a change in road conditions or traffic patterns.

The increasing use and reliability of continuous emission monitors on major point sources also presents an opportunity to make emission inventories dynamic. The information on real-time stack emissions could be routinely transmitted to a dynamic emission inventory model that showed the variation in emissions as unit production fluctuates in response to demand. This information, coupled with forecasts of electricity generating load by plant, could provide valuable information to air quality forecasting programs.

The examples of strategies to obtain more robust and dynamic activity factor and/or emission data for future emission inventories noted above are suggestive, not comprehensive. They were selected to make the point that information technology is advancing, and that efforts to construct and maintain better emission inventories will need to take maximum advantage of society's general tendancy to gather more data in a more timely manner in many spheres of activity.

2.4.3 Improving Emission Models

Emission models for point, nonpoint, and mobile sources are becoming more sophisticated. Efforts to capture wider ranges of sources and better apportion emissions in time and space are bearing fruit. Nevertheless, significant weaknesses remain in representing offroad and some onroad mobile sources and stationary area sources. Also, source categories whose emissions are dominated by a small fraction of random events or high emitters can be especially difficult to characterize.

Successful deployment of emission models across North America requires not only the improvement of existing emission models but also the development of models which are consistent across countries. This requirement is most apparent for models of mobile source emissions but it also applies for many emission models for stationary nonpoint source categories.

2.4.4 Enhancing Data Integration and Access

Emission inventory data need to be more accessible in forms relevant for a variety of applications and users. For instance, there is a clear need to integrate emission data from multiple inventories in order to support public outreach, emission trends reporting, control strategy application studies, benefit analyses, and estimation of air quality in large regional areas. The overarching challenge in developing a comprehensive emission inventory is to integrate data that are distributed among many sources without

requiring strict data format standards or introducing a new repository to centrally store and maintain the data. The objective is to create a network of data and associated tools that is:

- Distributed. Data are shared but remain distributed and maintained by their original inventory organizations. The data are dynamically accessed from multiple sources through the internet rather than collecting all emission data in a single repository.
- Non-intrusive. The technologies needed to bring inventory nodes together in a distributed network need not be intrusive in the sense of requiring substantial modifications by the emission inventory organizations in order to participate.
- Transparent. From the emission inventory user's perspective, the distributed data should appear to originate from a single database to the end user and should include supplemental documentation (metadata). One point of access and one interface to multiple data sets are desired without required special software on the user's computer.
- Flexible/Extendable. An emission network should be designed with the ability to easily incorporate new data and tools from new nodes joining the network so that they can be integrated with existing data and tools. One example would be the capability to assess the impact of changes in emission factors as technology and controls change over time.

The guiding principles of an integrated emission inventory follow those of distributed databases and distributed computing. Innovative information technologies and increasing collaboration among emission inventory organizations are leading to the creation of a network that shares data for easier access and integration while maintaining each individual inventory's existing system of data management. Spatial data should be available in a Geographical Information System (GIS) format that can display emissions from point, area, and mobile sources on a range of scales from neighborhood to hemispheric. Ideally, temporal data will be formatted so that spatially resolved movies of trends in temporal emissions can be visualized for appropriate time scales.

2.4.5 Fostering International Cooperation

It is clear from both the scientific and policy perspectives that effective management of air quality in North America requires cooperation among the three countries of the continent. It is also becoming apparent that oceans are ineffective barriers to air pollution, and that increasing emissions in Asia and Africa may contribute to the decline of air quality in North America. These observations suggest that there will be future requirements for each continent in the northern hemisphere to construct and maintain comprehensive, robust and dynamic emission inventories for exchange as well as internal use. Ideally, the international cooperation that has been necessary to develop accepted global emission inventories for substances that deplete stratospheric ozone (WMO, 2002) or drive global warming (IPCC, 2001) will be replicated to achieve this goal.

In North America, the environmental impacts of manufacturing and transportation activities will respond to changes stimulated by the North America Free Trade Agreement. Cooperative programs aimed at environmental improvement are supported by the Commission for Environmental Cooperation, which maintains an active air quality program that includes efforts to encourage better emission reporting from all three North American countries.

The diversity of inventory-related needs among Canada, the United States, and Mexico should be noted. Stemming from geographical and industrial differences as well as varying states of inventory development, this diversity suggests that Canada, the United States, and Mexico should place different emphases on immediate development efforts in several specific areas. Table 2.2 provides an indication of these varying emphasis levels for Canada, the United States, and Mexico. However, international cooperation should continue to be enhanced to ensure compatibility and comparability among emission inventories for North America.

2.4.6 Coordinating Prioritization of Enhanced Emission Inventory Development

Section 2.2 cataloged the increasing number of societal-driven air-quality issues requiring

comprehensive emission inventories, and Section 2.3 outlined the expanded ranges of chemical species, spatial scales, and temporal resolutions that emission inventories must consider. This range of air quality problems that require effective management and their corresponding needs for emission inventories with enhanced chemical content, spatial coverage, and temporal resolution, will place severe demands on the chronically under-funded emission inventory community. Prioritizing resource allocation so that ongoing efforts will yield the most crucially needed inventory improvements of the three North American nations will be a continual challenge.

Efficient use of scarce resources will require an effective prioritization process that includes key stakeholders on scales from municipal, to state/provincial, regional, national and, as noted above, continental to global. Further, emission inventory priorities will change both as progress is made and as society's concern about specific air quality and global change issues shift; so today's emission inventory priority list will need updating tomorrow. Broadly based technical organizations, such as NARSTO, the CEC, and others, may be helpful in setting and reviewing emission inventory priorities and coordinating enhanced emission inventory development to meet these serious technical and financial challenges. The issue of prioritization and a set of suggested initial action plan for achieving the highest priorities in emission inventory improvement is discussed in more detail in Chapter 9.

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CHAPTER 3

CURRENT STATUS OF NORTH AMERICAN EMISSION INVENTORIES

Chapter 3 Objective: ***To present an overview of current emission inventories at the national, stte, local, and regional levels and to serve as a locator resouce for persons wishing to access and apply this information for pollution management applications.***

This chapter provides a guide to North American emission inventories at the international, national, regional, state, provincial, tribal, and local levels. Its objective is to provide a location resource for those wishing to access and utilize this information for pollution management applications. Reflecting this objective, the material in the following sections, combined with that in Appendix A, may be conveniently considered as a signpost to identify individual inventories and point to their locations and the references that describe them in detail. Many of these references appear in the form of links to websites that can be accessed directly for more comprehensive information. This chapter summarizes the most current national and regional inventories constructed for Canada, the United States, and Mexico, and representative metropolitan, local, and specialized inventories, along with the purpose, pollutants included, and directions for locating the inventory. The larger inventories and some regional, state, provincial, local, and specialized inventories are described in more detail in the text.

As described in Chapter 2, emission inventories must respond to a wide range of societal drivers including a) international and national analysis of trends in pollutant emissions, b) regional strategies to reduce ozone exposure and haze in pristine areas, c) regulatory requirements (see also Box 3.1) to demonstrate emission reductions in statewide or local jurisdictions, and d) key sources of toxic pollutants in urban areas. Each of these uses places its own set of demands on inventory developers. Trends-inventories on large geographic scales require inputs from diverse political entities with different priorities and resources, the use of top-down models for natural and non-point sources (which use generic default values for some key pollutants and sources), large databases, and coordination among many people with different interests. Inventories used to demonstrate emission reductions are similar to large trend- inventories, but can use data collected locally and on smaller geographic grids to reflect local conditions. Regional inventories are generally developed as inputs for atmospheric models and require temporal, spatial, and species resolution. With the exception of temporal data collected with CEMS (which mostly measure SO_2 and NO_x emissions from utility sources) and location data for large point sources, the temporal, spatial, and species allocation process relies on models developed for representative sources. Emission inventories prepared for one purpose may not be transferable to other requirements. For example, considerable processing is required to prepare regional modeling inventories from the national inventories.

The quality, completeness, detail, and timeliness of emission inventories are functions of available funding. The resource-intensive nature of compiling emission inventories cannot be overemphasized. Large-scale national emission inventories involve the expenditure of millions of dollars by industry, and local, state, provincial, and federal agencies. Even local emission inventories require the commitment of many thousands of dollars. Much of the cost of preparing emission inventories is incurred in establishing the infrastructure, which includes

Box 3.1 Legislative Drivers For Future North American Emission Inventories

In the United States, the 1968 *Clean Air Act* and its amendments prescribe that NAAQS are to be set at levels to protect the public health. In addition, the *Clean Air Act* stipulates that controls are needed on 188 HAPs (U.S. EPA, 2003a). The *Clean Air Act* amendments also address air quality related values in pristine or remote areas, including visibility and ecological stress from chemical deposition. Accurate and timely emission inventories for criteria pollutants and their precursors are widely recognized as crucial for developing state implementation plans (SIPs) to achieve NAAQS compliance as well as for reviewing the effectiveness of adopted SIPs. Further, emission inventories are important inputs for numerous research activities associated with health risk assessments and standard setting activities. Finally, in the United States the 1986 *Emergency Planning Community Right-to-Know Act* increased the demand for both criteria pollutant and HAP emission data.

The Canadian federal government passed its Clean Air Act in 1969 (Environment Canada, 1973). National Ambient Air Quality Objectives (NAAQOs) were developed in the early 1970s to protect human health and the environment by setting limits for key criteria air pollutants such as CO, NO_2, ozone, SO_2, lead, and TSP. In June of 2000, the Canadian federal, provincial, and territorial governments (except the province of Quebec), signed the Canada-Wide Standards for PM and Ozone (Environment Canada, 2000). These air quality standards committed the governments to significantly reduce PM and ground-level ozone by 2010. The Canada-Wide Standards for PM and ozone, and similar ones that have been put in place for HAPs (benzene, dioxins and furans, and mercury) are an important step toward the long-term goal of minimizing the risks of these pollutants to human health and the environment. They represent a balance between the best health and environmental protection possible and the feasibility and costs of reducing the atmospheric releases of these pollutants. The Canadian Environmental Protection Act of 1999 (CEPA, Environment Canada, 1999) reinforced the legal authority of the federal government to collect information from any person or facility for the purpose of conducting research, creating an inventory of data, formulating objectives and codes of practice, issuing guidelines or assessing or reporting on the state of the environment. This Act also requires the Minister of the Environment to establish a national inventory of releases of pollutants using the information collected under its authority, and any other information to which the Minister has access. Air pollutants such as PM_{10}, NO_x, SO_2, VOC, and NH_3 have recently been declared toxic under CEPA. Since 2002, these substances along with total PM, $PM_{2.5}$, and CO are required to be reported by the Canadian industries to the NPRI on an annual basis (Environment Canada, 2001).

Mexico established a framework for the development of specific Official Mexican Norms. These are public health supported, and specify maximum allowable limits for stack emissions from combustion sources, for point source emissions from specific industries, and for mobile sources. These apply to all sources under federal jurisdiction and represent minimum criteria, although states may implement more stringent standards. All states including the Federal District (Mexico City) have established local environmental protection and management agencies for air pollution prevention and control. Some municipalities having large industrial parks or extensive industrial development within their boundaries have established additional regulations to control air pollution. Ambient air quality standards are established by the Secretariat of Health; however, air quality information is retrieved, stored and maintained by Secretariat of Environmental and Natural Resources. Local environmental authorities are responsible for setting up plans and programs that are based on emission inventories and ambient pollutant concentrations from monitoring stations. These plans are designed to prevent exposure of populations to high pollutant concentrations (Government of Mexico, 1996).

developing emission estimation and allocation tools, establishing database formats, preparing quality assurance plans, training staff, and establishing lines of communication. These estimates do not include the costs of emission measurements.

As late as the 1970s, air pollution was viewed almost exclusively as an urban phenomenon associated with energy production and factories that was manifested as smog in Los Angeles, New York, London, and other large cities (Wark and Warner, 1976). For this reason, inventories of air pollutant emissions in the United States were originally developed at metropolitan-area scales. These inventories were used to evaluate the effectiveness of control strategies and as inputs for air quality models to evaluate locations for ambient air quality monitors (Stern et al., 1973). The focus of initial emission inventory efforts was primarily on SO_2, NO_x, lead, PM, CO, and VOCs.

In Canada, the compilation of national inventories was initiated by Environment Canada in the 1970s. The first national inventory was compiled for the year 1970 using point source emission information compiled through surveys by Environment Canada, and activity statistics compiled by various federal departments. Between 1970 and 2000, national inventories were compiled every five years in collaboration with the provincial and territorial ministries of the environment and energy. With the compilation of the 1985 National Acid Precipitation Assessment Program (NAPAP) Emission Inventory, Environment Canada instituted more rigorous quality assurance procedures. Throughout the years, close collaboration has been maintained with the U.S. EPA to ensure the comparability of the emission estimation methodologies and the emission inventories.

The first attempt by the United States and Canada to produce coordinated national emission inventories for use by policy makers, modelers, human and ecological effects researchers, and industry was the 1985 NAPAP Emission Inventory (Saeger et al., 1989). A fundamental objective of NAPAP research was to investigate emission sources that contribute to acid deposition. The 1985 NAPAP Emission Inventory built on the pioneering work in the 1970s and early 1980s by the California Air Resources Board (CARB), the St. Louis Regional Air Pollution Study (RAPS) (U.S. EPA, 1979), the Sulfate Regional Experiment (SURE) (Klemm and Brennan, 1981), the Northeast Corridor Regional Modeling Project (NECRMP) (Sellars et al., 1982), the 1980 NAPAP Emission Inventory (Wagner et al., 1986), and others.

In the United States, the process for developing the 1985 NAPAP Emission Inventory involved compiling point source emission data submitted by U.S. states, conducting computerized quality assurance checks, sending flagged data back to the states for review, and calculating nonpoint (including mobile) source emissions using U.S. EPA models. In parallel, Environment Canada, working with Canadian provinces, provided anthropogenic point and non-point source emission data. Biogenic emissions of VOCs, calculated by the U.S. EPA, were also included in a national inventory for the first time.

To support atmospheric and deposition modeling, the NAPAP Emission Inventory reflected spatial, temporal, and chemical species allocation factors developed for the United States and Canada. County-level emissions from nonpoint sources were allocated spatially into 1/4° longitude by 1/6° latitude (approximately 20 x 20 km) grid cells using 14 surrogate indicators (e.g., population, housing, land use, arboreal type). Representative emissions were also estimated for weekday, Saturday, and Sunday for each season. Biogenic emissions were adjusted for hourly temperatures. For chemical speciation, 600 VOCs were organized into a set of 32 reactivity categories. The 1985 NAPAP Emission Inventory, completed in 1989, became the gold standard and the progenitor for future national emission inventories.

An outgrowth of the 1985 NAPAP Emission Inventory process was the identification of key areas needing improvement to quantify sources and pollutants comprehensively, to better assess control strategies, to characterize the linkage between emissions and effects, and to provide accurate resolved inputs for atmospheric modelers. Key needs included better emission models for onroad and offroad mobile sources, better emission estimation algorithms and emission data for nonpoint sources, data on biogenic and other natural source emissions, and better chemical speciation. As these areas began to receive attention from the inventory community, the uses for inventories, and hence the demands on them, began

to increase. Emission inventories are now developed for criteria pollutants, hazardous air pollutants, greenhouse gases, and other pollutants important to human health, ecological effects, climate change, and regional haze. Spatial coverage encompasses states, regions, countries, continents, and the entire globe. The increased sophistication of air quality models demands finer spatial, temporal, and species resolution of emissions. Over the past 15 years, many of the procedures begun during NAPAP have been modified and improved, although the basic approach to creating national and regional inventories has remained essentially the same.

The development of emission inventories in Mexico began formally with the first air quality management program that was issued for Mexico City in 1991 – *Programa Integral Contra la Contaminación Atmosférica en el Valle de México* (PICCA). Currently several inventories are available, mainly at the level of urban airsheds, that support the comprehensive programs for urban air quality management. A first comprehensive National Emission Inventory is currently being developed while other emission inventories are also being compiled to support Mexico's pollutant release and transfer registry, which will provide the public with information about specific pollution sources.

3.1 NATIONAL EMISSION INVENTORIES

Canada, the United States, and Mexico all prepare national emission inventories. These inventories are extensive and require the compilation of massive amounts of information. This section first addresses principal pollutant inventories for Canada, the United States, and Mexico, then discusses hazardous air pollutant inventories, and finishes by describing existing greenhouse gas inventories.

Figures 3.1 and 3.2, which show the emission density for total NO_x emissions in 2001 and 1999, respectively, for the three North American countries, illustrate the type of data typically available in national inventories. In Figure 3.1, emission densities are shown at the county level. Figure 3.2, which shows emission density in 36 km square grid cells includes only the southern regions of Canada and the northern portion of Mexico. Coverage for Mexico in both maps is incomplete because of the incomplete status of the Mexican national inventory.

Figure 3.3 shows NO_x emissions from the electric utility sector; similar maps could be generated for SO_2 and VOC using existing inventory data. All three figures show a dramatic increase in emissions east of the 100º West meridian, closely following the pattern of industrialization and population concentration, and indicating the dominance in North America of U.S. emissions.

National emission inventories are also useful in evaluating long-term trends. Figures 3.4 and 3.5 show trends for the United States and Canada in total emissions of six principal pollutants (CO, SO_2, NO_x, VOC, PM, and lead) from 1970 to 2003, and 1985 to 2003, respectively. Also plotted are trends in gross domestic product, vehicle miles traveled, energy consumption, and population. While the economic and demographic indicators increased, total emissions decreased, thereby demonstrating the effectiveness of air quality management programs. Comparable data are not available for Mexico.

3.1.1 U.S. National Emission Inventory

The U.S. NEI can be accessed at http://www.epa.gov/ttn/chief/index.html. This inventory includes annual emissions for all 50 states and their counties, the District of Columbia, Puerto Rico, the Virgin Islands, and tribal lands. The U.S. NEI is prepared by the Emission Inventory Group of the U.S. EPA's Office of Air Quality Planning and Standards (OAQPS) and is a compilation of inventories submitted by states. The inventory is designed to meet five specific needs: to (1) provide input to national and regional modeling; (2) serve as the basis for toxic air pollutant risk analyses; (3) serve as a starting point for rule development; (4) provide trends and *Government Performance and Results Act* tracking; and (5) provide readily accessible information for the public. Figures 3.1, 3.2, and 3.4 provide examples of the uses of NEI data.

This inventory includes data on all criteria pollutants (pollutants for which there are national ambient air

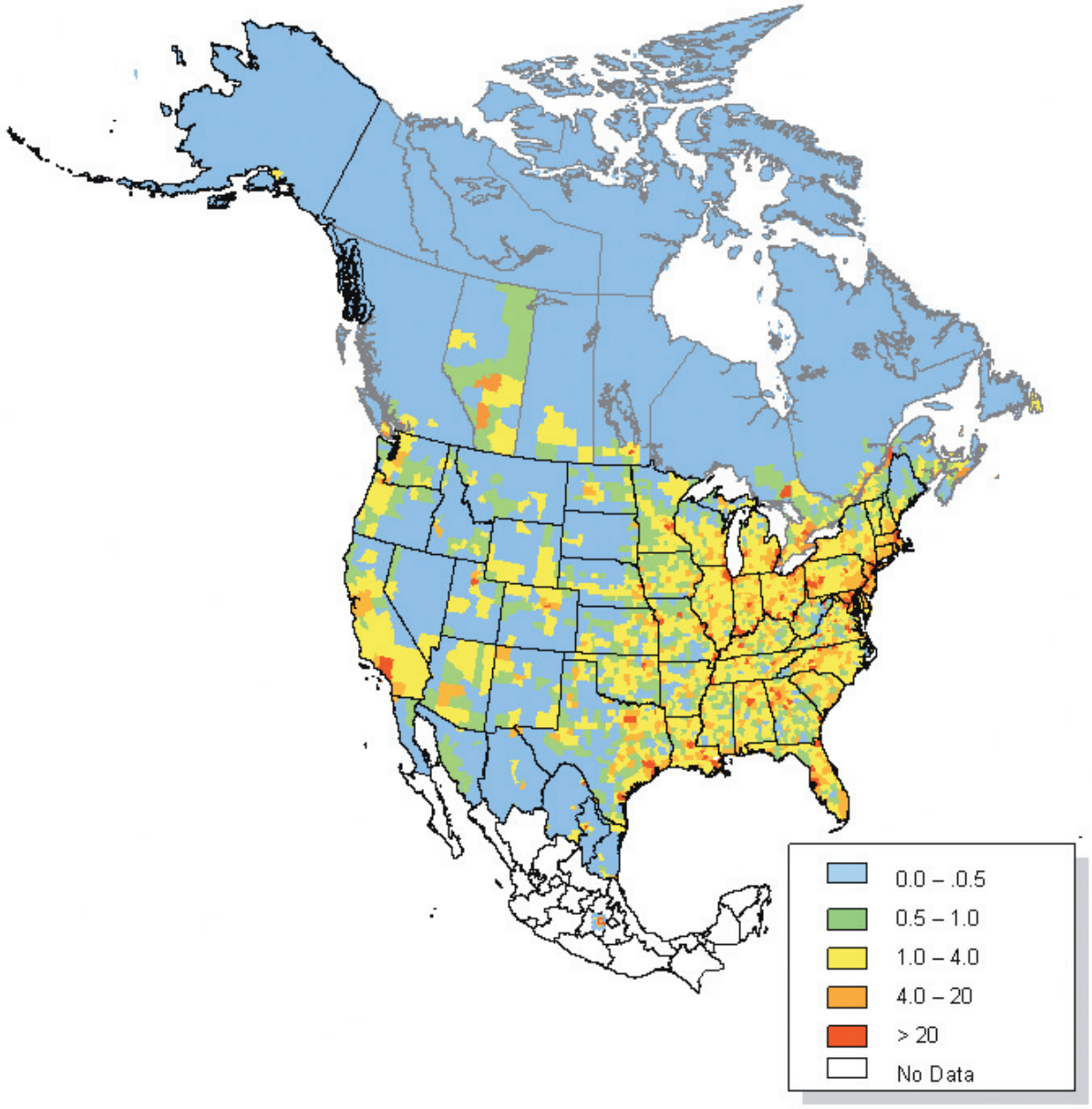

Figure 3.1. 1999-2000 North American Nitrogen Oxide Emission Density by County (tonnes per year/square kilometer). The data sources are as follows: Canada – 2000 National Emission Inventory, Version 1.0; United States – 1999 National Emission Inventory, Version 3.0; Mexico – 1999 Mexico National Emission Inventory for Six Northern States, finalized on April 30, 2004.

quality standards) and criteria-related pollutants, including ozone and $PM_{2.5}$ precursors (NO_x, SO_2, VOCs, CO, primary PM_{10}, primary $PM_{2.5}$, and NH_3) and all 188 HAPs including individual HAPs reported for compound groups listed in the *Clean Air Act*. The U.S. NEI is organized into four main groupings of source categories: point sources (divided into electrical generating units – EGUs - and non-EGUs); nonpoint (area) sources; onroad mobile sources; and nonroad mobile sources. Biogenic and other natural source emissions are not included in the U.S. NEI. These emissions are normally calculated during emission processing for the specific episode under consideration so that the season and temperature effects are properly considered. These data can be captured and accessed but are not stored in the U.S. NEI with the anthropogenic source emission data.

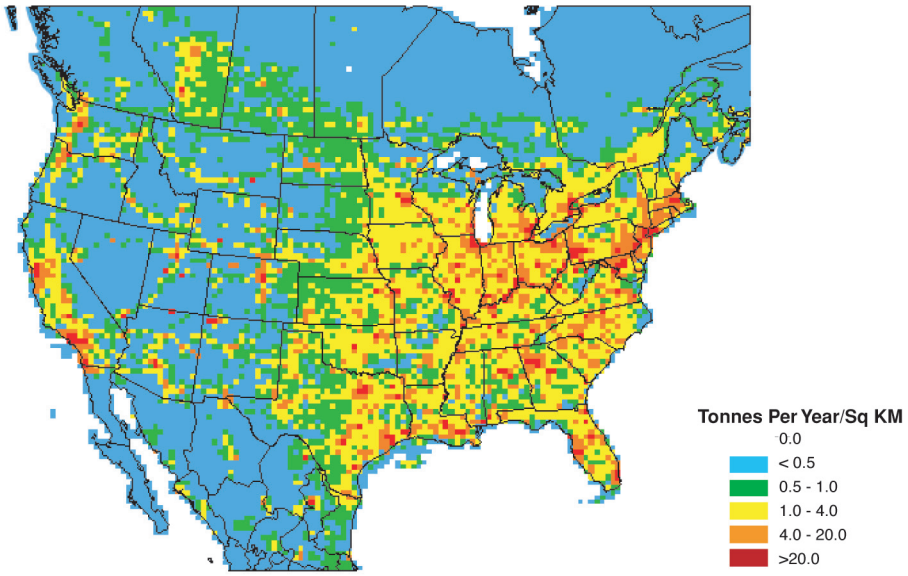

Figure 3.2. Combined-Sector 36 km Square Gridded NO_x Emissions for Canada, the United States, and Mexico. The highest densities are found in urban areas.

Figure 3.3. Electric Utility NO_x Emissions for the Canada, the United States, and Mexico.

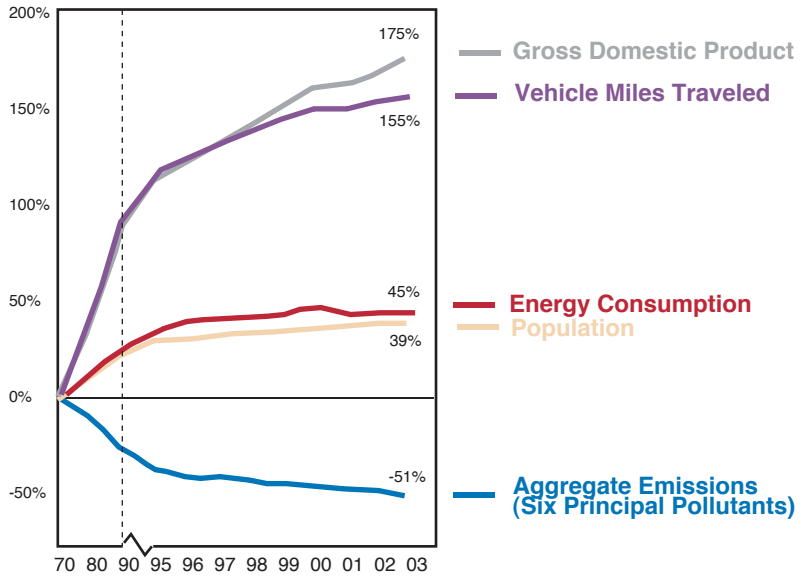

Figure 3.4. Comparison of Growth Areas and Emissions in the United States. Aggregate emissions of key pollutants have decreased in spite of dramatic increases in demographic and economic drivers. (Source: U.S. EPA Trends Report, 2004).

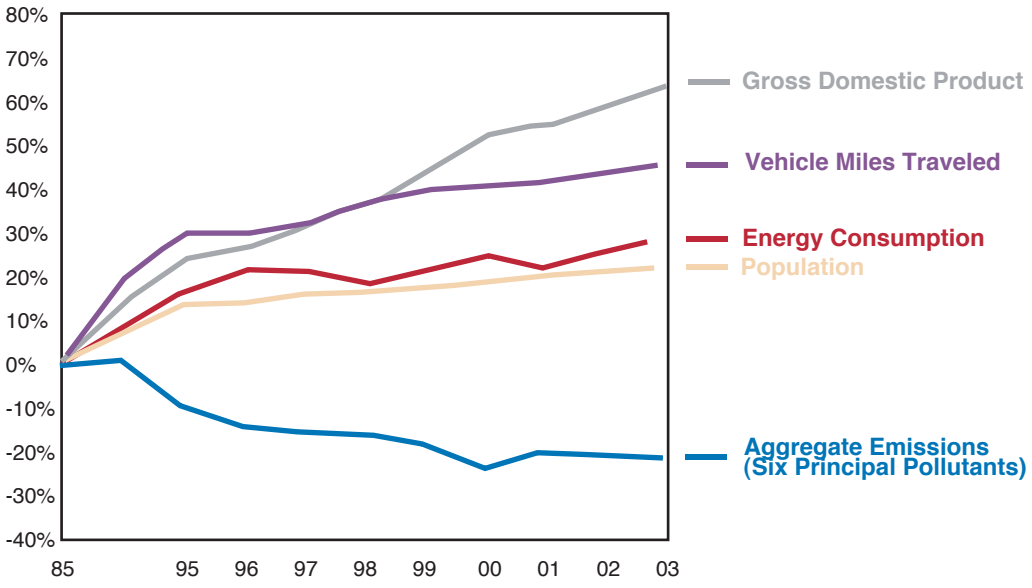

Figure 3.5. Comparison of Growth Areas and Emissions in Canada. Although emissions have decreased while demographic and economic drivers have increased since 1985, total emissions have leveled off over the past four years. (Source: Environment Canada).

The sources for the data in U.S. NEI are summarized in Table 3.1.

The 1999 U.S. NEI for criteria pollutants can be downloaded at http://www/ttn/chief/net/1999inventory.html. The draft 2002 data can be downloaded at http://www/ttn/chief/net/2002inventory.html. Both websites have links to data summaries. 1999 data for individual states can be downloaded at http://www.epa.gov/ttn/chief/net/index.html#dwnld in Microsoft Access. The 2002 NEI is scheduled to be completed and posted in December 2005. Additional information can be obtained from INFO CHIEF at info.chief@epa.gov or www.epa.gov/ttn/chief or by phoning 919.541.1000.

3.1.2 Canadian National Emission Inventories for Criteria Air Contaminants

Environment Canada compiles national emission inventories for criteria air contaminants (CACs) on an annual basis. The CAC inventories include NO_x, SO_2, VOC, CO, PM, PM_{10}, $PM_{2.5}$, and NH_3. The emission inventories are compiled by the Pollution Data Branch and provide a breakdown of the emissions for all 10 provinces and the 3 territories (http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm). More detailed emission summaries are also available online for major urban centers and communities using an online mapping application and queries on the Environment Canada website http://gis.ec.gc.ca/npri/root/main/map.asp#skipNav. These comprehensive emission inventories include multiple emission sources categorized in reports as industrial sources, non-industrial fuel combustion (which includes electric power generation), transportation, incineration, miscellaneous, and open sources. Biogenic emissions are also captured in these emission inventories but are reported separately. Sources for Canadian NEI data are provided in Table 3.2.

The CAC emissions from industrial and commercial facilities are collected annually through Environment Canada's NPRI. The NPRI collects information on releases into the air, water, and land for more than 323 substances. Canadian facilities that meet the reporting requirements of the NPRI must report their releases to Environment Canada by June 1st of the following year. The information collected through the NPRI is supplemented with information compiled for smaller industrial and commercial facilities to ensure that all releases from these sources are captured in the national emission inventories. The compilation of the annual emission inventories and additional activities

Table 3.1. Sources for U.S. NEI Data.

Source Type	Pollutants	Data Source
Electricity generating units (EGU)	NO_x, SO_2	EPA/CAMD/ETS CEMS data (CAMD = Clean Air Markets Division) (ETS = Emission Trading System)
EGU	Hg	EPA/OAQPS model
EGU	Other criteria and HAPs	DOE/EIA 767 data and AP-42
Non-EGU point sources	Criteria	State, local, and tribal submittals supplemented by EPA/OAQPS
Non-EGU point sources	HAPs	State, local, and tribal submittals, EPA/OAQPS, industry, EPA/TRI database
Non-EGU point sources	NH_3	EPA/TRI database
Nonpoint stationary sources	Criteria and HAPs	State, local, and tribal submittals supplemented by EPA/OAQPS
Onroad mobile sources	Criteria and HAPs	State, local, and tribal submittals, OTAG, FHWA, MOBILE6 model
Nonroad mobile sources	Criteria and HAPs	State, local, and tribal submittals; OTAG, NONROAD model

Table 3.2. Sources for Canadian NEI Data.

Source Type	Pollutants	Data Source
EGU	Criteria, HAPs, NH_3	NPRI supplemented by the provinces, the GVRD, and the CAC Division of Environment Canada
Non-EGU point sources	Criteria, HAPs, NH_3	NPRI supplemented by the provinces, the GVRD, and the CAC Division of Environment Canada
Area sources	Criteria, HAPs, NH_3	CAC Division of Environment Canada supplemented by the provinces and the GVRD
Onroad mobile sources	Criteria, HAPs, NH_3	CAC Division of Environment Canada supplemented by information from the GVRD and the province of Ontario, Canadian version of the MOBILE6 model
Nonroad mobile sources	Criteria, HAPs, NH_3	CAC Division of Environment Canada supplemented by information from the GVRD, Canadian version of the NONROAD model
Paved and unpaved roads	TPM, PM_{10}, $PM_{2.5}$	CAC Division of Environment Canada
Forest fires	Criteria, HAPs, NH_3	CAC Division of Environment Canada
Natural sources (biogenic)	NO_x, VOC	CAC Division of Environment Canada, GloBEIS model 3.1

Notes:
Criteria: Criteria Air Contaminants (CACs) are SO_2, NO_x, VOCs, CO, Total Particulate Matter (TPM), PM_{10}, $PM_{2.5}$, and NH_3.
GVRD: Greater Vancouver Regional District
GloBEIS: Global Biosphere Emission and Interactions System, version 3.1.

to improve the estimates are led by Environment Canada and performed in collaboration with the environmental agencies located in the provinces, territories, and specific regions of Canada. These activities are coordinated through the Emissions and Projections Working Group, which includes emission inventory practitioners representing the federal/provincial/regional ministries of the environment and energy.

The Canadian NEIs are compiled to track the progress of current emission reduction programs and initiatives, and evaluate the needs for adjustments. They are also compiled to support the scientific assessment of the air pollution problems and fulfill the reporting requirements of various domestic and international protocols and agreements such as the Canada-Wide Standards for PM and Ozone, the Canada-Wide Acid Rain Strategy, the United Nations Economic Commission for Europe Long-Range Transboundary Air Pollution protocols, and the Canada-U.S. Air Quality Agreement.

The Canadian NEIs are compiled with estimation techniques that are comparable to the ones used in compiling the U.S. NEI. Comparability of the inventories between the two countries is essential owing to the joint analyses, air quality modeling, and reporting that are required as part of the Canada-U.S. Air Quality Agreement.

Currently the most comprehensive emission inventory available for air quality modeling and data analysis is for calendar year 2000. A comprehensive emission inventory for calendar year 2002 is currently being compiled. A first version of this emission inventory will be publicly available in the fall of 2005, and the data files for air quality modeling and data analysis will be available by the end of 2005.

Additional information on the Canadian emission inventories for CACs can be obtained from the Criteria Air Contaminants Division of the Pollution Data Branch, located in Gatineau, Quebec, Canada (cac@ec.gc.ca).

3.1.3 Mexican National Emission Inventory

A project to develop the first comprehensive national emission inventory for Mexico began in 2000, building on earlier efforts by the Grand Canyon Visibility Transport Commission and the Western Governors Association (WGA) to build emission inventory capacity in Mexico. The Mexican NEI has financial and technical support of the WGA, the U.S. EPA, the North American Commission for Environmental Cooperation (CEC), and Mexico's *Secretaría de Medio Ambiente y Recursos Naturales* (SEMARNAT, Secretariat of Environmental and Natural Resources) and *Instituto Nacional de Ecología* (INE, National Institute of Ecology). Representatives from these partners, along with other stakeholders from government, academia, and private-sector entities on both sides of the U.S.-Mexican border, participate in the Technical Advisory Committee and provide guidance for the Mexican NEI.

Title VI of the *Ley General del Equilibrio Ecológico y la Protección al Ambiente* (General Law of Ecological Balance and Environmental Protection; government of Mexico, 1996) establishes the regulatory framework for Mexico's air quality program, including the development of the Mexican NEI. According to this law, maintaining and updating the Mexican NEI is the responsibility of SEMARNAT's *Subsecretaría de Gestión para la Protección Ambiental* (Under-Secretariat of Environmental Management).

The objectives of the Mexican NEI program include: (1) development of the first NEI for Mexico to help institutional efforts in the areas of air quality and health impacts, (2) compliance with the Mexican Federal Environment Law mandate to integrate and update an NEI for Mexico, and (3) promotion of institutional capacity-building to compile, maintain, and update emission inventories. Mexico's NEI will also serve to support CEC efforts in the development of a regional emission inventory and will be a valuable input to regional haze compliance in border U.S. states.

The geographic domain of the Mexican NEI is the entire country of Mexico. Emissions are estimated at the municipality level. The base year is 1999. The NEI includes the pollutants and pollutant precursors for which Mexico has air quality standards: NO_2, SO_2, CO, PM_{10}, VOCs, $PM_{2.5}$ and NH_3. The NEI includes all sources of air pollution: point, nonpoint, onroad mobile, nonroad mobile, and natural sources.

SEMARNAT has offices (*Delegaciones*) located in each of the 31 states plus the Federal District. These offices have responsibility for implementing the emission inventory program on a state level with assistance from the Under-Secretariat of Environmental Management and the individual state and municipal environmental agencies. For example, SEMARNAT *delegaciones* receive, compile, and transfer Annual Operating Reports (*Cédula de Operación Annual*) from federal jurisdiction facilities to SEMARNAT's Under-Secretariat of Environmental Management for inclusion in the national point-source emission database. While in the past, INE worked with the national point-source emission database, currently data are collected by the *Registro de Emisiones y Transferencia de Contaminantes* (RETC). The data related to federal industrial sources used to update urban air shed inventories are obtained from the RETC database or directly from the submitted forms of the *Cédula de Operación Annual*.

There are or can be different definitions for the point and nonpoint sources for the Mexican NEI. Similarly, there can be varying definitions for area and point sources for emission inventories developed for the Mexico City Metropolitan Area (MCMA). According to Mexican federal environmental law, there is no specific definition to differentiate between large and small emission sources. The regulatory framework does not classify sources based on size, but it classifies them depending on the main activity. SEMARNAT directly enforces compliance for the 15 largest industrial sectors, including oil, petrochemical and chemical, cement, pulp and paper, hazardous waste management, and automotive. Data on mobile sources for emission estimation are collected from local authorities responsible for enforcing federal *Normas Oficiales Mexicanas* (NOMs) on mobile-source emissions at the local level. Local authorities are responsible for establishing inspection/maintenance programs to check compliance of mobile sources registered within their jurisdiction.

Nonpoint sources pose a special challenge for compiling emission data, since there is no uniform method for defining point and nonpoint sources of air pollution in Mexico. The Federal Environmental Law does not provide the level of specificity needed for identifying sources under state and municipal jurisdictions, nor does it differentiate between "large" and "small" polluters. Hence, data for these sources are gathered from other authorities (i.e., the Energy Secretariat, PEMEX, the Transport Secretariat) or from individual trade associations.

The Mexican NEI has been completed for the six northern states, but the data are still being revisited. The national inventory will be completed by mid-2005, including municipality-level emissions for the entire country (i.e., 32 states and 2,443 municipalities) for 1999. Currently, the inventory report is available on a password-protected website; however, in the future, the inventory will be available on INE's website (http://www.ine.gob.mx/dgicurg/calaire/lineas/inventario_nacional.html) and the U.S. EPA's website (http://www.epa.gov/ttn/chief/net/mexico.html).

Table 3.3 summarizes the sources for the data used to develop the Mexican NEI.

3.2 STATE, LOCAL, AND TRIBAL EMISSION INVENTORIES

State, local, and tribal inventories form an important foundation for larger-scale inventories and are particularly useful for detailed analyses of local air quality problems. Appendix A provides a comprehensive guide to state, local, and tribal agencies that maintain emission inventories. The following text describes important features of representative state, local, and tribal inventories.

3.2.1 U.S. State, Local, and Tribal Emission Inventories

In the United States, emission inventories are critical for the efforts of state, local, and federal agencies to attain and maintain the NAAQS that the U.S. EPA has established for criteria pollutants such as ozone, PM, PM_{10}, $PM_{2.5}$, SO_2, NO_x, and CO. Under the authority of the *Clean Air Act*, the U.S. EPA has long required SIPs to provide inventories containing information regarding the emissions of criteria pollutants and their precursors (e.g., VOCs). These requirements were adopted in 1979 and amended in 1987.

The 1990 Amendments to the *Clean Air Act* revised many of the provisions related to the attainment of the NAAQS and the protection of visibility in Class I areas. These revisions established new periodic emission inventory requirements applicable to certain areas that were designated nonattainment for certain pollutants. For example, since 1990 states have been required to submit an emission inventory every three years for ozone nonattainment areas. Similarly, states must submit an emission inventory every three years for CO nonattainment areas.

In 1998, the U.S. EPA promulgated rules requiring the eastern states and the District of Columbia to submit regulations capping NO_x emissions in order to reduce their adverse impact on downwind ozone nonattainment areas. As part of those rules, the U.S. EPA established emission reporting requirements. Another set of emission reporting requirements, termed the Consolidated Emission Reporting Rule (CERR), was issued by U.S. EPA in 2002. These requirements significantly expanded the geographic extent and increased the number of pollutants (including $PM_{2.5}$) covered in emission inventory reporting. The CERR required states to prepare and submit periodic statewide inventories, rather than just for nonattainment areas. Most states in the United States produce their own emission inventories, as do many local agencies. A listing of state and local government inventory contacts is provided in Table A.2 of Appendix A. Information for this table was obtained from State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials (STAPPA/ALAPCO) at http://www.cleanairworld.org/scripts/stappa.asp. Many Native American Indian tribes develop their own emission inventories. A listing of some Native American Indian tribes can be obtained from http://www.epa.gov/owindian/tcont.htm. Information reagarding emission inventories that has been submitted to the Institute for Tribal Environmental Proffesionals at Northern Arizona University is listed in Table 3.4.

Table 3.3. Sources for Mexican NEI Data.		
Source Type	Pollutant(s)	Data Source(s)
EGU	Criteria plus $PM_{2.5}$	SENER
Refineries and bulk terminals	Criteria plus $PM_{2.5}$	PEMEX
Non-EGU/refineries/bulk terminal point sources	Criteria plus $PM_{2.5}$	Federal and state COAs, DATGEN
Paved and unpaved roads	PM_{10}, $PM_{2.5}$	Satellite imagery, orthographic photography
Area source fuel combustion	Criteria	National Fuels Balance
Area sources (excluding paved/unpaved roads, fuel combustion)	Criteria plus $PM_{2.5}$ and NH_3	Various government agencies, trade associations, academic institutions (e.g., SAGARPA, INEGI, ANAFAPYT, UNAM)
On-road motor vehicles	Criteria plus $PM_{2.5}$ and NH_3	Per capita VKT estimates; MOBILE6-Mexico model
Nonroad mobile sources	Criteria plus $PM_{2.5}$	SAGARPA, INEGI, PEMEX; OTAQ's NONROAD2002 model (modified)
Natural sources	NO_x, VOC, CO	SMN, NCDC, UNAM, SAGARPA; GloBEIS3 model

Notes:
ANAFAPYT: *Asociacíon Nacional de Fabricantes de Pinturas y Tintas* (National Association of Paint and Dye Manufacturers)
COAs: *Cédulas de Operación Anual* (Annual Operating Reports)
DATGEN: *Datos Generales* (Emission inventories for areas with air quality plans)
GloBEIS: Global Biosphere Emission and Interactions System, Version 3.1
INEGI: *Instituto Nacional de Estadística, Geografía e Informática* (National Institute of Statistics, Geography, and Computing)
NCDC: U.S. National Climatic Data Center
OTAQ: U.S. EPA's Office of Transportation and Air Quality
PEMEX: *Petróleos Mexicanos* (Mexican National Petroleum Company)
SAGARPA: *Secretaría de Agricultura, Gandería, Desarrollo Rural, Pesca y Alimentación* (Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food)
SENER: *Secretaría de Energía* (Secretariat of Energy)
SMN: *Servicio Meterológico Nacional* (Mexican National Weather Service)
UNAM: *Universidad Nacional Autónoma de México* (National Autonomous University of Mexico)

State and local agencies rely heavily on U.S. EPA methods and guidance for the development of emission inventories. State and local agency staff also spend a considerable amount of time gathering and checking emission inventory data annually for major point sources and periodically for other sources. Emission inventory development is an ongoing process; the annual starting point for many state/local agencies is a draft NEI provided by the U.S. EPA that reflects information submitted in previous years and information developed by the U.S. EPA. A few state/local/tribal inventories are highlighted for illustrative purposes in the following sections. Appendix A provides information on how to obtain emission data for other jurisdictions.

Table 3.4. Native American Tribal Emission Inventories.

Tribe	Location	Pollutants Covered	Year
Penobscot Indian Nation	Maine	Criteria and HAPs	2002
Mississippi Band of Choctaw	Mississippi	Criteria	1997
Fond du Lac Band of the Minnesota Chippewa Tribe	Minnesota	Criteria and HAPs	2001
Oneida Nation of Wisconsin	Wisconsin	Criteria and HAPs	2002
Pueblo of Acoma	New Mexico	Criteria	1997
Pueblo of Laguna	New Mexico	Criteria	1996
Pueblo of Santa Ana	New Mexico	Criteria and HAPs	1998
Assiniboine and Sioux Tribes of the Fort Peck Indian Reservation	Illinois	Criteria and HAPs	2000
Ute Mountain Ute Indian Tribe	Colorado	Criteria and HAPs	1999
Bishop Paiute Tribe	California	Criteria and HAPs	2001
Cortina Indian Rancheria of Wintun Indians	California	Criteria	2001
Gila River Indian Community	Arizona	Criteria	1997
La Posta Band of Mission Indians	California	Criteria	1999
Paiute-Shoshone Indians of the Lone Pine Community	California	Criteria	2000
Pauma Yuina Band of Luiseno Mission Indians	California	Criteria and HAPs	2000
Salt River Pima-Maricopa Community	Arizona	Criteria and HAPs	1997, 1999
Coeur d'Alene Tribe	Idaho	Criteria and HAPs	1998, 2001
Confederated Tribes of Umatilla Indian Reservation	Oregon	Criteria	1998

California

The California Air Resources Board (CARB) and 35 local air quality districts in the state are responsible for addressing some of the most severe air quality problems in the United States, so it is not surprising that CARB and the local districts have developed some of the best emission inventory tools and data in the country and have helped support the development of national tools and information used by other states. CARB works closely with the local air districts and other data providers in developing a comprehensive statewide inventory of criteria and hazardous air pollutant emissions that is used for policy applications and air quality modeling. This emission inventory includes annual and daily emissions from point, nonpoint, onroad mobile, offroad mobile, and biogenic source categories. Local air districts are responsible for developing inventories for point sources and some offroad mobile and nonpoint source categories. CARB is responsible for developing onroad and biogenic estimates, as well as the majority of offroad mobile and nonpoint source estimates. Onroad mobile, offroad mobile, and biogenic emissions are estimated using CARB emission models (EMFAC [see section 4.4.2], NONROAD [see section 4.4.3], and BEIGIS [see section 4.4.7]). For nonpoint categories for which CARB is responsible, districts have the prerogative to use their own methods and data sources to better reflect local conditions.

The local districts and CARB cooperate in the development of inventories that are used for SIPs, as well as publication of an annual statewide inventory that is available at http://www.arb.ca.gov/aqd/

almanac/almanac.htm. CARB provides the statewide inventory to U.S. EPA for incorporation into the U.S. NEI and also makes the data available to the public through a variety of web tools at http://www.arb.ca.gov/ei/emissiondata.htm. CARB has also developed a web-based interface that allows the local air districts secure and immediate access to their own inventory data. This facilitates and streamlines the quality assurance process and also provides the districts with control over their own data. Most of the local air districts, especially the large districts such as the South Coast Air Quality Management District, also maintain their own emission inventory databases and make information available to the public through district websites.

Delaware

On the opposite side of the country, and at a much smaller scale, Delaware is an example of a small state that has paid close attention to the development of emission inventory information for multiple purposes. The 2002 statewide Delaware emission inventory was prepared for the following purposes: to (1) provide the baseline inventory for the new 8-hour ozone and $PM_{2.5}$ standards, (2) provide the last periodic emission inventory under the 1-hour ozone standard, (3) meet the CERR requirement to submit an inventory to the U.S. NEI, and (4) provide a toxic air pollutant modeling inventory. The Delaware inventory was developed by the Air Quality Management Section (AQMS) of the Delaware Department of Natural Resources and Environmental Control (DNREC).

To meet all these uses, the 2002 inventory includes all criteria pollutants, as well as ozone and $PM_{2.5}$ precursors and the 188 HAPs for the entire state. Source sectors inventoried included major point sources, stationary nonpoint sources, onroad mobile sources, and offroad mobile sources.

Point-source data were obtained from facilities through the use of *i*-Steps, an Internet reporting system (Williams, 2003). The electronically submitted point-source data were downloaded into the point-source database. The data were reviewed and corrections were made with input from the facilities. Because facilities were not familiar with reporting $PM_{2.5}$ emissions, Delaware AQMS estimated emissions for this pollutant based on fuel throughputs and AP-42 emission factors (U.S. EPA, 2005) or through the use of size fraction profiles. The Delaware AQMS also augmented toxic pollutant data for combustion processes.

The area-source inventory relied on standard methods of estimating emissions. Delaware AQMS obtained state-specific activity data where available. Surveys were used for several source categories, including chrome plating operations, dry cleaners, and sand and gravel operations. Data obtained from the Tanks Management Branch of DNREC enabled site-specific emission estimates to be generated.

For onroad and offroad mobile source categories, DNREC relied on MOBILE6 and NONROAD to develop emissions. Link-level VMT data were obtained from the Delaware Department of Transportation, allowing for a high spatial resolution inventory.

Northern Front Range Air Quality Study, Colorado

The Denver metropolitan area has had several air quality studies devoted to the understanding of high PM concentrations and poor visual air quality, the most recent of which was the Northern Front Range Air Quality Study. The objective of this latter study was to apportion measured ambient carbonaceous particles in the $PM_{2.5}$ size range to sources in the Denver area (Norton et al., 1998). Sources receiving attention as the most significant contributors to carbonaceous particles were: (1) light-duty gasoline and diesel vehicles; (2) heavy-duty diesel vehicles; (3) residential wood combustion; and (4) commercial meat cooking. Chemical data collected from each of these different source types were used to construct pollution source profiles for receptor modeling.

In-use vehicle testing included a set of 111 vehicles in the summer of 1996 and 83 vehicles in the winter of 1997. Each vehicle was tested using the Urban Dynamometer Driving Schedule of the Federal Test Procedure (40 CFR 86) driving cycle on a chassis dynamometer. In addition, other test cycles including the IM240 emission test (Pidgeon and Dobie, 1991) were performed. To simulate real-world conditions, both summer and winter study vehicles were tested outdoors at ambient temperatures and indoors at

controlled temperatures. In addition, city/county/state officials also recruited 24 smoking vehicles and 22 light-duty diesel vehicles during the two periods. Chemical analysis of the collected PM samples from these vehicles provided source profiles for light-duty vehicles for receptor modeling.

Chassis dynamometer testing of 21 heavy-duty diesel vehicles was performed to obtain a chemical source profile from heavy-duty diesel vehicles. The emphasis for vehicle recruitment was to obtain data for in-use, higher mileage vehicles because particle emissions from these vehicles were thought to be significantly higher than those from new vehicles. Each vehicle was given a series of tests using the Central Business District, heavy-duty transient truck test, and the West Virginia University truck cycle.

To provide source samples from residential wood combustion and meat cooking, a special dilution source sampler was constructed to collect combustion-formed particles at sampling temperatures representative of ambient conditions. Information on the Northern Front Range Air Quality Study can be obtained at http://www.nfraqs.colostate.edu/nfraqs/.

Minnesota

Minnesota is included in this Assessment as an example of a middle-sized state that has an ongoing process for updating its emission inventory for multiple purposes. Minnesota has developed toxic pollutant emission inventories for calendar years 1996, 1997, and 1999. The 2002 emission inventory will be available in mid-2005. These emission inventories include emission estimates for point, area, and mobile sources and use the Regional Air Pollution Inventory Development System (RAPIDS) as set forth for the Great Lakes Regional Air Toxic Emission Inventory Project. RAPIDS includes emission factors from the U.S. EPA's Factor Information Retrieval Data System (FIRE, described in Chapter 4).

Minnesota has a well established hierarchy for estimating emissions from point sources. Application of data directly reported from companies is the preferred method for estimating emissions from point sources. If directly reported values are not available, Minnesota attempts to use emission factors from RAPIDS for estimating emissions. Minnesota has also collaborated with certain industrial sectors (e.g., metal mining/iron ores process, electric services/coal burning facilities) to develop source-specific emission factors. Finally, Minnesota draws upon the Toxic Release Inventory (TRI) for emission data, although for many facilities the emissions reported to TRI are incomplete in terms of the number of pollutants included. Nevertheless, when source-specific or generic emission factors are not available, TRI emission estimates are used for some facilities.

Minnesota conducts surveys to collect activity data from certain area-source categories, such as residential wood combustion and dry cleaners. Minnesota applies source-specific activity data to estimate emissions from aircraft and locomotives.

Although Minnesota has quality assurance/quality control procedures in place for the development of its emission inventory, well documented uncertainties and limitations still need to be taken into account. For example, the largest concern in the point-source inventory is a lack of source-specific emission information from some large facilities that do not respond to requests for voluntary reporting. Because chemical processing varies from one facility to the other, particularly for solvent-based operations such as surface coating and printing, the lack of source-specific information precludes the estimation of emissions from these facilities. In addition, activity data for some nonpoint source categories and all nonroad equipment categories are highly uncertain. For these categories nationwide default activity values are used for calculating emissions. Nevertheless, with each new inventory, improvements are made in terms of pollutants covered, source and source categories included, emission estimation methods, and the accuracy of emission estimates.

The Minnesota toxic air pollutant emission data can be accessed at http://www.pca.state.mn.us/air/toxics/toxicsinventory.html and http://www.pca.state.mn.us/data/edaAir/.

Allegheny County, Pennsylvania

Allegheny County (Pittsburgh, Pennsylvania) was one of the first air quality programs in the nation and has consistently maintained and improved an emission inventory that addresses the heavy industrial sources found in the Ohio Valley area, such as integrated steel mills, coke ovens, glass plants, and chemical plants.

Allegheny County's local air quality control program integrates source inspection, testing, and permitting activities with emission inventory development, providing important ground-truth information to substantiate national emission analyses.

For its point-source emission inventory, Allegheny County collects and evaluates all HAP emissions, plus significant other emissions such as hydrogen sulfide (H_2S) and NH_3, as well as criteria pollutant emissions. Data are collected from minor and 25-ton-potential sources as well as from major sources. These include highly complex and varied sources, such as chemical and resin manufacturers; glass plants, including one with unusually high selenium emissions; a coal-fired power plant; steel mills; and the world's largest producer of metallurgical coke. The inventory of 135 point sources is consistently evaluated and completed within 12 months of the calendar year of the inventory. The inventory makes full use of electronic reporting; the only hard copy required is of the certification with the signature of the responsible official.

Three full-time staff work directly at compiling and validating emission data. Two full-time engineers observe and verify stack tests, the data from which may be used in calculating the inventory. Other engineers contribute through permitting and inspection activities.

Austin, Texas

An ozone-episode modeling emission inventory was compiled for 1999 for the Austin, Texas area for CO, VOCs, and NO_x. The inventory includes all types of sources in the five-county Austin metropolitan statistical area. It is divided into five types of sources: point, nonpoint, onroad mobile, nonroad mobile, and biogenic. Each category is further divided into source subcategories. In addition to the values for 1999, projections were developed for 2007. Point-source data were retrieved from the Texas Council on Environmental Quality (TCEQ) Point-Source Database. These emission estimates were verified by comparison with measurements for individual sources. Nonpoint source emissions were generally calculated using national default emission data. For 1999, emissions from the largest nonpoint source categories were calculated with bottom-up approaches based on survey data or on local data. Projections to 2007 were based on estimates of population growth and economic forecasts specific to the Austin area. Nonroad mobile emissions were calculated with the U.S. EPA's NONROAD and EDMS emission models. Local equipment data and activity data were used in the models. Projections for 2007 were based on estimates of population growth and economic data. Onroad mobile emissions were determined based on the U.S. EPA's MOBILE6.2 emission-factor model and current detailed, link-based travel demand models. MOBILE6.2 was run with data specific to the area. Projections to 2007 were based on forecasts from the travel demand data. Biogenic emissions were estimated by the TCEQ based on GloBEIS with vegetation survey and satellite data. Projections to 2007 include implementation of all state and federal control measures.

Houston/Galveston Area, Texas

The 2000 Texas Air Quality Study (TexAQS) for the Houston area has prepared one of the most advanced and refined local emission inventories to date. This study focused on ozone precursors because of the local ozone problem and because the area is currently in attainment for PM. The emission inventory contains data on actual emissions for individual days of an episode between August 18, 2000 and September 6, 2000.

Hourly emissions for large EGUs were retrieved from the U.S. EPA Acid Rain Program database. For other large point sources, a special survey was conducted. These sources were required to supply actual hourly emissions. In some cases, hour-specific speciation was provided and included in the inventory. Biogenic emissions were estimated using field surveys and satellite-derived land-use data. Emissions from ship operations and off-road construction equipment were estimated from actual ship operations data and from a special activity survey, respectively. Onroad mobile-source emission estimates were based on state-of-the-science travel-demand modeling, including a newly developed humidity adjustment for diesel vehicles. The inventory was evaluated extensively using data collected during the TexAQS period by a variety of airborne and surface monitors, including a Supersite located in the upper floors of a skyscraper.

VOC emissions were speciated into components for all emission sources. Where possible, emissions from point sources were speciated using information supplied by the source in either the periodic or special inventories. For other source categories, the best available information was used to develop speciation profiles which were used to estimate the components of VOC. For inventory validation purposes (and later for targeted control strategy development), emissions were first speciated into their actual chemical makeup. These data were later merged into lumped Carbon-Bond IV categories for modeling applications.

The results from TexAQS airborne sampling suggest that the standard emission factors and approaches for calculating emissions from certain industrial facilities may not be sufficiently accurate. This study also emphasized the importance of emissions from non-routine operations, including startups, shutdowns, and malfunctions. As a result of these airborne measurements, the emission estimates for some alkenes from photochemcal facilities (mainly ethene and propene) were increased. These findings were corroborated by several independent studies.

Penobscot Nation Native American Tribe, Maine

The Penobscot Nation, located in Maine, has served as a model air program for Native American tribes in New England. As such, their emission inventory serves as a format for all the New England tribes. Criteria and toxic pollutant emissions have been quantified for calendar year 2002. These emissions include both stationary (point and nonpoint) and mobile sources. The most significant stationary sources within the Penobscot Nation are combustion sources and biogenic sources. Mobile sources include privately owned vehicles belonging to residents of the Penobscot lands as well as service trucks, buses, and automobiles that visit the Penobscot Nation. In addition, the Penobscot conduct timber-cutting and recreational activities such as camping and hunting on various tracts of land. Emission estimates were developed for timber-cutting equipment, campfires, roadway dust, and vehicle fuel combustion. Additional emission sources considered include household product usage and activities such as bonfires and lawn maintenance. Emissions were calculated for criteria pollutants and for HAP using varying methodologies.

3.2.2 Canadian Regional and Provincial Emission Inventories

Provinces, territories, and regional agencies collaborate closely with Environment Canada for the compilation of the Canadian emission inventories (national, provincial, territorial, and regional). Appendix A provides a comprehensive guide to agency contacts that support the development of the emission inventories. The following text describes the emission inventories for the agencies that publish their own inventories as well as support the different inventories compiled by Environment Canada.

Quebec Inventory

Quebec compiles emission inventories for criteria air contaminants and GHGs on an annual basis. The emission inventories are compiled through a voluntary annual survey of industrial facilities, and are supplemented with information for area, mobile, and natural sources compiled in collaboration with Environment Canada. Information on Quebec's GHG emission inventory for calendar year 2000 can be obtained at http://www.menv.gouv.qc.ca/changements/ges-en/. This website provides a detailed and comprehensive summary and analysis of Quebec's GHG emissions. Information on Quebec's emission inventory for criteria air contaminants is also available at http://www.menv.gouv.qc.ca/air/qualite-en/index.htm.

Ontario Inventory

Ontario compiles emission inventories for CACs on an annual basis. The CACs include CO, NO_x, SO_x, VOCs, PM, including both PM_{10} and $PM_{2.5}$. The latest emission inventory of CACs available for Ontario is for 2000. In July 2000, Ontario enacted an emission monitoring and reporting regulation that requires the owners and operators of approximately 5,000 facilities across the province in the industrial, commercial, institutional and municipal sectors to report on over 350 contaminants that they release to the air. The contaminants covered under this regulation encompass CACs, GHGs, and toxic air

pollutants such as metals, PAHs, dioxins and furans. As well as reporting this information to the provincial government, these facilities are required to make their reports available to any member of the public. The reporting organization is responsible for the validity and quality of its reported data. Information on this monitoring and reporting regulation is available at http://www.ene.gov.on.ca/envision/monitoring/monitoring.htm.

Ontario also prepared a toxic air pollutant emission inventory for certain target substances as part of the 1999 Great Lakes Regional Air Toxic Emission Inventory Project. This 1999 emission inventory includes point and area sources only. In order to prepare the inventory, Ontario followed the Air Toxic Emission Inventory Protocol and the emission source methodologies agreed upon by the project's technical steering committee in the development of the inventory.

Alberta Inventory

The latest emission inventories compiled for CACs and GHGs in Alberta are for the year 2000. These emission inventories include contributions from large industrial facilities, transportation, commercial operations, and agricultural operations, as well as natural sources. Data for the large industrial facility (point source) category were collected through a survey. The data support the Canada Wide Standards for PM and ozone, the Alberta framework for management of acid deposition, the Canada-Wide Acid Rain Strategy for Post-2000, the management of regional air quality, and reporting to the public.

The focus of the 2000 emission inventory effort was on major industrial operations that emit significant amounts of CACs and GHGs. Some emission estimates have been reported through Alberta Environment's mandatory reporting process. Information on generic industrial processes, activity levels of these emission producing processes, emission quantities, and stack parameters for major stacks were also collected. Other sources of emissions, such as transportation and unregulated sources, were accounted for in supplementary projects conducted in collaboration with Environment Canada.

The Government of Alberta and Alberta industry are currently working together to establish a formal mechanism and framework describing how companies with large volumes of GHG emissions will track and report their emissions on an annual basis. The information gathered under this provincial reporting program will assist both the province and industry in characterizing emission sources and in identifying opportunities for emission reductions.

Additional information on these emission inventories can be found at http://www3.gov.ab.ca/env/air/emissions_inventory.

British Columbia Inventory

British Columbia has prepared an emission inventory of CACs for 2000. Source categories included in the inventory are: point sources, area sources, mobile sources, and natural sources. Additional information on this emission inventory can be found at http://wlapwww.gov.bc.ca/air/airquality/.

Greater Vancouver Regional District Inventory

For calendar year 2000, the Greater Vancouver Regional District prepared an emission inventory for the Lower Fraser Valley Airshed. Contaminants inventoried included CACs and three GHGs: CO_2, CH_4, and N_2O. Sources of emissions inventoried included: point sources, nonpoint sources, and mobile sources. Further information on this emission inventory can be obtained at http://www.gvrd.bc.ca/air/inventory_reports.htm.

3.2.3 Mexican Local Emission Inventories

Local inventories for industrial, area, onroad motor vehicle, and natural sources are an important part of the air quality plans or *Programas para Mejorar la Calidad del Aire* (PROAIRE) developed for several metropolitan areas in Mexico. Most of these inventories have been developed by SEMARNAT and INE in coordination with local environmental authorities, while several have been sponsored by the U.S. EPA, WGA, and TCEQ. In addition, several other inventories are underway including inventories for the areas of Salamanca, Guanajuato and the La Laguna Region (Torreón, Coahuila; and Gómez Palacio and Lerdo, Durango), as well as the states of Tabasco, Hidalgo, and Puebla. State authorities may classify industrial and commercial sources as

area or point sources, depending on how a specific state regulation is stated or on the emission inventory methodology being applied. For example, in critical air quality management areas such as Mexico City or Monterrey, state authorities develop source-specific inventories for industrial or commercial activities such as printing, manufacturing, and food processing (for a detailed description refer to *Gobierno del Distrito Federal* (1998) *Inventario de Emisiones de la Zona Metropolitana del Valle de México Secretaria del Medio Ambiente* online at http://www.sma.df.gob.mx/bibliov/download/archivos/inventario_de_emisiones_1998.pdf).

The following paragraphs describe these inventories. They can be downloaded from the INE website at http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas, except where otherwise indicated. A list of Mexican offices and officials involved in emission inventory and air quality issues is presented in Appendix A.3.

Mexico City Metropolitan Area (MCMA)

The MCMA is the largest urban center in the country, comprising 1,347 square miles (i.e., 3,489 square kilometers) including parts of the states of México, Hidalgo, and Tlaxcala, and all of the Federal District. Approximately 18 million people live in the area.

The fourth biennial emission inventory for 2000 was developed for the air quality plan for MCMA. This inventory can be downloaded from the Mexico City's *Secretaría del Medio Ambiente* (SMA Secretariat of the Environment) website at http://www.sma.df.gob.mx/bibliov/modules.php?name=News&file=article&sid=204.

The inventory includes NO_x, SO_x, CO, total organic compounds, VOC, PM_{10}, $PM_{2.5}$, and NH_3 emissions from industries, on-road motor vehicles, area sources, and natural sources. Also, CO_2 and CH_4 are included for combustion sources.

In the spring of 2003, a multinational team of experts led by the Massachusetts Institute of Technology conducted an intensive, five-week field campaign in the MCMA. The overall goal was two fold: 1) to contribute to the understanding of the air quality problem in megacities by conducting measurements and modeling studies of atmospheric pollutants in Mexico City, and 2) to provide a scientific base for devising emission control strategies for the MCMA (Molina and Molina, 2004; Molina et al., 2004).

Suggested improvements to the inventory concentrate on three critical areas. First, it is necessary to develop an emission inventory for $PM_{2.5}$ focusing on the sources of primary organic and soot particulates. Second, it is important to resolve the serious underestimate of VOC emissions. Third, the NO_x inventory must be improved.

Other suggestions aimed at verifying the emission inventory include (Molina and Molina, 2002):

- Develop a fuel-based inventory using remote sensing data
- Develop a coherent energy-related database for the metropolitan area
- Conduct a detailed source receptor analysis (all exhaust and evaporative emissions)
- Improve characterization of the vehicle fleet and knowledge of driving cycles
- Develop VOC emission estimates that speciate emissions, and express emissions as weighted by reactivity or ozone-forming potential
- Conduct direct emission rate measurements and source profile measurements for vehicles, as well as for biogenic, industrial, and household sources.

Guadalajara, Jalisco

The Guadalajara metropolitan area is the second largest metropolitan area in Mexico with 3.7 million inhabitants. The emission inventory for 1995 was developed as part of the air quality plan for that area (SEMARNAT, 1997a). This inventory includes NO_x, SO_x, CO, HC, TSP, and Pb emissions from industries, *servicios* (small industries and businesses), onroad motor vehicles, and soils and vegetation (e.g., wind erosion). This inventory, as well at those described below for Monterrey, Júarez, Mexacali, Tijuana-Rosarito, and Toluca can be accessed on http://www.ine.gob.mx/ueajei/publicaciones/consultaListaPub.html?id_tema=6&dir=Temas.

Monterrey, Nuevo León

Monterrey is the largest city in the Mexican states bordering the United States, and it is third largest in Mexico. Although technically outside of the 100-km border zone as defined by the La Paz Agreement, emission sources located within the Monterrey metropolitan area may contribute to air pollution within the U.S.-Mexican border area. An inventory for 1995 was developed for the Monterrey Air Quality Plan (SEMARNAT, 1997b).

This inventory includes NO_x, SO_x, CO, HC, TSP, and lead emissions from industries, *servicios*, onroad motor vehicles, and soils and vegetation. The inventory reports that PM emissions from natural sources come mostly from wind erosion of disturbed lands. The absence of area-source SO_x emissions indicates that emissions from fuel combustion in the industrial, commercial, and residential sectors are not accounted for in this inventory.

Ciudad (Cd.) Júarez, Chihuahua

Cd. Juárez lies directly across the U.S.-Mexican border south of El Paso, Texas. It is the largest Mexican metropolitan area within the 100-km border zone. Cd. Juárez has been an area of focus for many regional air quality studies. These studies have emphasized the effects of emissions from Cd. Juárez on criteria pollutant air quality standards, visibility, and public health in the Paso del Norte region (i.e., Cd. Juárez, Chihuahua; El Paso, Texas; and Doña Ana County, New Mexico) (Parks et al., 1998, Yocke et al., 2001, and Parks et al., 2003).

An inventory for 1996 was developed for the Cd. Juárez Air Quality Plan (SEMARNAT, 1998). The inventory includes NO_x, SO_x, CO, HC, and TSP emissions from industries, *servicios*, onroad motor vehicles, and soil. The inventory results indicate a significant contribution to the overall inventory by onroad motor vehicles for every pollutant except PM_{10}. Given the size of the significant maquiladora industry in Cd. Juárez during 1996, the point source emissions in this inventory are surprisingly low relative to area source SO_x emissions, indicating that point-source fuel combustion may be under-reported. Recent projects sponsored by the TCEQ have focused on improving the area-source inventory (ERG, 2003),which is also thought to be under-represented.

Mexicali, Baja California

Mexicali, the capital of the state of Baja California, lies directly across the U.S.-Mexican border south of Imperial County, California. An inventory for 1996 was developed for the Mexicali Air Quality Plan (Government of the State of Baja California, 1999). The inventory was developed as a special task under the Mexico Emission Inventory Program sponsored by WGA, the U.S. EPA, and INE (Radian International, 2000). The inventory includes NO_x, SO_x, CO, HC, and PM_{10} emissions from industries, area sources, onroad motor vehicles, and soil and vegetation (i.e., soil NO_x, vegetative VOC, and wind erosion).

Tijuana-Rosarito, Baja California

Tijuana lies directly across the U.S.-Mexican border south of San Diego, California. After Cd. Juárez, it is the largest metropolitan area directly adjacent to the border. The impact of this area on ozone levels in Southern California has been studied for over a decade as part of the Southern California Ozone Study-North American Research Strategy for Tropospheric Ozone. An inventory for 1998 was developed for the Tijuana Air Quality Plan (Government of the State of Baja California et al., 2000). The municipality of Playas de Rosarito is also included in the inventory domain.

The inventory includes NO_x, SO_x, CO, total organic gas, and PM_{10} emissions from industries, *servicios*, onroad motor vehicles, and soil and vegetation (i.e., soil NO_x, vegetative VOC, and wind erosion).

Toluca, México

The Metropolitan Zone of the Valley of Toluca comprises the municipalities of Toluca, Metepec, Lerma, San Mateo Atenco, and Zinacantepec. The area has approximately 1.1 million inhabitants. An emission inventory for 1995 was conducted as part of the air quality plan for that area (SEMARNAT and INE, 1997).

This inventory includes NO_x, SO_2, CO, HC, TSP, and lead emissions from industries, *servicios*, onroad motor vehicles, and soils (wind erosion, only) and vegetation.

3.3 REGIONAL EMISSION INVENTORIES

3.3.1 U.S. Regional Planning Organizations (RPOs)

Five RPOs have been formed in the United States to coordinate air planning and management activities to meet the requirements of the Regional Haze Program. The RPOs as shown in Figure 3.6 are: Western Regional Air Partnership, Central States Regional Air Partnership, Midwest Regional Planning Organization, Visibility Improvement State and Tribal Association of the Southeast, and Mid-Atlantic/Northeast Visibility Union. The RPOs initiated development of inventories for 2002 that include criteria pollutants and their precursors, including NH_3. The 2002 inventories cover all geographic areas at the county or sub-county level for each sector. The inventories are being used to support air quality planning activities for regional haze and the ozone and $PM_{2.5}$ NAAQS.

The RPO emission inventory activities are being coordinated with the U.S. EPA's NEI. The RPOs focus on collecting the best temporally and spatially resolved activity data available from their member state, local, and tribal agencies. They also focus on improving emission estimation methods and supporting data for categories determined to be significant contributors to visibility impairment and/or ozone and fine PM pollution, or for which previous emission estimates have a high degree of uncertainty. For mobile sources, this work has included populating the U.S. EPA's MOBILE6 and NONROAD models with county- or state-specific

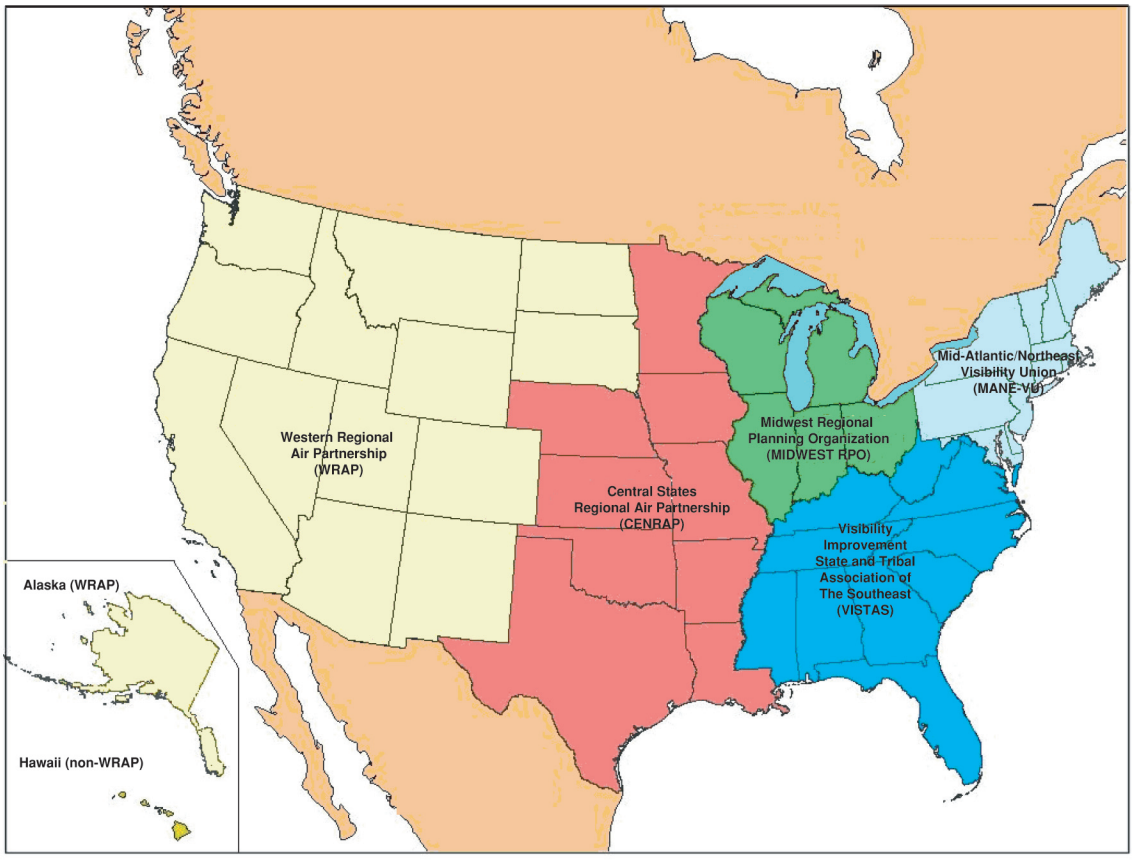

Figure 3.6. Map of U.S. Regional Planning Organizations.

data (e.g., local VMT and temperature data, nonroad equipment populations). For stationary nonpoint sources, work has focused on improving emission estimates and the spatial and temporal distribution of emissions for subsectors that are important within each RPO (e.g., livestock waste, agricultural burning, wildfires, and residential wood combustion). The state, local, and tribal agencies generally survey stationary point sources to obtain inventory data. Thus, inventory work has centered on quality assurance of the point-source data (e.g., reviewing emission rates, operating schedules, stack parameters, geographic coordinates).

This section contains information on the individual RPOs and emission inventories that they have prepared. Summary data on individual emission inventories, as well as contact information for the various RPOs are presented in Appendix A, Table A.3.

Visibility Improvement State and Tribal Association of the Southeast (VISTAS)

VISTAS developed 2002 emission inventories for mobile sources (including onroad and nonroad sectors) and stationary sources (both point and nonpoint). Much of the work to date has involved supplementing the 1999 U.S. NEI with local data (onroad and nonroad) and updating it to create a 2002 inventory. Point source emissions from the 1999 NEIv2 were quality assured and the inventory was checked for new and retired facilities. County-level NH_3 emission estimates were developed using the Carnegie Mellon University model. Data on 2002 fires were obtained from federal and state agencies. Work also has been conducted to improve spatial and temporal allocation of emissions. In addition to the 2002 base year inventory, VISTAS is developing a 2015 projection year inventory. VISTAS makes information regarding its emission inventories and other work available at http://www.vistas-sesarm.org.

Central States Regional Air Partnership (CENRAP)

CENRAP's 2002 emission inventory efforts involve supplementing the U.S. NEI with data supplied by state and local agencies. CENRAP has sponsored work on improving agricultural and prescribed burning and agricultural ammonia emission estimates. Work is ongoing to develop better activity data for nonroad and onroad sources and agricultural dust. CENRAP also plans to sponsor work to improve point and nonpoint inventories for sources that are lacking data. Some of the emission inventory work sponsored by the Western Regional Air Partnership (WRAP), described below, includes states in the CENRAP region. CENRAP completed a comprehensive inventory for the region in December 2004. Information on CENRAP's activities and emission inventories is available at http://www.cenrap.org.

Mid-Atlantic/Northeast Visibility Union (MANE-VU)

Inventory work conducted by MANE-VU includes the development of a regional, area, point-, and mobile-source base year inventory for 2002, using state-supplied data to update the U.S. EPA's preliminary 2002 NEI. For area sources, 2002 inventories of criteria and hazardous air pollutants were developed for open burning (residential solid waste, brush and leaf burning, land-clearing debris) and residential wood burning. Inventories of 2002 NH_3 emissions were developed for publicly owned treatment works, composting, cement plants, and industrial refrigeration. Ongoing work includes the development of a 2002 modeling inventory, which will include biogenic data, CEMS data, and area source temporal and spatial allocation methods, and development of future base-case inventories for 2009, 2013, and 2018. Information regarding MANE-VU's activities and emission inventories can be accessed at http://www.marama.org/visibility/ and http://www.manevu.org/.

Western Regional Air Partnership (WRAP)

WRAP has developed 1996 base-year inventories for all sectors. The mobile-source inventory contains criteria-pollutant emission estimates for onroad sources (including paved road dust) and nonroad sources. Special studies have been conducted to estimate emissions for wind-blown dust, wildfires and prescribed burns, agricultural burning, unpaved roads, and NH_3. Both point- and nonpoint-source emissions cover the WRAP and CENRAP domains. The 1996 point-source inventory (based on the

1996 National Emission Trends inventory) has been revised following a quality assurance/quality control (QA/QC) analysis. The 1996 nonpoint-source inventory was also revised based on input from state and local agencies. In addition to the 1996 inventory, WRAP has developed a 2018 projection year inventory. Information on WRAP and emission inventories that it has prepared are available at http://www.wrapair.org/.

Midwest RPO

The Midwest RPO is preparing regional inventories to support air quality modeling for ozone, $PM_{2.5}$, and regional haze. The inventories reflect a base year (2002) and future years (e.g., 2009 and 2018). Primary data sources include the U.S. EPA's initial NEI for 2002, the CERR inventories for the Midwest RPO states (and a few neighboring states), transportation network data for major metropolitan areas in the region, NH_3 emissions based on Carnegie Mellon University's latest model, biogenic emissions based on BIOME3 (equivalent to BEIS3), a regional fire inventory, and an updated Canadian inventory. The Midwest RPO has sponsored improvement activities for several portions of the inventory, including utility temporal profiles based on CEM data, local activity data for several nonroad source categories, region-specific temporal and speciation profiles, and new tribal inventories. Work is ongoing to develop a new emission model (CONCEPT) and a new process-based NH_3 emission model for agricultural sources. The future-year inventories will reflect application of appropriate growth factors and consideration of candidate control strategies (e.g., "on the books" controls, "on the way" controls, and other possible regional and local measures).

Inter-RPO Emission Inventory Projects

The National Wildfire Emission Inventory is an inter-RPO project managed by WRAP. The purpose of this project is to develop a national wildfire emission inventory to support atmospheric modeling of fine PM and visibility.

MARAMA is managing the National Emission Inventory Warehouse project, an inter-RPO effort that will support the development of a web-based system to facilitate emission inventory sharing and versioning. This system in expected to come online during the second half of 2005.

3.3.2 Canada/U.S. Regional Emission Inventories

As part of the Canada-U.S. Air Quality Agreement, former U.S. EPA Administrator Christine Todd Whitman and Canada's Minister of the Environment, David Anderson, announced on January 6, 2003 the commitment by the two countries to build on the existing transborder air quality cooperation by developing new cooperative projects to reduce cross-border air pollution and enable greater opportunities for coordinated air quality management. Two pilot projects are currently in place, located in the Georgia Basin/Puget Sound International Airshed Strategy (which covers British Columbia and northwestern Washington state), and the Great Lakes Basin Airshed Management Framework (which covers southeastern Michigan and southwestern Ontario).

The purpose of these pilot projects is for the United States and Canada, with partners from other levels of government, to engage in a joint investigation of local and sub-regional airshed management in a contiguous urban area that crosses the Canada-U.S. border. The goals are to: (1) exchange information on the emission sources and air quality measurements; and (2) identify opportunities, challenges, and obstacles in developing a template for a coordinated airshed management approach, should it prove feasible. The template would be available for adaptation and adoption by local communities as their airshed management framework.

Detailed emission inventories are currently being compiled for these airsheds and should be completed by 2007.

3.3.3 Mexico/U.S. Regional Emission Inventories

Regional inventories for criteria air pollutants have been developed for geographic domains that include parts of Mexico and the United States. Most of these regional inventories were developed for input to models for assessing impacts on ozone levels in the

U.S.-Mexican border region, and visibility impacts across the United States and into Canada.

Paso del Norte Ozone Study

Paso del Norte includes the area around El Paso, Texas, and Cd. Juárez, Chihuahua. The Paso del Norte Ozone Study was conducted during the summer of 1996 to assist U.S. EPA, the TCEQ and others in collecting the data needed to perform reliable ozone modeling. Summary information on this study can be accessed at http://www.epa.gov/earth1r6/6pd/air/pd-q/elpaso.pdf.

The Paso del Norte emission inventory was developed for the modeling domain (i.e., all of El Paso County in Texas, parts of Doña Ana and Otero counties in New Mexico, part of Hudspeth County in Texas, and the metropolitan area of Cd. Juárez in Chihuahua, Mexico). This inventory is not currently available on the Internet. The inventory was developed primarily using existing emission data for point, area, mobile, and biogenic sources. The exception was that U.S. EPA's BEIS-II was used to estimate the biogenic emissions (Haste et al., 1998).

For the U.S. portion of the domain, the inventory values were provided by a number of sources including TCEQ, the Emission Trends Database for 1995, and the Sunland Park (New Mexico) SIP. A QA review of these emission estimates determined that they were reasonable, and no adjustments were made.

For Cd. Juárez, 25 point sources, 32 major nonpoint sources, mobile sources, and biogenic sources were included in the inventory. Emissions for point, nonpoint, and mobile sources were provided by the *Instituto Mexicano de Investigación y Planeación* (IMIP) in Cd. Juárez. A quality assurance review of the VOC and NO_x emissions from approximately one-half of the industrial sources in the Cd. Juárez inventory revealed some problems with emission estimates provided by IMIP (e.g., unexpectedly small VOC emissions from a pharmaceutical production facility, and unexpectedly large VOC emissions from an electrical accessory fabrication plant). Mobile-source emissions were found to be consistent with gasoline sales data; however, heavy-duty diesel truck NO_x emissions may have been underestimated.

SCOS97-NARSTO Inventory

The 1997 Southern California Ozone Study-NARSTO (SCOS97-NARSTO) was organized as a follow-up study to the Southern California Air Quality Study completed more than a decade earlier (Shah et al., 1998). The SCOS97-NARSTO emission inventory was developed for use as input to photochemical models for assessing the contributions of, and interactions among, air pollution sources in the region, and for developing, implementing, and tracking the progress of control strategies (Funk et al., 2001). The SCOS97-NARSTO emission inventory memo related to the Mexican portion of the domain is available on the CARB website at http://www.arb.ca.gov/research/scos/scospub.htm.

This modeling region for SCOS97-NARSTO, and thus the emission inventory, contains a portion of northern Baja California, including Tijuana, Tecate, and Mexicali. The SCOS97-NARSTO emission inventory for northern Baja California was developed using per capita scaling factors, and other inventories conducted in 1990 for northern Baja California and for 1996 in Mexicali (SAI, 1997). The scaling factors provided a reasonable method to scale emissions that are highly uncertain and of unknown quality.

Border 2012 Inventory

The Border 2012 program was established by U.S. EPA, Mexico's SEMARNAT, and other U.S. and Mexican environmental agencies as a successor to the Border XXI program. Border 2012 is designed to address environmental issues that exist in the U.S.-Mexico border region. The 1983 La Paz Agreement defined the U.S.-Mexico border region as following the border between the two countries from the Gulf of Mexico to the Pacific Ocean and extending 100 km from both sides of the border. To increase the understanding of emission sources located within the border region, and support an air quality assessment for Border 2012, an emission inventory was developed (ERG, 2004). Currently, the draft Border 2012 inventory is not available on the internet; however, after it is finalized it will be available on the U.S. EPA Border 2012 website at http://www.epa.gov/usmexicoborder.

The Border 2012 emission inventory combines existing criteria air pollutant emission inventories for the year 1999 from the U.S. NEI and the Mexican NEI using GIS techniques. This inventory includes annual emissions for NO_x, SO_x, VOC, CO, PM_{10}, $PM_{2.5}$, and NH_3. Source types include point, area, onroad motor vehicle, and nonroad mobile sources.

In its current draft form, the Border 2012 emission inventory summarizes emissions in three ways:

- Based only on the portion of the counties/ municipalities that lie within the 100 km border zone
- Based on the entire land mass of all counties/ municipalities of which any portion lie within the 100 km border zone
- Based on state-level emissions for the 10 Border States.

Future finalized versions of the Border 2012 emission inventory will include projections to years 2002 and 2012, as well as results provided in 4 km x 4 km grids for use in air quality models.

BRAVO Inventory

The Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study examined visibility impairment at Big Bend National Park in Southwest Texas. To support BRAVO, an emission inventory for 1999 was developed for visibility-related pollutants and their precursors (Kuhns et al., 2001). The BRAVO inventory was used as input by the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (Kuhns and Vukovich, 2003). Information regarding the BRAVO inventory is available at http://www.epa.gov/ttn/chief/net/mexico.html.

The BRAVO domain includes seven U.S. states (Texas, New Mexico, Colorado, Kansas, Oklahoma, Louisiana, and Arkansas) and 10 Mexican states (Baja California, Sonora, Chihuahua, Coahuila, Nuevo León, Tamaulipas, Sinaloa, Durango, Zacatecas, and San Luis Potosí). It also includes emissions from the three municipalities of Tula, Vito, and Apaxco (i.e., the largest industrial grouping of SO_2 sources in Mexico). The BRAVO inventory consists of emissions from point, nonpoint, onroad motor vehicle, nonroad mobile, and natural sources including the Popocateptl volcano (located in the Mexican state of Puebla). Windblown dust and forest fires are not included.

The Mexican portion of the BRAVO study emission inventory relied upon previous inventories for Mexico including the Monterrey, Cd. Juárez, Mexicali, and Tijuana Air Quality Planning inventories. Nonpoint and mobile emission factors were calculated for these four cities based upon five activity surrogates: population, number of households, total number of registered vehicles, agricultural acreage, and cattle populations. Activity data from Mexico's *Instituto Nacional de Estadística, Geografía e Informática* (INEGI) were used to estimate emissions from the uninventoried areas in Mexico. Point source emissions were estimated using data contained in the National Mercury Inventory and fuel consumption data provided by the CEC (Acosta-Ruiz and Powers, 2003).

The U.S. portion of the BRAVO study emission inventory used the 1999 NEIv1 as a starting point. The TCEQ provided improved emission data for onroad motor vehicles, commercial ships, construction equipment, and oil field equipment in Texas. Hourly emission data from CEMS on power plants were obtained from the U.S. EPA's Clean Air Market Program. These SO_2 and NO_x emission data were reconciled with the NEI datasets by matching facility process emissions in the NEI to stack emissions from the CEMS.

3.4 TOXIC AIR POLLUTANT, GREENHOUSE GAS, AND SPECIALTY INVENTORIES

Emission inventories are also prepared by international bodies (see, e.g., Box 3.2), federal agencies, states and provinces, and industries to address specific issues not supported by the inventories described in the previous sections. These inventories address toxic air pollutants, GHGs, geographical categories not described by political boundaries, and specific pollutants. This section presents a sample of emission inventories that fall into this category.

Box 3.2. International Emission Inventories

Major efforts to compile global emission inventories have been organized around two cooperating programs: the Global Emission Inventory Activity (GEIA) and Emission Database for Global Atmospheric Research (EDGAR).

GEIA was created in 1990 to develop and distribute global emission inventories of gases and aerosols emitted into the atmosphere from natural and anthropogenic (human-caused) sources. This effort was initially documented by Graedel et al. (1993) and is maintained at the website http://www.geiacenter.org/. The emission data sets can be downloaded in gridded form at 1° x 1° spatial resolution. The goal of GEIA is to assemble data for the year 1990, and emissions are presented at annual, seasonal, or monthly temporal resolution. GEIA accepts emission and related databases provided they have undergone substantial peer review as reflected by acceptance for journal publication and agreement among the various GEIA project teams. Because the data sets are developed by different research teams, there is no consistency of methodology. The major species presently available in GEIA are NH_3, BC, CO_2, CO, CFCs, HFCs, PFCs, SF_6, lead, mercury, CH_4, N_2O, NO, NO_x, SO_2, and VOC. GEIA has proved valuable to atmospheric scientists by providing uniformly presented inventories to drive air quality models. Support to field measurements and regulatory and policy development has also been provided. Data management and communication are coordinated by the GEIA Center in Boulder, Colorado, which is supported by the U.S. National Science Foundation.

EDGAR is a compilation of global emissions of direct and indirect greenhouse gases from anthropogenic sources on a country basis as well as on a 1° x 1° grid. The EDGAR database was developed jointly by the National Institute of Public Health and the Environment in the Netherlands and the Netherlands Organization for Applied Scientific Research, in cooperation with GEIA. The initial Version 2.0 of the database (Olivier et al., 1996) for the year 1990 has been used extensively in atmospheric modeling and other studies, but is now obsolete and replaced by Version 3.2 (Olivier and Berdowski, 2001); see http://arch.rivm.nl/env/int/coredata/edgar/. EDGAR Version 3.2 comprises an update of the 1990 emissions and new emission estimates for 1995. Unlike GEIA, emissions of all species are calculated in an internally consistent way from the same activity levels. Still under development, Version 3.2 of the database presently contains emission data for CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, CO, NO_x, non-methane VOC, and SO_2. A historical inventory of global anthropogenic emissions from 1890-1990 at 10-year time steps, based on the EDGAR present-day emissions, is also available in gridded form and by world region (van Aardenne et al., 2001).

3.4.1 Toxic Air Pollutant Inventories

Canada, the United States, and Mexico all prepare emission inventories of toxic air pollutants, though they do not all address the same pollutants and source categories. The three countries have active pollutant release and transfer registries (PRTR). PRTRs are databases of releases of pollutants to air, water, underground injection, and land filling. In addition, PRTRs typically quantify pollutants that are recycled or sent off-site for further processing. PRTR data are submitted by industries and facilities and housed in a centrally located database. In the United States and Canada these databases are accessible to the public, and they serve as a primary reference point for obtaining air emission release data from point (and some nonpoint) sources. Once the first Mexican PRTR is finalized, it will be public as required by recent amendments to federal law.

This section addresses the efforts by each country in developing toxic air pollutant inventories and also discusses their PRTR efforts.

U.S. National Toxic Air Pollutant Inventory

The U.S. National Toxics Inventory (NTI) was designed to support analyses required by the *Clean Air Act* that depend on a high-quality, comprehensive toxic air pollutant inventory. The NTI contains estimates of 188 toxic air pollutant emissions from stationary and mobile-source categories. It was

envisioned that the NTI would be updated on a three-year cycle. The NTI was compiled from emission inventories for 1996 and 1999 (U.S. EPA, 2004). After 1999, the U.S. EPA integrated the NTI into the NEI. Currently, the NEI is the central repository for toxic air pollutant data submitted by states, local agencies, and tribes to the U.S. EPA.

U.S. Toxic Release Inventory

The Toxic Release Inventory (TRI) is the U.S. PRTR, and was mandated by the *Emergency Planning and Community Right-To-Know Act*. The TRI started in 1988 and is now collecting data on releases to air, water, and ground (including deep well injection) of more than 650 chemicals from over 20,000 facilities in the United States that manufacture, process, or use significant quantities of toxic chemicals (http://www.epa.gov/tri). The TRI is designed to "increase public and industry understanding of the types and quantities of chemicals released into the environment and transferred off-site (CEC, 2004) as waste (http://www.cec.org/takingstock/)." The TRI is publicly accessible through the internet using various tools. Data can be obtained by querying the TRI database (http://www.rtk.net or http://www.scorecard.org or http://www.epa.gov/triexplorer).

Canadian Toxic Inventories

Canada develops comprehensive toxic air pollutant inventories for selected pollutants, such as mercury, lead and cadmium, and for persistent organic pollutants (dioxins, furans, polycyclic aromatic hydrocarbons (PAH), and hexachlorobenzene). These emission inventories are compiled on an annual basis to support the reporting requirements of the Heavy Metals and Persistent Organic Pollutant protocols of the United Nations Economic Commission for Europe, and of the Canada-Wide Standards for mercury, dioxins, and furans.

Canadian National Pollutant Release Inventory

The National Pollutant Release Inventory is Canada's PRTR as well as an important source of information for the development of the CAC, heavy metal, and persistent organic pollutant inventories. The NPRI collects emission information from individual facilities for a large number of pollutants that have been declared toxic under CEPA. The NPRI was initiated in 1993 and currently collects data on releases and transfers of over 323 substances for more than 8,000 facilities annually. The releases reported to the NPRI are publicly available on the internet at http://www.ec.gc.ca/pdb/npri/npri_home_e.cfm.

Mexican Toxic Air Pollutant Inventories

Mexico does not currently produce a national-scale toxic air pollutant inventory. Inventories of toxic air pollutants have focused on transboundary impacts between Arizona in the United States and Sonora in Mexico. Also, an emission inventory was sponsored by the CEC to identify sources of mercury in Mexico. However, Mexico is now implementing a PRTR program, called the *Registro de Emisiones y Transferencia de Contaminantes* (RETC).

Mexico's PRTR program formally started in 2001, when a voluntary guideline with a list of chemicals, the reporting format, and the reporting procedures was published. Mexico passed regulations for a mandatory reporting system for toxic air pollutants in 2004, and many states have been developing state-level RETC systems since then. In addition, Mexico has been augmenting its list of mandatory chemicals for reporting to the RETC. In 2003, over 170 facilities reported voluntarily to the RETC, and it is expected that this number will increase in the next (mandatory) reporting cycle.

Mexican Mercury Inventory

A preliminary inventory of mercury emissions was developed for Mexico under the sponsorship of the CEC (Acosta-Ruiz and Powers, 2003), and is available on the CEC website at http://www.cec.org. The objectives of this inventory were to develop a comprehensive list of potential stationary sources of atmospheric mercury emissions in Mexico, to provide annual process throughputs for these sources, and to estimate mercury emissions using indirect approaches (e.g., emission factors). This inventory includes only industrial point sources of mercury.

Transborder Inventories of Toxic Air Pollutants

All three NARSTO member countries have developed emission inventories that address the movement of toxic air pollutants across borders. For example, toxic air pollutants can move from Mexico into

the United States, and pollution originating in the United States can move into Canada. Presented in this subsection are three examples of transborder emission inventories.

Great Lakes Regional Air Toxic Emission Inventory

The Great Lakes Toxic Emission Regional Inventory compiles emission data from eight Great Lakes states and the province of Ontario. As such, it is the largest multijurisdictional project of its kind in North America. This emission inventory includes emission estimates for point, area, and mobile sources and uses the Regional Air Pollution Inventory Development System (RAPIDS). The latest iteration of this inventory is based on data that were collected in 2001. Listing pollutants by type, quantity and source, the inventory categorizes emissions by more than 600 industrial classifications and more than 2,000 types of sources. Additional information on this emission inventory can be obtained at http://www.glc.org/air/.

Nogales, Sonora, and Nogales, Arizona

The Ambos Nogales HAP emission inventory followed the development of HAP emission inventories for four regions of Arizona under the Arizona HAP Research Program (Radian International, 1997). This inventory was developed for the transboundary region of Nogales, Arizona and Nogales, Sonora, and included point, area, and onroad motor vehicle sources. The inventory currently is not available on the Internet.

The Ambos Nogales HAP inventory was developed for the year 1994. The inventory domain measured 12 km x 19 km and was equally divided between Nogales, Arizona and Nogales, Sonora. The inventory included 113 individual HAPs drawn from the Arizona HAP Research Program list, as well as PM_{10} and $PM_{2.5}$. Reporting focused on 25 compounds of interest that were initially identified as having the greatest potential impact on human health within the inventory domain. The inventory results were allocated to 500-m grid cells by hour for each season for dispersion modeling and health risk assessment.

The Nogales, Sonora, portion of the inventory included 49 point sources (primarily maquiladoras). Emissions were estimated for 23 area-source categories, including some unique categories such as residential biomass combustion, wire reclamation, and produce fumigation. Onroad motor vehicle emissions were estimated using the MOBILE-Juárez emission factor model (Radian International, 1996). Locomotive emissions were estimated as an area source. Other nonroad mobile-source categories were not estimated.

The Nogales, Arizona portion of the inventory included three point sources. Emissions were estimated for 20 area-source categories (including locomotives). Onroad motor vehicle emissions were estimated using the U.S. EPA's MOBILE5a and PART5 emission factor models. Nonroad mobile source emissions were obtained from the existing Grand Canyon Visibility Transport Commission inventory (Radian International, 1995).

Agua Prieta, Sonora, and Douglas, Arizona

Under the Arizona HAP Research program, the Arizona Department of Environmental Quality conducted an air quality monitoring program for Douglas, Arizona and Agua Prieta, Sonora, and a HAP emission inventory (Meszler et al., 2002). The Douglas/Agua Prieta HAP inventory is not available on the Internet.

The inventory was developed for the year 1999. The inventory domain includes Douglas and Agua Prieta and contains emission data for NO_x, SO_x, VOC, CO, PM_{10}, $PM_{2.5}$ and HAPs (1000 compounds from the U.S. EPA's HAP list and Integrated Risk Information System).

The Agua Prieta portion of the inventory includes 71 point sources (i.e., *maquiladoras*, brick kilns, dry cleaners, a lime kiln, and a landfill). Emissions were estimated for only 11 nonpoint source categories (i.e., paved and unpaved road dust, degreasing, pesticide and consumer product use, residential butane combustion, residential wood combustion, printing operations, structural fires, automobile fires, trash fires, and charbroiling). Onroad motor vehicle emissions were estimated by using the U.S. EPA's

MOBILE6 emission factor model. Nonroad mobile source and biogenic emissions were also estimated.

3.4.2 Greenhouse-Gas Emission Inventories

Compilations of national emissions of GHGs are being assembled in accordance with the United Nations' Framework Convention on Climate Change (UNFCCC). These inventories are compiled in an on-line searchable database for Annex I and non-Annex I parties (http://ghg.unfccc.int/). The site contains summary tables and emission estimates for the six main direct GHGs: CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6, as well as for the indirect species CO, NO_x, non-methane VOCs, and SO_2. These data are in general available for the period 1990-2000. The emission estimates are presented in accordance with the source categories of the IPCC Guidelines for National Greenhouse Gas Inventories. Many important countries of the developing world, such as China and India, are not included in this database.

The United States, Canada, and Mexico each have prepared GHG emission inventories for each country's primary anthropogenic sources and sinks of GHGs. A brief discussion of each emission inventory follows.

U.S. Greenhouse-Gas Inventories

The United States has prepared GHG inventories for the years 1990-2000. These inventories adhere to a common and consistent mechanism that enables signatory countries to the UNFCCC to compare the relative contributions of different emission sources and GHGs. The GHGs accounted for in the U.S. inventory include: CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. The GHG emission inventory contains information on both the emissions of GHGs and on GHG sinks. Emissions are generally reported in teragrams of CO_2 equivalent for all pollutants. Information on the U.S. GHG inventories can be obtained at http://www.epa.gov/globalwarming/.

In addition to a national GHG inventory, 38 states and Puerto Rico have developed GHG inventories. In addition, two other states are developing GHG inventories. Each state inventory identifies the major sources of GHG emissions and creates a baseline upon which reduction strategies are based. The inventories present annual emissions of GHGs by sector (e.g., energy, agriculture, waste), by source (e.g., transportation, manure management, etc.), and by gas (e.g., carbon dioxide, methane). The U.S. EPA makes state GHG inventory data available on the Internet at (http://yosemite.epa.gov/globalwarming/ghg.nsf/emissions/StateAuthoredInventories).

Canadian Greenhouse-Gas Inventory

To support Canada's National Implementation Strategy on Climate Change and Canada's commitments under the UNFCCC, national emission inventories on sources and sinks for GHGs are compiled on an annual basis. Canada has published GHG emission inventories for the past 11 years using the UNFCCC guidelines. This progression of GHG emission inventories is used to track Canada's progress toward reducing emissions to 6 percent below 1990 levels over the period of 2008 to 2012 as required under the Kyoto Protocol. The Canadian GHG emission inventory reports include analyses of the emission trends, factors affecting the trends, and detailed descriptions of the methods, models, and procedures used to develop and verify the data. The report documents emissions of the following pollutants: CO_2, CH_4, N_2O, SF_6, PFCs, and, HFCs.

The Canadian inventory uses an internationally agreed-upon reporting format that groups emissions into six sectors: energy, industrial processes, solvent and other product use, agriculture, land-use change, forestry, and waste. More information on this emission inventory is available on the Internet at http://www.ec.gc.ca/pdb/ghg.

Mexican Greenhouse-Gas Inventory

A preliminary national GHG emission inventory for Mexico was developed by sector for the year 1990 with the first IPCC methodologies. This inventory was reported in the First National Communication to the UNFCCC in 1997. In 1998, Mexico signed the Kyoto Protocol, and subsequently in July 2001, the inventory was updated for the years 1994, 1996, and 1998 and reported in the country's Second National Communication to the UNFCCC. Both of these National Communications are available at

INE's website at http://www.ine.gob.mx/dgicurg/cclimatico/comnal.html and full reports are available at http://www.ine.gob.mx/dgicurg/cclimatico/inventario.html. Only the 1996 inventory includes updated estimations for the land use change category. The 2002 base year GHG inventory will be published by INE in late 2005 and is to be included as part of the third National Communication to the UNFCCC.

The following external agencies have contributed to the compilation of the National Greenhouse Gases Emission Inventory: the U.S. Country Studies Program, the U.S. EPA, the Global Environmental Facility by the United Nations Development Programme and the United Nations Environment Programme.

A system was developed to store the GHG emission data for 1999, to systematize the national inventories, and to make the results accessible to the general public at http://www.ine.gob.mx/dgicurg/cclimatico/inventario/intro.html.

INE's *Dirección General de Investigación sobre la Contaminación Urbana, Regional y Global* (DGICURG, General Directorate of Urban, Regional, and Global Air Pollution Research) coordinates a team of experts from academia and other government agencies and is responsible for compiling and updating Mexico's GHG inventory in compliance with its commitment to the Kyoto Protocol and UNFCCC reporting requirements. DGICURG has updated the GHG inventory to 2001 for the transportation and fugitive emission sectors, and is currently updating the agricultural sector (Fields, 2004).

3.4.3 U.S. National Parks Emission Inventories

The U.S. National Park Service's Air Resources Division prepared criteria-pollutant emission inventories for 21 national parks in 2000/2001. Principal stationary sources include fossil-fuel-fired space and water heating equipment, generators, fuel storage tanks, and wastewater treatment plants. Stationary nonpoint sources include wood stoves, fireplaces, campfires, wildfires, and prescribed burning. Mobile source emissions are generated by vehicles operated by visitors, tour operators, Park Service employees and contractors, and nonroad vehicles and equipment. National Parks for which emission inventories have been prepared are identified in Table 3.5. Information on U.S. National Park emission inventories can be obtained at http://www2.nature.nps.gov/air/aqbasics/docs/InparkEmissionInventorySum.pdf.

3.4.4 Minerals Management Service (MMS)

In 2000, the MMS prepared emission inventories for oil/gas production platforms in the Gulf of Mexico. The 2000 emission inventory had four objectives. The first was to provide support for the development of the Breton National Wildlife Refuge Area current-year outer continental-shelf emission inventory. The second was to estimate historical outer continental-shelf Gulf-wide emissions for 1977 and 1988 for CO, NO_x, SO_x, TSP, PM_{10}, $PM_{2.5}$, total hydrocarbons, and VOC. The third goal was to spatially resolve area and mobile sources to the grid-cell level, and point sources to specific coordinates. The fourth objective was to develop computer software tools to assist the MMS in collecting and managing the outer continental-shelf emission inventory in the future. Information on the MMS emission inventories can be obtained at http://www.gomr.mms.gov/homepg/regulate/environ/techsumm/2002/2002-073.html.

3.4.5 Military Emission Inventories

The U.S. Department of Defense (DoD) has six distinct services: the Air Force, Army, Marine Corps, National Guard, Navy, and specific Defense Agencies. The Clean Air Act Amendments of 1990 require that DoD installations prepare emission inventories. DoD installations have prepared both stationary and mobile source emission inventories. Many DoD installations are large and have varied sources of emissions. For example, typical stationary sources include boilers, paint booths, storage tanks, fuel transfers, energy plants, sandblasting operations, engine testing, arms firing, incinerators, woodworking, and wastewater treatment plants. Mobile sources include tanks, trucks, aircraft, government-owned and privately-owned vehicles, nonroad equipment, and ground equipment to service aircraft needs.

Approximately 66 Air Force, 80 Army, and 55 Navy installations prepare emission inventories on an annual basis. Each of the major branches of DoD publishes its own guidance documents for the preparation of emission inventories. Guidance for Air Force emission inventories is prepared by the Air Force Institute for Operational Health (available at http://www.brooks.af.mil/afioh/). Army guidance is provided by the Center for Health Promotion and Preventive Medicine (available at http://chppm-www.apgea.army.mil). Guidance for conducting Navy emission inventories is provided by the Chief of Naval Operations (available at http://enviro.nfesc.navy.mil/).

The military prepares emission inventories to demonstrate compliance with rules and regulations affecting its operations. For example, emission inventories are used for determining whether a facility is a major or minor source. Furthermore, many Air Force installations are subject to the requirements of the Aerospace National Emission Standard for Hazardous Air Pollutants (40 CFR 63 Subpart GG). Boilers and storage tanks at bases may be subject to various New Source Performance Standards. The military also prepares emission inventories for the preparation of air emission statements and annual emission fees. Emission inventories help DoD

Table 3.5. U.S. National Park Service Lands with Emission Inventories.

Park Name	Location	Emission Inventory Type		
		Point	Nonpoint	Mobile
Badlands NP	South Dakota	✔	✔	✔
Big Cypress NP	Florida	✔	✔	✔
Carlsbad Caverns NM	New Mexico	✔	✔	✔
Chiricauha NM	Arizona	✔	✔	✔
Crater Lake NP	Oregon	✔	✔	✔
Craters of the Moon NP	Idaho	✔	✔	✔
Denali NP	Alaska	✔	✔	✔
Glacier NP	Montana	✔	✔	✔
Grand Canyon NP	Arizona	✔	✔	✔
Grand Teton NP	Wyoming	✔	✔	✔
Great Sand Dunes NM	Colorado	✔	✔	✔
Great Smoky Mountains NP	North Carolina and Tennessee	✔	✔	✔
Guadalupe Mountains NP	Texas	✔	✔	✔
Lake Mead NRA	Nevada and Arizona	✔	✔	✔
Mammoth Cave NP	Kentucky	✔	✔	✔
Mesa Verde NP	Colorado	✔	✔	✔
Padre Island NS	Texas	✔	✔	✔
Theodore Roosevelt NP	North Dakota	✔	✔	✔
Wind Cave NP	South Dakota	✔	✔	✔
Yellowstone NP	Wyoming, Montana, North Dakota	✔	✔	✔
Lake Meredith National Recreation Area	Texas	✔	✔	✔

facilities quantify their emissions, and they also help quantify the levels of air pollutants emitted in communities and specific geographic locales.

3.4.6 Carbonaceous PM Inventories

Carbon components (VOC, BC, and OC) are key components of air quality issues including ozone and fine particle attainment and radiative forcing (Hansen et al., 2000; Hansen and Sato, 2001; Andreae, 2001; Penner et al., 2001; Jacobson, 2001, 2002; Chameides and Bergin, 2002). Carbonaceous PM consists of fine particles, mostly less than 1 μm in diameter, which are usually classified as either BC or OC. Although inventories have been developed for carbonaceous PM, their sources are ill defined. Because of their importance to local, regional, national, continental, and global air quality, there is a compelling need for accurate inventories of carbonaceous aerosols.

Worldwide, Chameides and Bergin (2002) estimated that uncontrolled burning of coal is a major BC source, with China and India contributing 25 percent of global BC emissions. Streets et al. (2003) have developed BC emission factors for various combustion source types, although these estimates are acknowledged to be highly uncertain. Combustion efficiency is a major factor in determining BC emissions. For example, the residential burning of coal in a traditional stove is estimated to have a BC emission factor of 3.7 g kg^{-1}, while the corresponding factor for a large coal-fired boiler using an electrostatic precipitator is only about 0.0001 g kg^{-1}. BC emissions from fossil-fuel combustion and other anthropogenic activities in the United States are in the range of 300-400 Gg C per year.

3.4.7 Canadian Ammonia Inventories

Environment Canada has compiled a national emission inventory for atmospheric NH_3 for the period of 1995 to 2000. The inventory provides estimates of NH_3 on a national, provincial, and territorial basis for industrial and non-industrial activities. Emission estimates for agricultural livestock and fertilizer application were calculated using livestock statistics and recently developed emission factors. The estimates took into consideration Canadian manure management techniques and other farming practices, soil types, and climatic factors. The emission estimates for the other contributing sources were based on activity statistics such as population and VKT, and plant-specific information collected through the CAC inventories and the NPRI. Environment Canada is currently updating the NH_3 emission inventory for 2002 and subsequently on an annual basis.

3.5 INVESTMENT IN EMISSION INVENTORIES FOR NARSTO MEMBER COUNTRIES

This section presents information on the annual investments made by individual countries for emission inventory development. Investment estimates for use in this Assessment were received from Environment Canada, the U.S. EPA, and the Mexican INE. The varying levels of complexity in the information which follows indicate the difficulties encountered with quantifying this type of information. In addition, the relative maturity of the emission inventory programs for the three respective countries varies substantially; therefore, more information is available for the U.S. program and less information is available for Mexico.

It is difficult to determine cost for inventory development because it is an inherent part of many air quality management activities. This Assessment provides an estimate based on available information.

3.5.1 U.S. Emission Inventory Investment

For the United States, the estimate was determined by drawing from a report on "Federal Air Quality Research – 1998-2000" (CENR, 1999), the "NARSTO Strategic Execution Plan, Science Plan for Suspended Particulate Matter" (NARSTO, 2001), the Consolidated Emission Reporting Rule, the Conceptual Future of the U.S. EPA's Emission Factor Program, and U.S. EPA grant funding.

The CENR report covered the investments in air quality management by the Department of Agriculture, Department of Energy, Department of the Interior, Environmental Protection Agency,

National Oceanic and Atmospheric Administration, National Science Foundation, and the Tennessee Valley Authority. Table 3.6 presents the estimates from this report.

From the CENR report, it is assumed that the average of approximately $126 million per year is invested in air quality programs. It is further assumed that this level of investment has remained approximately constant through 2004 as it is not apparent that there has been a significant air quality program change.

Table 3.7 presents investment information from the NARSTO report on particulate matter research.

It should be noted that the assumed federal funding in the NARSTO report is for FY2000 and that health research was not included. From the NARSTO report, it is assumed that about 15 percent of the funding for air quality research is invested in emission-related activities. However, if this percentage is adjusted to reflect health research, as in the CENR report, then the percentage for emissions would be cut in half. If this assumption is applied to the $126 million invested in all air quality programs, it would appear that approximately $9.5 million or about $10 million is invested annually in emission characterization and emission inventory programs. Because these estimates cover primarily research activities, this total should be supplemented by the approximately $2 million that the U.S. EPA's regulatory program invests in compiling emission inventories. Based on these assumptions, total U.S. federal agency investment is about $12 million.

In addition to these investments, the U.S. EPA grants to state, local, tribal, and regional programs also should be acknowledged as some of this funding goes to support emission inventory programs. Table 3.8 presents estimates of these grants for FY04.

Grants to state/local agencies require matching funding. If it is assumed that state/local agency expenditures equal federal funding and that these

Table 3.6. U.S. Federal Investments in Air Quality Research (CENR, 1999).

Program	Investment ($million)		
	1998	1999	2000
Particulate matter and visibility	68.4	71.5	79.7
Ozone and associated air pollutants	29.8	32.6	19.6
Acidic deposition	3.7	3.7	3.6
Hazardous air pollutants	17.8	20.2	20.7
One atmosphere	1.3	4.4	0.7
Total	**121.0**	**132.4**	**124.3**

Table 3.7. U.S. Federal Investments by Program Areas for FY 2000 (NARSTO, 2001).

Program Element	Investment ($million)
Aerosol characterization – physical and chemical measurements	23.1
Fine particle and precursor emissions	6.3
Aerosol dynamics: mechanistic aspects of aerosol physics and chemistry	5.7
Fine particle and precursor removal processes	0.5
Air quality modeling and analysis	4.1
Interactions with decision makers, stakeholders, and the public	0.5
Total	**40.2**

Table 3.8. Investment in U.S. EPA Grants to State, Local, Tribal and Regional Air Quality Management Programs.			
Jurisdiction	**Total Funding ($ million)**	**Emission Percentage**	**Emission Funding ($ million)**
States/locals	170	6	10.2
Tribes	11	10	1.1
RPOs	10	20	2.0
Total	**191**	**7**	**13.3**

agencies invest an equal percentage in emission inventory programs, an additional $10 million is probably spent by state/local programs for emission inventory activities. The estimate of 6 percent for state/local funding was determined from FY92-93 grant funding allocations. This is the last year in which detailed allocations by program area are available. This number was verified by consultation with the Chair of STAPPA/ALAPCO's Emissions and Modeling Committee. It should be noted that tribal and RPO grants do not require matching funding. A higher percentage was assigned to tribal grants since many are in the capacity-building phase and emission inventory activities would be a major component of their programs. Finally, the work plans from the RPOs indicated that approximately 20 percent of their FY04 funds were planned for emission-related activities. However, it may not be reasonable to expect this level of funding to be sustained over time as emission inventory preparation is an important current emphasis.

Table 3.9 presents the assumed U.S. federal funding for emission characterization and emission inventory programs.

As noted, it is also assumed that U.S. state/local programs invest an additional $10 million in emission inventory programs. These funding estimates do not attempt to cover the investment by private companies, research consortiums, or universities invest in emission characterization programs. However, the Consolidated Emission Reporting Rule estimated that industry expends approximately $1.5 million to comply with emission inventory reporting requirements. This does not include costs that industry absorbs to measure emission rates from their facilities to report on the forms.

An important part of emission inventory investment is the development of emission factors. An analysis under the Conceptual Future of the U.S. EPA's Emission Factor Program (http://www.epa.gov/ttn/chief/conference/ei13/index.html#efs) indicated that U.S. EPA funding for emission factor development in the 1970s was approximately $100 million/year (in constant 2004 $) whereas funding in the last few years has been near zero (refer to Figure 3.7). To some extent, increased emission measurements by industry have offset this decline. However, industry testing is conducted to support permit applications and other regulatory requirements. These activities may not be appropriate or accessible for emission characterization activities. For example, few industry tests measure individual chemical species or size fractions of their emissions. On the other hand, CEMs have significantly improved the characterization of emissions from large utility and industrial sources.

In summary, it appears that U.S. federal funding for emission inventory activities is approximately $25 million/year. This is augmented by approximately

Table 3.9. Estimated U.S. Federal Funding for Emission Characterization.	
Funding Categories	**Emission Inventory Funding ($ million per year)**
U.S. federal agencies	12
U.S. grants to state, local, regional or tribal agencies	13
Total	**25**

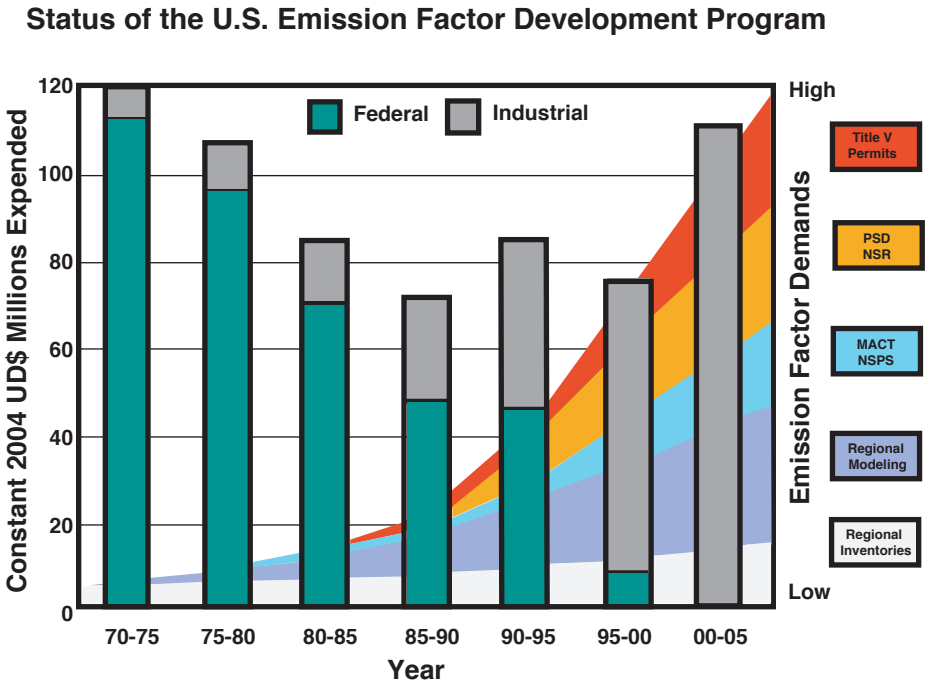

Figure 3.7 Estimate of U.S. Expenditures on Emission Factor Development and User Demands (U.S. EPA, 2004).

$10 million invested by state/local agencies. In addition, there are resources from industry, research consortiums, and academia invested in emission inventories which have not been quantified. These resources, however, have not offset the significant decline in U.S. EPA resources for emission factor development, which has declined from $100 million to near zero from the 1970s to now.

3.5.2 Canadian Emission Inventory Investment

In Canada, approximately $6 million USD/year is invested for the compilation of the emission inventories. This estimate takes into account the annual collection of emission information from industrial and commercial facilities through the NPRI for various air pollutants. Of the total amount, approximately $2.4 million USD are invested in the annual compilation of the Canadian NEI for CACs, selected heavy metals, and persistent organic pollutants. A large portion of the total funding (80 percent) was made available in 2001 to deliver on the Canadian commitments in the Ozone Annex of the Canada-U.S. Air Quality Agreement, and to support the implementation of the Canadian Clean Air Agenda. This funding allowed Environment Canada to expand the coverage of the NPRI program to include the criteria air contaminants (starting in 2002), to collect emissions for additional VOC substances and improve the VOC speciation profiles (starting in 2003), and to initiate the compilation of the annual emission inventories.

This estimate of Canadian expenditures excludes the funding invested by provincial/regional governments and industry to support the emission inventory requirements and their contribution to the compilation of the Canadian NEI.

3.5.3 Mexican Emission Inventory Investment

The first National Emission Inventory will be finished during the second half of 2005. This project has had an average investment of approximately $591,000 USD/yr from 2002, through 2004. This estimate includes funding from international agencies, as well as from the Mexican federal government. The Western Governor's Association, the U.S. EPA

and the CEC have been the international funding entities for the period 2000-2004. It is estimated that by the time the final report is released the CEC will have invested approximately $300,000 US and the U.S. EPA around $1.8 million US, during the 2000-2004 time period. The U.S. EPA's funding has been administered through the WGA and it has included payments to consultants working for WGA at SEMARNAT and INE; payments for state inventory meetings conducted in Mexico; and, finally, the salary and related costs of the Project Manager at WGA. These figures do not include other related costs, such as hardware and software that have been used in the project.

The Mexican Government, represented by SEMARNAT through the General Directorate of Air Quality Management and Pollutants Emissions and Transfer Registry (*Dirección General de Gestión de la Calidad del Aire y Registro de Emisiones y Transferencia de Contaminantes*) and the General Directorate of Research on Urban, Regional and Global Pollution (*Dirección General de Investigación sobre la Contaminación Urbana, Regional y Global*) from the National Institute of Ecology (INE), has invested approximately $174,000 US in this effort for the 2002-2004 period. This estimate includes the amount spent in salaries for human resources from these two Mexican agencies that have been directly involved in the project. Also, the above estimates do not include resources that state and local authorities may have incurred while involved in activities that they may have conducted to support the fulfillment of the Mexican National Emission Inventory, or to develop their own emission inventories.

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CHAPTER 4

TOOLS FOR DEVELOPING EMISSION INVENTORIES

As summarized in Figure 2.1, the emission inventory development process begins with emission measurements, compilation of activity data, development of emission factors and models, and collection of data from individual sources. Emission inventories are then compiled at the local, state or provincial, regional, or national level, subjected to quality assurance checks and reviews, and enhanced as necessary for their particular use.

Extensive guidance on preparing emission inventories is available from several sources:

Canada: http://www.ec.gc.ca/pdb/npri/2002guidance/cac2002/CACs_2002_p6_e.cfm

United States: http://www.epa.gov/ttn/chief/eidocs/eiguid/; http://www.epa.gov/ttn/chief/eiip/

Mexico: http://www.epa.gov/ttn/catc/dir1/volume.pdf

International global climate: http://www.ipcc-nggip.iges.or.jp/public/gp/english.

This chapter discusses the ensemble of inventory development tools and associated programs, focusing primarily on methods applied by Canada, the United States, and Mexico. The reader is introduced to emission inventory methods and guidance, emission factors and speciation profiles, emission-related activity data, emission inventory models, emission processors, emission projections, emission test methods, data management, and QA/QC methods. In addition to the excellent guidance provided by the websites listed above, references are provided for each tool. The strengths and weaknesses of the tools introduced here are addressed in Chapter 5.

Chapter 4 Objective: ***To present an overview of the tools available for the development of emission inventories.***

4.1 EMISSION INVENTORY METHODS AND GUIDANCE

4.1.1 U.S. Emission Inventory Improvement Program (EIIP)

The EIIP began in 1993 as a jointly sponsored effort of STAPPA/ALAPCO and the U.S. EPA. It was funded and spearheaded by state and local agencies, but also involved resources from the U.S. EPA and in-kind contributions from industries. EIIP products were produced by those actually doing emission inventories. EIIP and its many committees are no longer in existence. However, the communications, relationships, and interactions among participants were invaluable to the emission inventory community and continue to provide positive results. The program produced documents that continue to help emission inventory developers.

The EIIP was developed to complement the emission inventory work done by the U.S. EPA. Although emission factors were available and a data reporting

system was in place at the U.S. EPA in the early 1990s, no standardized procedures or recent guidance manuals on how to calculate and assemble emission inventories existed. The EIIP responded to this obvious need by producing documents to provide detailed guidance and procedures on estimating emissions. These documents are considered as the equivalent of non-binding federal guidance. The U.S. EPA, state, local, and tribal agencies, and others retain the discretion to employ or to require other approaches that meet the requirements of the applicable statutory or regulatory requirements in individual circumstances.

The EIIP sought to improve and refine the emission inventory preparation process by assembling and developing:

- Hierarchies of methods for estimating emissions
- Preferred methods for collecting data and calculating emissions
- Guidance on locating activity data
- Improved reporting systems
- Procedures for quality control
- More consistent documentation.

EIIP guidance includes sets of "preferred and alternative methods" for most inventory-associated tasks. This standardization improves the consistency of collected data, provides better quality control and documentation, and results in increased usefulness of emission information. Later in the program, the EIIP updated some emission factors.

EIIP documents, consisting of the 10 volumes described in Table 4.1, are available at http://www.epa.gov/ttn/chief/eiip/techreport/index.html.

New funding for EIIP was discontinued after FY 2003. However, a suite of projects underway will be completed during FY 2005 using existing program funds. Although new funding for the EIIP

Table 4.1. EIIP Document Descriptions. The 10 volumes cover emission estimating, data management, QA/QC, and emission projections.

Volume	Title	Description
I	Introduction	Introduction
II	Point Sources	16 chapters describing methodologies for estimating emissions from point sources
III	Area Sources	24 chapters, some of which have not been completed, on methodologies for estimating area sources.
IV	Mobile Sources	3 chapters on methodologies for estimating emissions from mobile sources.
V	Biogenic Sources	Preferred methods for estimating emissions from biogenic sources.
VI	Quality Assurance/Quality Control	5 chapters and 6 appendices for ensuring quality assurance and quality control in emission inventories. Also contains a chapter on evaluating uncertainty in emission inventories.
VII	Data Management Procedures	2 chapters on a conceptual data model and an implementation guideline.
VIII	Greenhouse Gases	16 chapters on methodologies for estimating greenhouse gas emission from various sources.
IX	Particulate Emissions	A chapter on conducting $PM_{2.5}$ emission inventories, and 22 documents that provide NEI methodology for estimating PM emissions from various source categories.
X	Emission Projections	Information and procedures to assist state and local agencies in projecting future air pollution emissions.

is not expected, the U.S. EPA intends to update EIIP guidance materials as resources permit, or remove them from the EIIP website as more current U.S. EPA guidance materials become available.

4.1.2 Canadian Emissions and Projections Working Group

Canada has established the Emissions and Projections Working Group (EPWG) under the National Air Issues Coordinating Committee. Operating jointly on behalf of the Canadian Ministers of Energy and Environment, the mandate of the EPWG is to support development of coordinated air quality management plans and strategies, track progress in achieving targets to reduce air pollutants, facilitate national shareholder consultations, and advise the federal government regarding negotiations on international air quality programs. To implement this mandate, the EPWG has developed methodologies, processes, and procedures for the timely and accurate preparation of emission inventories and projections of Canada's CACs. In addition to supporting federal activities, the emission information developed by the EPWG supports various international, provincial/territorial, and local air management initiatives.

The EPWG has four primary responsibilities:

1. Develop emission inventory, forecast, backcast, and trend information on Canada's CACs which consist of NO_x, SO_x, VOCs, CO, PM_{10}, and $PM_{2.5}$.

2. Improve the coordination of federal, provincial, and territorial inventory schedules for compiling emission inventories, trends, and projections.

3. Evaluate, and where necessary, develop standardized methodologies for compiling emission inventories, and for performing projections and backcasts which are to be used by jurisdictions throughout Canada.

4. Consult with stakeholders to inform them of emission inventory activities, and to solicit their input on these activities.

The EPWG also assumes a consultative role. There are various emission inventory products (e.g., GHGs, toxic air pollutants) that are completed on an ad-hoc basis in Canada or are developed by other organizations. These are not always regularly scheduled products, and are often completed within a larger process such as that for the Canada-Wide Standards. The EPWG is available to serve as a venue to review and provide comments on the emission estimates that are contained in these inventories. The EPWG's website can be accessed at http://ccme.miupdate.com/initiatives/climate.html?category_id=34.

4.1.3 Mexican Emission Inventory Development Program

Since 1994, the WGA, U.S. EPA, and INE have led a comprehensive emission inventory development program for Mexico. A primary goal of this program is to increase capacity within Mexico among government, academic, and other emission inventory stakeholders for the development of emission inventories. A major objective of the emission inventory capacity-building work is the development of a set of 10 manuals. These manuals, some of which contain Mexico-specific emission factors and emission estimation methodologies, are designed to help guide the emission inventory development process throughout the country. INE has provided access to these manuals in Spanish on its website. Table 4.2 provides a list of the completed manuals and a description of each. The 11 volumes cover planning, emission estimating, data management, QA/QC, uncertainty analysis, and emission verification. Also, an Advanced Training Workbook provides sample calculations and case studies involving the use of emission factors and activity data especially for sources found in Mexico. The manuals are being revised and updated and will be compiled in a series of three books to be distributed among national officials in charge of emission inventory development.

A series of workshops and capacity building activities are programmed for the 2005-2006 period to support the update and continuity of the Mexican NEI.

The methodology detailed in the manuals has been used since 1998 for emission inventory development. Mexico City emission inventories utilize specific

Table 4.2. Mexican Manuals for Emission Inventory Development.		
Volume	**Title**	**Description**
I	Emission Inventory Program Planning	Provides planning issues that must be considered in an air emission inventory program.
II	Emission Inventory Fundamentals	Presents the fundamentals of emission inventory development and discusses inventory elements that apply to multiple source types.
III	Basic Emission Estimating Techniques	Presents methodologies used to develop emission estimates.
IV	Point Sources	Provides guidance for developing the point source emission inventory.
V	Area Sources	Provides guidance for developing the area source emission inventory.
VI	Motor Vehicles	Provides methodologies for estimating emissions from mobile sources.
VII	Natural Sources	Provides guidance for developing natural source emission inventories (i.e., biogenic VOCs and soil NO_x).
VIII	Modeling Inventory Development	Provides guidance for developing inventory data for use in air quality.
IX	Emission Inventory Program Evaluation	This manual consists of three parts: QA/QC, uncertainty analysis, and emission verification.
X	Data Management	Addresses the needs associated with the data management element of the Mexico National Emission Inventory Program.
XI	References	This manual is a compendium of tools that can be used in emission inventory program development.

emission factors when available. In cases where Mexico City-specific emission factors have not been developed, international emission factors are used. The Mexican emission data (i.e., emission factors and activity data) for point, nonpoint, and nonroad mobile sources were assigned confidence ratings according to the approach shown in Table 4.3. The confidence ratings will be used to identify the priorities for future improvements to the inventory.

4.2 EMISSION FACTORS AND SPECIATION PROFILES

4.2.1 Compilation of Air Pollutant Emission Factors (AP-42)

An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere to an activity associated with the release of that pollutant. Designed for use in compiling contributions from various sources into overall inventories, emission factors are usually expressed as the weight of the pollutant divided by a unit weight, volume, distance, or duration of the activity (e.g., pounds of SO_2 per ton of coal burned). These factors are usually simple averages of all available data that are of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in a given source category.

The principal repository of emission factors is the U.S. EPA's Compilation of Air Pollutant Emission Factors, commonly referred to as AP-42. AP-42, available at http://www.epa.gov/ttn/chief/ap42/index.html, contains 14 major categories of emission sources and over 150 subcategories. The major source categories are listed in Table 4.4.

AP-42 emission factors are developed from emission tests, mass balances, control-equipment vendor

Table 4.3. Confidence Rating Approach for the Mexican NEI.			
Rating		**Activity Data**	**Emission Factor**
A	High	Based on comprehensive Mexico-specific data	Based on comprehensive Mexico-specific data
B	Medium	Based on limited/extrapolated Mexico-specific data	Based on limited Mexico-specific data
C	Low	Based on expert judgment	Based on expert judgment
D	Preliminary Estimate	Based on extrapolated U.S. data	Based on U.S. factors
E	Not Quantifiable	Insufficient data	No emission factors exist

specifications, and emission models. Factors are assigned a rating from A through E, reflecting the robustness of the factor. The assignment of factor ratings involves a two-step process. The first step involves an appraisal of the test data quality used to calculate an emission factor. The second step involves an assessment of the representativeness of the factor as a national annual average for the source category. Test-data quality is rated from A through D as shown in Box 4.1.

It must be emphasized that AP-42 emission factors are default values to be used when source-specific emission information is not available. Because AP-42 factors are source-category-wide averages they should not be used to calculate emissions from specific sources. Where test data or source specific data are available, these data should be used in lieu of AP-42 factors.

AP-42 emission factors and support documents are available at http://www.epa.gov/ttn/chief/efinformation.html. AP-42 factors are also retrievable from a searchable FoxPro database: the Factor Information and Retrieval (FIRE) system (see Section 4.2.3), available at http://www.epa.gov/ttn/chief/software/fire/.

Many of the existing emission factors in versions of AP-42 (U.S. EPA, 2005) are old and outdated, and not always used appropriately. In addition, the current emission factor development program is both expensive and cumbersome. Increased emphasis needs to be given to key sources that

Table 4.4. Major Source Categories Contained in AP-42. Emission factors are grouped into 12 stationary source categories.	
Chapter	**Title**
1	External Combustion Sources
2	Solid Waste Disposal
3	Stationary Internal Combustion Sources
4	Evaporation Loss Source
5	Petroleum Industry
6	Organic Chemical Process Industry
7	Liquid Storage Tanks
8	Inorganic Chemical Industry
9	Food and Agricultural Industries
10	Wood Products Industry
11	Mineral Products Industry
12	Metallurgical Industry
13	Miscellaneous Sources
14	Greenhouse Gas Biogenic Sources

Box 4.1. U.S. EPA Emission Factor Quality Rating System

AP-42 emission factors also have qualitative data ratings. AP-42 emission factors are developed from emission tests, mass balances, control-equipment vendor specifications, and emission models. Emission test data are assigned ratings of A-D. Emission factors are assigned a rating from A through E, reflecting the robustness of the factor. The following tables explain the emission test data quality and emission factor ratings.

Emission Test Data Quality Ratings	
Rating	Explanation
A	Tests are performed by a sound methodology and are reported in enough detail for adequate validation.
B	Tests are performed by a generally sound methodology, but lacking enough detail for adequate validation.
C	Tests are based on an unproven or new methodology, or are lacking a significant amount of background information.
D	Tests are based on a generally unacceptable method, but the method may provide an order-of-magnitude value for the source.

Emission Factor Ratings	
Rating	Explanation
A (Excellent)	Factor is developed from A or B rated source test data taken from many randomly chosen facilities in the industry population. The source category population is sufficiently specific to minimize variability.
B (Above Average)	Factor is developed from A or B rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with an A rating, the source category population is sufficiently specific to minimize variability.
C (Average)	Factor is developed from A, B, or C rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if facilities tested represent a random sample of the industry. As with the A rating, the source category population is sufficiently specific to minimize variability.
D (Below Average)	Factor is developed A, B, or C rated test data from a small number of facilities, and there may be reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source population.
E (Poor)	Factor is developed from C and D rated test data, and there may be reason to suspect that the facilities tested did not represent a random sample of the industry. There also may be evidence of variability within the source category population.

influence common pollutants (PM or ozone) or relate to HAPs. Particular attention should be placed on small nonpoint stationary sources of NH_3, and carbonaceous compounds which challenge current measurement capabilities. The U.S. EPA's conceptual future for its emission factor program is presented and described in Box 4.2.

4.2.2 SPECIATE

SPECIATE is the U.S. EPA's repository of total organic compound (TOC)- and PM-speciated emission profiles for a variety of sources. Emission profiles are used, for example, to divide an estimate of total VOC into estimates of emissions of individual compounds. Emission profiles reflect source tests that may be representative of similar sources. Profiles are used in ozone formation models, source receptor models, and other source apportionment studies.

SPECIATE contains more than 1,000 speciation profiles of TOC and PM emission sources for use by the modeling community available in a user-friendly data management system. Many of the profiles in SPECIATE are outdated, reflecting, for example, gasoline formulations in the 1980s. For this reason SPECIATE requires continual updating. The model and additional information can be obtained at http://www.epa.gov/ttn/chief/software/speciate/. A project to update SPECIATE is underway in 2005.

Box 4.2. The Conceptual Future of the EPA's Emission Factor Program

The U.S. EPA is currently exploring methods for restructuring its emission factor program. EPA has identified four primary reasons for this restructuring effort. First, the existing process of developing emission factors for inclusion in AP-42 is labor-intensive, time-consuming, and expensive. Second, the existing emission factor rating system documented in Procedures for Preparing Emission Factor documents is largely subjective in nature and provides limited information regarding the precision, accuracy and in-source variability of the emission factors. Third, the emission factors presented in AP-42 are arithmetic means and do not indicate the range of values that might be applicable for a given factor. Fourth, emission factors are being used for many applications for which they were not intended.

The U.S. EPA is evaluating technology and innovative approaches to change the way the current emission factor program operates. For example, EPA is currently investigating methods and developing options for revising emission factor quality assessments. These new methods would provide a more objective assessment of emission factor quality and a more quantitative assessment of the precision, accuracy, and in-source variability of the emission factors.

The U.S. EPA is also exploring methods for automating many parts of the emission factor development and delivery process. For example, it is exploring the use of the eXtensible Markup Language (XML) to provide for data-rich source test reports. The underlying rationale is that the sources and test contractors would submit source-test reports in a digital format that lends itself to data extraction and manipulation. The process of submitting data-rich source tests electronically to state agencies would save time and make the data contained therein more usable and manageable.

The U.S. EPA is also exploring methods by which state agencies can make source test reports available for emission factor development. The rationale for this effort is that a wealth of source test data exists at state agencies that are not being used for the development of emissions factors. State and local agencies would be encouraged to make their source tests available online so that EPA can mine the reports for data used for the development of emissions factors. EPA is considering offering grant money to state and local agencies for the development of an online source test database base management system.

On its own end, EPA is considering the development of a state-of-the-art interactive website where users can download the latest emission factors online. In addition to the emission factors, conceptual plans call for the capability to obtain source-test data online, as well as background data on existing emission factors.

The U.S. EPA hopes that a restructuring of its emission factors program will result in a more streamlined process for developing and maintaining these factors. The restructuring is also intended to reduce the costs of the program while at the same time yield more up-to-date emission factors.

4.2.3 Factor Information and Retrieval Database (FIRE)

FIRE is a database management system linking emission estimation factors and source classification codes. It contains the U.S. EPA's recommended emission estimation factors for criteria and hazardous air pollutants and the master list for source classification codes. FIRE includes information about industries and their emitting processes, the chemicals emitted, and the emission factors themselves. FIRE allows easy access to criteria and HAP emission factors obtained from AP-42. The database and associated documentation for FIRE can be obtained at http://www.epa.gov/ttn/chief/software/fire/.

4.2.4 California Air Toxic Emission Factors (CATEF)

CARB sponsored a program to develop toxic air pollutant emission factors from source test data collected under California's Air Toxics "Hot Spots' Information and Assessment Act (AB 2588) of 1987. Approximately 2,000 emission factors were developed based on over 800 source tests collected from a wide range of devices including asphalt dryers, boilers and heaters, reciprocating internal combustion engines, turbines, glass and metal furnaces, polystyrene reactors, and coating and plating operations. Emission factors were calculated from a selection of 200 priority source tests for trace metals including hexavalent chromium, polychlorinated dibenzo-p-dioxin / polychlorinated dibenzo furan, PAH and other semi-volatile organic compounds (SVOCs), benzene, toluene, aldehydes, and H_2SO_4. The emission factors can be obtained by querying the CATEF database at http://www.arb.ca.gov/ei/catef/catef.htm.

4.2.5 Canadian Emission Factors

Studies and measurement campaigns are conducted by the Canadian government, industries, and industrial associations for the development of emission factors and speciation profiles that are specific to Canadian sources. These studies and campaigns take into account the effect of the climate, fuel types, and process equipment in use by Canadian industries. Canada makes use of AP-42 emission factors, and the speciation profiles of SPECIATE whenever Canadian-specific information is not available. In addition, it makes available a metric version of the U.S. EPA's FIRE database at http://www.ec.gc.ca/pdb/npri/documents/2004ToolBox/docs/sect_2_5_4_e.cfm.

4.2.6 Mexican Emission Factors

Several projects have been conducted to develop emission factors, activity data, and methodologies for Mexico-specific sources. The reports and manuals resulting from these projects are available on the U.S. EPA *Centro de Información sobre Contaminación de Aire en la Frontera entre E.U. y México* (CICA - Information Center on Air Pollution for the U.S.-Mexico border) bilingual website at http://www.epa.gov/ttn/catc/cica/cicaeng.html, unless otherwise noted in the following text.

Per Capita and Per Employee Emission Factors for Solvent Sources

As part of the development of the Mexican NEI, data were collected that provided the basis for development of Mexico-specific emission factors for some nonpoint source solvent categories. Per capita emission factors were developed for the architectural surface coating and graphic arts source categories; per employee emission factors were developed for the industrial surface coating, automobile body shop refinishing, and dry cleaning source categories. These emission factors are described in detail in Appendix C of the report "Mexico National Emissions Inventory, 1999, Final, Six Northern States" (ERG, 2004).

The basis for the per capita and per employee solvent emission factors was national-level sales statistics of paints, inks, and dry cleaning solvents from *Asociación Nacional de Fabricantes de Pinturas y Tintas* (National Association of Paint and Dye Manufacturers) and *Cámara Nacional de la Industria de Lavanderías* (National Chamber of the Dry Cleaning Industry). Because these per capita and per employee solvent emission factors are based upon national-level sales statistics, they can be used throughout Mexico.

Automobile Body Shops

A study co-sponsored by the U.S. EPA's OAQPS and CICA examined the paint and solvent emissions from automobile body shops operating in Cd. Juárez, Chihuahua, Mexico (U.S. EPA, 1999a). The study included a survey of a representative sample of automobile body shops in order to determine:

- Solvent content of various coatings (e.g., lacquer, enamel, water-based, urethane)
- Extent of solvents used in surface preparation and cleanup activities (e.g., thinners petroleum distillates, blends, gasoline)
- Types of applications (e.g., spray booth, spray gun, open or enclosed nonpoint, ventilation techniques)
- Handling and disposal of waste (e.g., rags, sandpaper, paper, cans, tape)
- Suitable types of control technologies.

The survey data were extrapolated across the entire population of automobile shops operating in Cd. Juárez. Also, potential control techniques were examined. Although emissions were estimated using U.S. EPA emission factors, the types of activity data collected by this project are useful in estimating emissions from automobile body shops in other areas within Mexico.

Street Vendor Cooking (Charcoal Grilling)

A study co-sponsored by the U.S. EPA/OAQPS and CICA examined emissions from street vendor cooking devices, prevalent in the streets of Mexicali, Baja California (U.S. EPA, 1999b). (A related study (U.S. EPA, 1999c) made recommendations on emission estimation methods for charcoal grilling, as well as for open canal and sewage emissions.) Emissions from street vendors were examined experimentally by measuring levels of PM_{10} and $PM_{2.5}$, VOCs, SVOCs, aldehydes, NO_x and SO_x from a test grill chosen to simulate the street vendor cooking devices in Mexicali. Nine test runs were made, and both chicken and beef were grilled. Charcoals from Mexicali and the United States were used, owing to a shortage of Mexicali charcoal available for the tests.

Emission rates (g/hour) and emission factors (g/kg of meat) were estimated. The emission factors are useful for developing emission inventories for other areas in Mexico; they were used in a nonpoint source emission inventory for Cd. Juárez and in the Mexican NEI (ERG, 2003a).

Scrap Tire Combustion

A study jointed sponsored by the U.S. EPA/OAQPS, U.S. EPA/Office of Research and Development, and CICA examined air emissions from open burning of scrap tires and from tire-derived fuel in well-designed combustors (U.S. EPA, 1997). Existing laboratory test data were compiled for criteria pollutants, as well as for a list of 34 target compounds representing the highest potential for inhalation health impacts from open tire fires, along with test data on controlled burning of tire-derived fuel in a rotary kiln incinerator simulator.

Emission factors (i.e., g/kg tire mass) were compiled for VOCs, SVOCs, PAHs, and PM_{10} as well as organic and metal PM. Although these emission data were developed from tests conducted in the United States, the resulting emission factors are useful in the development of local emission inventories in Mexico where burning of tires in open pits and landfills may be prevalent. However, due to the difficulty in quantifying activity data (i.e., kg of tires burned), these emission factors may not be feasible for use in inventories covering larger geographic areas.

4.2.7 Emission Factors for GHG Inventories

The IPCC established a Task Force on National Greenhouse Gas Inventories in 1998 to oversee the IPCC National Greenhouse Gas Inventories Program (IPCC-NGGIP). A technical support unit has been established at the Institute for Global Environmental Strategies in Japan to administer the IPCC-NGGIP. The purpose of this activity is to establish an internationally-agreed methodology for the calculation and reporting of national GHG inventories and to encourage the use of this methodology by countries participating in the IPCC and by signatories of the UNFCCC. One product of

the IPCC-NGGIP is a database on GHG emission factors (EFDB), accessible at http://www.ipcc-nggip.iges.or.jp/EFDB/main.php. EFDB contains emission factor information from IPCC guidelines and from CORINAIR. The IPCC Guidelines for National Greenhouse Gas Inventories (Houghton et al., 1996) contain recommended data and methodologies for calculating GHG emissions from a wide variety of source types (http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm).

4.3 EMISSION-RELATED ACTIVITY DATA

Recent emission inventories show that nonpoint, mobile, and natural sources are an important fraction of criteria pollutant emissions – this is particularly true for VOCs – and that only limited progress has been made in improving the activity estimates used in North American emission inventories during the past 20 years. EIIP guidance has suggested that national and regional or local agencies conduct surveys in their jurisdictions to better quantify pollution generating activity for certain nonpoint source categories. While some regional planning organizations in the United States have sponsored research to improve activity estimates for certain nonpoint categories such as open burning and residential wood combustion, there is limited evidence that state, local and tribal agencies have performed surveys to improve activity estimates for nonpoint source categories. It is not likely that these agencies will invest the funds necessary to perform such surveys unless it is demonstrated that there is payoff to them in terms of reduced uncertainty in the emission estimates for certain source types, or added confidence in their ability to develop effective future control strategies for these categories. The U.S. CERR has been useful as a regulatory incentive for requiring state and local agencies to provide such information for non-permitted sources. However, association of the data collection to formal permitting approaches might be more effective for improving nonpoint source characterization.

For many nonpoint source solvent categories (e.g., consumer products, painting, auto body refinishing), emission factors are applied to surrogate activity indicators, such as population or industry employment to estimate emissions. These techniques rely on solvent usage patterns being consistent with time and there being a correspondence between product sales and usage. Pollution levels and fluxes from households are low enough that remote measurements are not likely to be effective in capturing hourly/daily activity patterns (and the emissions resulting from them).

For highway vehicles, there continues to be a significant amount of research on improving emission factor models (MOBILE and EMFAC; U.S. EPA, 2004a) as well as estimating VMT or VKT. The U.S. EPA is proposing to update these tools with MOVES. Developers of MOVES intend to build on current capabilities, improve upon them, and eventually replace them with a single, comprehensive modeling system. In MOVES, how activity is defined will depend on the emission process being modeled. For most processes, U.S. EPA plans to characterize total activity by *source-activity time* (source hours operating or source hours parked). Source time is an attractive way of characterizing activity, because it is common to all emission processes and operating modes. However, while source-time is an important new metric in MOVES, its use does not preclude areas using VMT to express activity of on-highway vehicles, because source hours operating and VMT are easily inter-changeable if average vehicle speed is known. In addition, some vehicle emission process activity is non-time based, so the activity indicator can be the number of vehicle starts, hours parked, engine-on hours, or gallons of fuel used.

Intelligent Transportation System data are now collected by roadway surveillance equipment that monitors traffic; namely, volumes, speeds, and lane occupancies. The most prevalent measurement technology is loop detectors embedded in the roadway. However, transportation agencies are increasingly turning to non-intrusive technologies, such as radar and video image processing. Video image processing offers the potential of providing length-based vehicle classifications, but this capability is still emerging. From an emission indicator improvement perspective, there are opportunities for better utilizing the more sophisticated traffic data collection devices available today to track travel demands on roadways and how these vary by time-of-day.

Roadway network usage is measured for many purposes, one of which is to provide estimates of vehicle travel activity for making emission estimates. Traditionally, measurements have been made using ground-based sensors. The sensors provide a temporally rich data set, but individual sensors lack spatial coverage, limiting their use and application. High-resolution imagery remotely sensed from satellite or airborne platforms is an attractive alternative that can potentially supplement and enhance the existing traffic monitoring programs with a spatially detailed data set. With the progress in image processing technologies, roads and vehicles can be identified from imagery automatically with a high level of accuracy.

During the last 10 years, tools or models have been developed by the U.S. EPA to allow users to perform more sophisticated assessments of nonroad vehicle/engine emissions. While default activity profiles are available in these models, these defaults may not provide acceptable information on actual activity for modeling specific areas of interest. Improvements can be obtained via surveys of off-road equipment usage, and stakeholders have been performing such surveys. Another research focus is on developing and using portable activity monitoring systems, either alone, or in conjunction with portable emission monitoring systems, to track how often equipment is used for the purpose of better quantifying activity by equipment type.

4.3.1 Onroad Sources

U.S. Mobile Activity Data

In the United States, several different types of activity data are used for calculating emissions from onroad sources. VMT is currently the most widely used activity factor for onroad sources, and is made available by the U.S. Department of Transportation (DOT). Other activity factors that are used in some cases include fuel consumed, duration of operation, number of vehicle trips, soak length (for hot soak emissions), and others.

One approach, used by the U.S. NEI, begins with data aggregated at the national level and allocates emissions to states or smaller geopolitical units using surrogate data such as fuel sales or road miles. Activity factors are based on VMT summaries by state and functional roadway class, and similar summaries for urban areas, collected by the Federal Highway Administration. The activity is then allocated to counties and functional roadway classes using a combination of county level population and roadway mileage by county and functional roadway class as VMT surrogates. A similar approach is applied in some cases using fuel sales data rather than VMT, and allocates accordingly. This type of approach to estimating activity for onroad sources has the advantages of applying a similar methodology and data source to a broad geographic area, such as the regional or national level. In the aggregate, these estimates are generally considered to be reasonable. However, when these activity data are examined for smaller geographic areas, such as at the county level, the estimates often vary significantly from actual activity.

Alternatively, activity data are developed from local factors such as measured activity and vehicle registration information. A more detailed approach to developing onroad activity is generally used in urban area modeling by metropolitan planning organizations. These organizations often use travel demand models to build link-level (i.e., roadway segment) VMT databases. Inputs to these models include factors such as land use and employment by zone within the modeled region. The models are calibrated to actual traffic count data. In addition to VMT, these models can also provide other types of activity related to onroad sources including number of vehicle trips, or hours of vehicle travel. Such models have the advantages of accounting for local detail and are generally considered the most accurate source of onroad activity for an urban area. These models sometimes have the capability to provide information on the temporal distribution of activity, by hour-of-day, day-of-week, or month-of-year, so that activity can be adjusted for any day of the year. Because so much detail is incorporated into the models, they provide more specific emission information than do other models. However, it is not possible to assemble such detail about larger geographic areas, such as statewide or regionally. For this reason this type of approach may be applied consistently only on the community scale.

In nearly every application, urban travel-demand models are built using data from household surveys. The surveys typically gather demographic and economic information for each household, plus a travel diary recording all of the trips each household member made during the survey period (generally one day). The survey data are used to estimate the coefficients of a hierarchy of models that mirrors a theoretical hierarchy of behavior by travelers. Trips are separated by purpose (such as home-to-work/work-to-home and home-to-shop/shop-to-home), and each purpose receives separate modeling treatment. Travel demand models based on population and employment are poorly suited for estimating heavy-duty diesel truck traffic that is mostly commercial in nature and driven by goods movement needs rather than population and workplace locations.

While travel models produce VMT estimates, some agencies and researchers directly estimate VMT from traffic counts or other types of empirical data. The most widely used method is the extrapolation from Highway Performance Monitoring System data. The Highway Performance Monitoring System includes data from traffic count stations that are used to monitor annual differences in traffic volumes by location. However, some urban areas need to improve their existing Highway Performance Monitoring System sample of links to ensure that they truly represent changes that are occurring throughout an area. More approximate VMT estimation methods are used in some areas. For example, some estimates have been based on aggregate fuel sales and the estimated fleet-wide fuel economy corrected for nonroad fuel consumption and out-of-state refueling and travel. Special studies, including license plate surveys, focused counts, and special travel surveys, may be used to estimate VMT for traffic not included in regional models, such as through trips, and truck travel.

Canadian Mobile Activity Data

Compared to the United States, the availability of motor vehicle activity data in Canada is limited. Environment Canada does not have the ability to draw directly on vehicle registration data, as Canadian privacy laws restrict access. Private companies may purchase provincial/territorial vehicle registration files, aggregate the data and redistribute it. These are the data that Environment Canada uses for its emission estimates and vehicle fleet profiles. The private companies that aggregate this data do so for purposes other than emission estimation; thus, aggregated classes do not always align with the needs of emission estimation modelers.

While there is a similar tendency in the United States and Canada to use travel-demand models for urban planning and to estimate vehicle kilometers traveled, there are differences between the two nations' approaches. As yet, no network has been established in Canada to pool these data for use in Environment Canada's emission estimates. As the need for greater resolution in emission inventories increases, census-district level or municipal-level estimates may need to be established. Local travel-demand model data will be invaluable in meeting this need for greater resolution. However, the current framework - where individual urban areas model their respective regions for local purposes - often excludes a consistent manner of data generation or compilation. For the time being, Canadian onroad emission estimation relies on aggregated activity data collected by private companies and government departments, at the provincial/territorial and national level.

Partnerships between Environment Canada, Transport Canada, Natural Resources Canada (NRCan) and the use of Statistics Canada data have enhanced the ability to model onroad activity. Statistics Canada and Transport Canada developed and maintain the Canadian Vehicle Survey. This survey is an excellent source of fleet profile data, and utilizes travel diaries to capture driving behavior and trends. Statistics Canada ensures that the sample size is representative, allowing for both local and aggregated uses of the data. Also, Transport Canada has provided data from the Company Average Fuel Consumption values to be used as fuel-efficiency input data in MOBILE6.2C. Currently, Environment Canada's CAC division compiles annual emission inventories at the provincial/territorial level. However, MOBILE6.2C does allow for finer resolution of estimates. The model has the capability to provide information based on the temporal and spatial distribution of activity (e.g., daily, intersection-level estimates).

Environment Canada uses MOBILE6.2C to estimate CACs from onroad activity. Generally, the data

requirements for MOBILE6.2C can be broken into the following categories: external conditions (e.g. calendar year, altitude), vehicle fleet characteristics (e.g. age distributions, diesel sales fractions), vehicle activity (e.g. VKT, trip end distribution), fuel characteristics (e.g. sulfur level, gasoline volatility), and other parameters (e.g. I/M programs, technology penetration rates). This approach is aligned with the methodology employed by the U.S. EPA. Harmonious emission estimation tools, techniques and methodologies are essential for meaningful comparisons to be made of emission estimates for trans-boundary air issues. MOBILE6.2C allows for the use of finer-resolution data on activity factors. Local data can be used as input, and region-specific estimates can be compiled. Local surveys on roadways use, vehicle counts, fuel characteristics, and travel behavior can all be incorporated into emission estimates. Further information on Environment Canada's CAC inventory, is available on the website http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm.

Further partnerships with the two active I/M programs in Canada have recently allowed for corroboration of purchased data, data from other government departments and assumptions of Canadian-specific characteristics. AirCare in the province of British Columbia has been running since 1992 in the Lower Fraser Valley. Drive Clean has been in operation in Ontario since 1999. Pass and fail results from these programs allow for a partial validation of basic emission factors for MOBILE6.2C. Other information collected during the test (such as odometer readings) has been compiled into databases and can be formatted as annual kilometer accumulation rates for MOBILE6.2C. If links can be made between vehicles captured within the I/M programs and registered vehicles, local vehicle fleet characteristics can overwrite national level assumptions.

Canada's national transportation-sector GHG inventory is prepared using estimates at a provincial/territorial level of segregation. A vehicle fleet profile is established, based on model year and gross vehicle weight rating. So-called 'technology fractions' are attached to this fleet profile. The 'technology fraction' is a proxy for the emission control measures in the fleet (e.g., no catalyst, 3-way catalyst, advanced control diesel). This approach provides an estimate of average fuel consumption per vehicle class, per kilometer traveled. Fuel sales data, from Statistics Canada (http://www.statcan.ca/), are then used as a limiting factor. VKT is varied until all onroad fuel sales data are allocated. Emission factors are applied to these activity data and the GHG inventory is derived. This approach complies with the IPCC and UNFCCC guidelines for the estimation of GHG emissions. Further information on Environment Canada's GHG inventory is available on the website http://www.ec.gc.ca/pdb/ghg/ghg_home_e.cfm.

Mexican Mobile Activity Data

The availability of motor vehicle activity data in Mexico is limited in comparison with the United States and Canada. Travel demand models are not now widely used in Mexico to estimate VKT, and the development of such models for the entire country is not technically or economically feasible.

In Mexico's current *Programas para Mejorar la Calidad del Aire* (PROAIRE– Programs for the Improvement of Air Quality), VKT are typically estimated using vehicle registration statistics combined with assumed daily VKT based upon limited traffic count statistics, informal surveys, and anecdotal information. Fuel sales data can be used to estimate VKT in situations where other VKT estimates are not available, if assumptions regarding fuel efficiencies for various vehicle classifications are made. However, fuel sales data are not currently available at the municipality level for Mexico. Because of limited motor vehicle activity data in Mexico, a unique methodology was developed for the Mexican NEI that utilized modeled traffic volumes and congestion levels at representative urban areas for different city size categories to generate daily per capita emission rates (ERG, 2004; Wolf et al., 2003).

The development of daily per capita emission rates began with identifying seven urban area size categories with a representative urban area for each category. A basic assumption used in this methodology was that the daily per capita emission rates estimated for each of the representative urban areas are transferable to other urban areas of similar size. This assumption is reasonable because it has been shown that trip generation rates across different urban-area locations and sizes are fairly stable when

disaggregated by socio-economic conditions such as household size, income, and employment (Pearson and Gamble, 1996).

Trip generation patterns were developed for each representative urban area based upon trip production and trip attraction rates from a well-documented transportation study conducted for Cd. Juárez, Chihuahua (Instituto Municipal de Investigación y Planeación, 1998). The trip generation patterns were developed for zone structures based upon census tracts called *Areas Geoestadísticas Básicas*. Relevant demographic and socio-economic information was obtained from INEGI for each of the representative urban area zone structures. Total trips for a zone were estimated from household size and income information and the number of employees across various economic sectors. Activity data used for MCMA emissions are taken from the data register of the Vehicular Verification Program of the Federal District and the State of Mexico.

A roadway network was developed for each of the representative urban areas in order to facilitate trip distribution. The networks were simplified versions of the current roadway infrastructure layout and include only freeways, main arterials, and collector roads. Local streets were modeled using artificial links called "connectors" which channel local traffic flows between the zones (represented at zone centroids) and the network system. Each link in the network was initially assigned a function class and flow direction based upon site visits and interviews with local transportation officials, and a link capacity and average speed based upon results from the Ciudad Juárez study. Individual link travel time was then computed using the assigned link speed. An iterative approach was used until the gravity model converged to a solution for the representative urban areas. A user-equilibrium algorithm was then used to assign traffic volumes to network links and then congestion levels between similar time alternatives using iteration.

Link-level VKT was estimated by multiplying each link's traffic volume by the corresponding link's length in kilometers. These link-level VKT estimates were combined with corresponding link-specific congested speed emission factors to estimate daily emissions on a link basis using PrepinPlus software. The link-specific congested speed emission factors were developed using MOBILE6-Mexico. The emission factors were developed for a generic set of scenarios with varied temperature ranges, altitude, and fuels. The speeds in the look-up matrices ranged from 4 to 100 kph in 2 kph bins.

Total hourly emissions for each link were estimated by combining the link-specific emission factors with link-level VKT. Daily emissions for each representative urban area were estimated by summing up emissions for each hour over the entire roadway network. These daily emissions were then used to estimate per capita emission rates for the generic temperature/altitude/fuel scenarios for each of the urban area size categories. Annual municipality-level emissions were then estimated by combining per capita emission rates with populations for each municipality.

It should be noted that although this methodology was considered appropriate to estimate mobile emissions on the municipality-, state-, and national-level for the Mexican NEI, an increase in the availability of detailed information on activity patterns at the local level is expected in the future. Hence, a methodology similar to those applied in the United States and Canada could be applied to future inventory updates.

4.3.2 Nonroad Sources

U.S. Nonroad Data

Nonroad engines/vehicles comprise a wide variety and size range of diesel and gasoline engines, which are used for numerous applications including aircraft, locomotives, agricultural and construction equipment, industrial and commercial equipment, and recreational vehicles. In response to the Clean Air Act Amendments of 1990, federal emission regulations have been developed for many of these engine types. With the increased recent interest in quantifying nonroad engine/vehicle emissions, both the U.S. EPA and CARB have developed models to more readily quantify emissions for many of these equipment types. These models contain estimates of equipment populations and usage patterns. Because the generic activity patterns in these models may not

apply equally well in all areas, area-specific surveys of equipment populations and usage patterns are recommended for the most prominent equipment types in each area. Efficient survey techniques can vary significantly by equipment type/use because some equipment is used commercially and others by homeowners/consumers/recreators. Thus, activity is often based on non-economic factors.

Apportioning fuel use to nonroad applications can be an effective tool for determining whether other methods that have been applied have produced reasonable emission estimates. However, this requires that onroad and nonroad fuel use be differentiated.

Three nonroad engine/vehicle types are not included in the U.S. EPA models: aircraft, locomotives, and commercial marine vessels. Other agencies have been examining emissions from these sectors. In particular, CARB is currently working to incorporate commercial marine vessels into the state's OFFROAD model. Models for aircraft emissions can be developed using data collected by the U.S. Federal Aviation Administration (FAA), such as is the case with the Emission Dispersion Modeling System, further described in Section 4.4.10. These data are also used by the U.S. EPA for developing NEI emission estimates (U.S. EPA 2004d). Models for locomotive emissions can be developed using data collected by rail companies. The U.S. EPA is currently developing a model that will calculate emissions from aircraft, commercial marine, and railroads.

Aviation

Aircraft activity data, in varying levels of detail, may be obtained for all aircraft categories at airports with traffic control towers. Towers at U.S. commercial and other civilian airports are managed by the U.S. FAA and are required to keep detailed activity records of air carrier traffic and less detailed records for other aircraft categories (U.S. FAA, 2004). The majority of smaller airports do not have traffic control towers and are therefore considered to be uncontrolled by the U.S. FAA. The number of uncontrolled airports far outnumbers controlled airports. Data recorded by smaller airports are inconsistent and unreliable, making data acquisition for purposes of emission inventory development difficult.

Aircraft activity levels are normally expressed as landing and takeoff cycles, which consist of four aircraft operating modes: taxi and queue, take-off, climb-out, and landing. Default values for the amount of time a specific aircraft type spends in each mode, or the time in mode, are normally included in the U.S. FAA's aircraft emission model. Aircraft emissions vary significantly between airports. Although landing and takeoff times are similar for similar fleet mixes, the amount of idle varies significantly from airport to airport, representing a key factor in the variability of emissions from aircraft during airport operations. Local air quality concerns are generally directed at aircraft operating below 3000 feet about ground level. However, as air quality concerns expand from urban to regional and continental scales, emissions from aircraft in transit also become an issue (Penner et al., 1999).

Commercial Marine

Emission and activity data for commercial marine vessels are normally categorized by five vessel types: ocean-going, tugs, ferries, dredges, and fishing vessels. Estimates of ocean-going vessel activity are available from the literature for a limited number of U.S. coastal and inland ports. Ocean-going vessel activity for other non-surveyed ports is typically estimated using an assignment process based on similar port characteristics. Key ocean-going vessel operating modes include cruise, reduced speed zone, maneuvering, and hotelling/dwelling (idling). For non-ocean going commercial marine vessels, most of the emission inventory data collection effort is in estimating vessel populations, with activity (hours of operation) and load factors based on typical usage profiles (U.S. EPA, 1999d; U.S. EPA, 1999e).

Emissions are also estimated from large marine vessel operations using a power-based approach. This methodology uses power output and time-in-mode to estimate emissions. Power output in a given mode (e.g., slow speed, medium speed, hotelling) is multiplied by the time of operation in mode and by an emission factor. Power output by a vessel is estimated based upon the percent of full

load for auxiliary engines and the Propeller Law for propulsion engines. The Propeller Law states that power demand increases with the cube of a vessel's speed. This approach can be used to develop estimates of power output on a vessel-by-vessel basis. The equation can also be used to develop power outputs for different segments of a transit into or out of port if there are significant differences in speed between segments (Starcrest Consulting, 2004). This methodology can also be applied to estimating emission from military marine vessels.

As for aircraft, marine vessel emissions from ports are of primary importance, but emissions from ships in transit are also of concern (Corbett and Fishbeck, 2000).

Rail

Locomotive activity is based on estimates of railroad locomotive diesel fuel consumption. Unless a rail company operates in a limited geographic area, the fuel consumption data for locomotives is typically available for a larger area than the inventory area. Three classes of railroads are defined for the United States. These are Class I railroads with operating revenues greater than $250 million, Class II railroads with operating revenues greater than $20 million and less than $250 million, and Class III railroads with operating revenues less than $20 million (49 CFR 1201). For Class I railroads, fuel consumption is typically estimated using locomotive fuel rates coupled with miles of track and traffic density in the inventory area. Fuel consumption for small railroads (e.g., Class II/III railroads and Amtrak in the United States) is based on system-wide fuel estimates allocated based on the percentage of track length within the inventory area. Fuel consumption reported in public sources may form the basis of national or regional locomotive emission estimates, which can be assigned to counties or other sub-state areas based on a surrogate indicator, generally rail track length or rail freight density.

Canadian Nonroad Data

Environment Canada compiles a CAC inventory that includes the contribution of nonroad engines/vehicles powered by a variety of fuel types (e.g., gasoline, diesel, compressed natural gas, liquefied petroleum gas or LPG, heavy fuel oil). Vehicle types covered are aircraft, marine vessels, locomotives and a variety of other applications such as residential and commercial equipment and off-highway vehicles. Emission estimates are handled distinctly for aircraft (sub-sector name 'Aviation'), for commercial marine vessels (sub-sector name 'Commercial Marine'), for locomotives (sub-sector name 'Rail'), and for all other nonroad applications (sub-sector name 'Nonroad'). The nonroad sector includes such things as recreational vehicles, lawn and garden equipment, and other commercial/residential engines and vehicles.

Aviation

Currently, Environment Canada uses a set of emission factors for various aircraft types. Activity level, in terms of number of landings and takeoffs, are used with these factors to estimate emissions. NAV Canada, Statistics Canada and Transport Canada all maintain databases on aircraft movement at Canadian airports that are used by Environment Canada for emission estimates for the aviation sector.

Commercial Marine

Considerable effort is being channeled into characterizing the commercial marine sub-sector and its related emission sources. A recent study (Entec, 2002) is considered to be an excellent source of information. Drawing on a large sample size, emission factors are generated for certain vessel classes under various modes of operation and an entire emission estimation methodology is outlined. This methodology relies on the use of the Lloyd's Marine Intelligence Unit (LMIU) database for determination of average vessel characteristics. The LMIU can be used in conjunction with other vessel activity data contained in the databases of the Canadian Coast Guard to develop marine emission inventories either with or without temporal and spatial resolution. The Coast Guard data are ideally suited for this purpose, as they allow for temporal and spatial allocation of emissions. The Coast Guard's data will be more attractive as they become entirely automated through the adoption of an Automatic Identification System. The Automatic Information System is endorsed and recommended by the International Maritime Organization and is currently being implemented in many other countries. Such an electronic database

will be highly useful with GIS-based applications, and may facilitate a better articulation of marine emissions both nationally and internationally. Select Canadian port authorities, chambers of shipping, and ship-owners associations have expressed interest in supplying survey data to help validate assumptions concerning terms of times in mode of operations and other shipping activities.

Rail

In 1995 the Railway Association of Canada signed a memorandum of understanding with Environment Canada to provide national level, annual traffic volumes and diesel fuel consumption for mainline, branchline, yard switching, and passenger service for the period 1990 through 2005. Data from Statistics Canada are used to disaggregate the Railway Association's national estimates to the provinces/territorial level required for the CAC inventory. The Statistics Canada report apportions fuel use to provinces/territories, assuming that emissions follow the same trend as fuel use. The sulfur content in diesel fuel can be obtained from an annual publication by Environment Canada's Oil, Gas and Energy Branch (Environment Canada). The Railway Association assumes that fuel sulfur content is 0.15% for all years and all provinces/territories.

Nonroad

Environment Canada's CAC inventory and related forecast for the nonroad sector has been compiled using the U.S. EPA's NONROAD model, with estimates used in support of proposed Canadian regulations. Canadian input data and other adaptations were implemented in the use of the NONROAD model. Due to the lack of a single source of data on the numerous engine applications modeled through NONROAD, an attempt was first made to compile the required engine population estimates. For many types of nonroad equipment, the Canadian market relies almost exclusively on importation as there is only limited manufacturing of these products in Canada. Statistics Canada maintains an excellent importation database providing the annual quantity and value of imported goods organized under an international classification called *Harmonized System*. When the harmonized system coding is such that one can be fairly confident that all, or nearly all, goods classified under a given code are powered by internal combustion engines and correspond to a category of nonroad equipment, the Statistics Canada database for this harmonized system code can be used to estimate the corresponding nonroad engine population in Canada. An important assumption in the allocation of nonroad Canadian engine populations is that the distribution of Canadian engines with respect to different engine categories (i.e., 2-stroke, 4-stroke, and horsepower range) and fuel types (i.e., gasoline, diesel, LPG, and compressed natural gas) is directly proportional to the corresponding U.S. distributions.

Mexican Nonroad Mobile Source Data

The types of nonroad sources included in emissions inventories in Mexico include aircraft, locomotives, commercial marine vessels (CMV), and construction and agricultural equipment. Local and regional inventories (e.g., Mexico City and Monterrey Metropolitan Areas), and the Mexican NEI generally group the aircraft, locomotive, and CMV emissions within area (or nonpoint) sources. Only the Mexican NEI contains emissions for construction and agricultural equipment, as until recently, the activity data needed to estimate emissions from these types of equipment have not been available (ERG, 2004).

Aviation

Aircraft emissions are generated during approach, taxi/idle-in, taxi/idle-out, and climb out. Only those portions of the flight that occur between ground level and the mixing height are included in the inventory. Annual activity information for the numbers of landing and take-offs (LTOs) are provided by INEGI; however, LTO data are not available for all airports in Mexico. Sulfur content of aircraft fuels (needed to calculate SO_x emission factors) is available from *Petroleós Mexicanos* (PEMEX).

Rail

Emissions are generated from locomotives during line-haul and yard operations. Activity data used to estimate these emissions include locomotive fuel consumption and length of tracks. Annual national railroad fuel consumption for line-haul and yard locomotives is available from the *Secretaría de Comunicaciones y Transportes* (Secretariat of

Communications and Transport). National- and municipality-level track length for Mexico is available from Environmental Systems Research Institute in the form of GIS data and shape files. Locomotive fuel sulfur content is available from PEMEX.

Commercial Marine

CMV emissions are generated by engines powered by either diesel (distillate fuel) or steam turbines (residual fuel). Activity data used to estimate these emissions include fuel usage and volume of cargo handled in Mexican commercial marine ports. Annual national-level marine distillate and residual fuel usage is available from PEMEX. (Note that assumptions must be made as to the percentage of total CMV fuel actually consumed in port. For the 1999 MNEI, it was assumed that 25% of the residual and 75% of the distillate was consumed by CMV in port.) Data on the volume of cargo handled is available from INEGI. Commercial marine fuel sulfur content is available from PEMEX.

Construction and Agricultural Equipment

Construction and agricultural equipment activity data consist of estimated horsepower-hours of operation for each equipment type/fuel/horsepower range combination. These estimates are combined with emission factors from the U.S. EPA's NONROAD2002 model, modified to reflect Mexico-specific conditions, to estimate construction and agricultural equipment emissions for the 1999 MNEI. (A current project is underway to develop a NONROAD-Mexico model using local data collected in Mexico.) State-specific data for diesel-powered agricultural tractors and pumps, along with percentage breakouts by horsepower are available from INEGI. For the Mexico NEI estimates, agricultural equipment populations (e.g., balers) were assumed to be present in the same proportion as in the U.S. Annual fuel usage by the agricultural sector (from PEMEX) was compared with NONROAD2002's estimated fuel consumption for the Mexico-specific equipment populations to obtain an adjustment factor for equipment activity (hours/year/unit) (i.e., fuel consumption in Mexico was 15% lower than predicted by NONROAD2002 using U.S. default hour/year values, so the activity data file was adjusted to reflect a 15% decrease in hours/year for diesel agricultural equipment). Annual state-level emission estimates were allocated to the municipality level using census of operating tractors from INEGI.

In the absence of construction equipment population and usage data, it was determined that the number of employees actually working at job sites, available for each state, was the best indicator of likely equipment usage. (Other surrogates, such as gross domestic product, book value of assets, etc., were evaluated, but number of workers was the most reliable and direct surrogate for this category.) The ratio of Mexican construction workers (from INEGI) to U.S. construction workers (from the U.S. Census) for 1997 (i.e., 0.124) was multiplied by the U.S. equipment totals in the NONROAD2002 model to approximate the Mexican construction equipment population. U.S. defaults were used for hours/year of operation for each equipment type. State-level totals were derived from the fraction of total construction workers by state (from INEGI). Annual state-level emission estimates were based on municipality-level population (from INEGI.)

4.3.3 Stationary Nonpoint Sources

Because of the diverse nature of nonpoint sources, many types of emission activity factors are used to develop nonpoint source emission inventories. This section focuses on three of the most important: energy consumption/production, population, and employment.

U.S. Nonpoint Data

Energy Consumption/Production Data

Because energy consumption and energy production are emission activities for many source categories, energy consumption/production data represent a key set of nonpoint source activity data. Examples of such source categories are residual fuel combustion and Stage I gasoline distribution. The U.S. Department of Energy's Energy Information Administration (EIA) develops databases and publishes reports that provide energy consumption and production data at various geographic levels. These databases and reports either focus on a particular energy sector (e.g., residential

energy consumption survey), energy source (e.g., annual coal report), or geographic area (e.g., state energy data). Depending on the particular resource, the EIA may report energy consumption/production on a national basis, by region (e.g., census division), or by state (county-level data are not provided) (see http://www.eia.doe.gov/ for information on each available EIA resource). The EIA's State Energy Data (formerly the State Energy Data Report) is a particularly valuable resource because it provides energy consumption data at the most-specific geographic level available, and covers most energy sources and energy sectors.

The EIA's State Energy Data is a database that provides historical annual energy consumption, price, and expenditure data. All of the State Energy Data estimates are developed using the State Energy Data System, which is maintained and operated by the EIA. Energy consumption is estimated using data from existing surveys of energy suppliers that report consumption, sales, or distribution of energy at the state level (State Energy Data can be accessed from the following EIA website http://www.eia.doe.gov/emeu/states/_use_multistate.html.

Population Data

For many nonpoint source categories, emissions are computed using per capita emission factors. For example, per capita emission factors are typically used to estimate consumer product emissions, if surveys cannot be conducted to develop local product use/sales data.

The Population Division of the U.S. Bureau of the Census develops annual July 1 population estimates at various geographic levels of detail for the United States and its territories. Population estimates are reported for the nation, as well as by state, county, metropolitan area, and city/town. Each census population data set can be downloaded from http://www.census.gov/popest/estimates.php. It is important to note that states, metropolitan areas, and cities may prepare population estimates for their own areas. Because these estimates may be developed using more specific local information, inventory preparers should investigate the availability of local population estimates as an alternative to using the census values (Census, 2004a; Census, 2004b).

Employment Data

Employment data are frequently used to estimate nonpoint source emission activity. Two primary U.S. agencies that compile employment data are the U.S. Department of Commerce's Bureau of the Census and the U.S. Department of Labor's Bureau of Labor Statistics (BLS, 2004a; BLS, 2004b).

The Bureau of the Census publishes County Business Patterns, which provide annual state and county employment data by industry. Beginning in 1998, County Business Pattern data are reported by 1997 North American Industrial Classification System (NAICS) industry. Data for 1997 and earlier years are reported using the Standard Industrial Classification (SIC) system. No data are published that would disclose the operations of an individual employer, and County Business Patterns excludes data on self-employed individuals, employees of private households, railroad employees, agricultural production employees, and most government employees. County Business Patterns employment data are available for download from the following Census website: http://www.census.gov/epcd/cbp/view/cbpview.html.

The Bureau of Labor Statistics (BLS) develops both occupational and industry employment estimates. The BLS' Occupational Employment Series reports national, state-, and metropolitan area-level non-farm employment estimates on an annual basis for each of over 700 occupations. The BLS also produces occupational employment and wage estimates for over 450 industry classifications at the national level. The industry classifications correspond to the 3, 4, and 5-digit NAICS industrial groups (pre-2001 data are reported by 4-digit SIC code). The BLS data do not cover self-employed persons, owners and partners in unincorporated firms, household workers, unpaid family workers, or farm workers. The BLS occupational employment data can be obtained from http://www.bls.gov/oes/home.htm.

The Quarterly Census of Employment and Wages (QCEW) program compiles employment data by industry sector; the data exclude members of the armed forces, the self-employed, proprietors, domestic workers, unpaid family workers, and railroad workers covered by the railroad unemployment insurance

system. Available data include monthly employment by NAICS industry and county. These data are also aggregated to annual levels, to higher industry levels, and to higher geographic levels (national, state, and metropolitan statistical area, or MSA). At the state and MSA level, the QCEW program publishes employment data down to the 6-digit NAICS industry level, if disclosure restrictions are met. BLS withholds publication of employment data for any industry level when necessary to protect the identity of cooperating employers. More information is available on the QCEW program from the following BLS website: http://www.bls.gov/cew/home.htm.

Because the Bureau of the Census and the BLS do not report comprehensive employment data, it is worthwhile to supplement these data, if possible, with estimates from market research companies. Several private market research companies (e.g., Dun and Bradstreet, Inc.) compile and report employment estimates for all sectors/firms. Unlike the Census and BLS, however, a fee must be paid for access to these data (e.g., options for obtaining Dun and Bradstreet estimates are described at http://www.dnb.com/us/dbproducts/sales_marketing/index.html.)

Canadian Nonpoint Data

Energy-consumption, population, and employment data are compiled and published in Canada by Statistics Canada. As an example, Canadian energy consumption and production information is available on a monthly basis. It is provided as energy balance sheets in natural units and heat equivalents, in primary and secondary forms, by province. Each balance sheet shows data on production, trade, interprovincial movements, conversion and consumption by sector. Information on natural gas liquids, electricity generated from fossil fuels, solid wood waste, and spent pulping liquor is also made available in these balance sheets.

Mexican Nonpoint Data

Energy-consumption data are provided by PEMEX - aggregated to the terminal level. However it is not easy to allocate these data to the state or municipality level as is typically necessary for emissions inventory use. The *Secretaría de Energía* (SENER, Secretariat of Energy) publishes an annual energy balance that provides primary energy consumption prior to transformation (i.e., fuel sent to refineries, coke plants, gas plants, or electric generating facilities). Also, SENER publishes fuel-specific documents with details on distribution by sector and region, called *"Prospectivas"*, which can be downloaded from SENER's website (www.sener.gob.mx). INEGI compiles and publishes information on population, employment and economic activity.

4.3.4 Point Sources

U.S. Point Source Data

Activity indicators for point sources include fuel consumption, amount of product produced, amount of throughput, and size/capacity of storage tanks. These activity indicators, or Source Classification Code units, are designed to provide the linkage between activity and the emission quantity. Point-source activity indicators are direct measures of the input or output of specific industrial processes. Pollution-generating activity information is typically (and most reliably) collected directly from individual sites or facilities via surveys or through the facility permitting process. These surveys are normally performed by state/provincial air pollution control agencies, with such authority delegated to local pollution control agencies in some states (e.g., California) or large metropolitan areas. In some cases, local agencies may collect activity data for large point sources using CEMS.

There are also sector-specific data sources – many of which are mentioned in the nonpoint source discussion above – which can be used as supplements to the point source surveys and local permit data. This information can be used as top-down checks to ensure that all fuel use in a sector is being captured in the point-source inventory. Within the point-source sector, the most prominent and widely studied sub-sector is the EGU sector. The history of how activity indicators (i.e., fuel consumption) have been estimated for EGUs and their evolution and improvement with time is illustrative of the different methods that can be applied to estimate emission activity.

In the United States, the responsibility and authority for performing point-source activity surveys has

resided with the states. The execution of these surveys and submission of the resulting data to the U.S. EPA were not performed consistently, which made it very difficult for regulators and researchers to quantify electric utility emissions, and to track changes with time. In the early 1980s, the use of annual power-plant survey data collected by the Department of Energy on fuel purchases and fuel consumption were used to develop methods for providing consistent longitudinal estimates of SO_2 emissions from EGUs. These methods were applied to estimate electric utility air pollution emissions for major research efforts such as NAPAP in the 1980s and early 1990s, and to establish a baseline for measuring progress toward meeting the Title IV requirements of the 1990 Clean Air Act Amendments.

More recently, researchers have taken advantage of the emission and activity information that is available hourly for the EGUs required to have CEMS. Activity information available for CEMS-equipped units are heat input and fuel use, by type. Because not all EGUs are required to have CEMS, state point-source surveys and fuel consumption information submitted to the Department of Energy continue to be valuable resources for quantifying pollution generating activity for this sector.

As trading programs are implemented to achieve regional or local goals for meeting Clean Air Act mandates, it is expected that continuous monitoring will be required for some non-EGU point sources. This change will improve the quantification of activity indicators for these sectors and sources.

Canadian Point Source Data

In Canada, activity indicators for point sources - such as materials consumed and produced, type, size/capacity, emission control equipment, and other characteristics of the processes used by the facilities - are collected by some provincial and regional air pollution agencies. This information is collected through permits and through surveys conducted to support the compilation of the emission inventories. The federal government also collects some of these data through special surveys conducted to support environmental and energy programs, and for the publication of annual statistics. Many EGUs across Canada are required to monitor and report their hourly emissions to the provincial agencies as required by their operating permits or specific regulations. As an example, an emission trading regulation for NO_x and SO_2 in Ontario requires that coal and oil-fired EGUs monitor their emissions using CEMS or other emission monitoring methods approved by the Ontario Ministry of the Environment. These emissions are reported annually to the Ministry and are used for the compilation of emission inventories. It is expected that other similar emissions trading programs will be implemented in the future in Canada. These programs may also include non-EGU point sources, and provide additional activity and emission information to improve the accuracy of the emission inventories.

Mexican Point Source Data

In Mexico, industrial facilities (i.e., point sources) operating in specific geographical "federal zones" or having potential significant interstate impacts or complex operating characteristics are under federal jurisdiction (i.e., SEMARNAT is in charge of regulating them). The federal government manages the regulation, administration, enforcement, and sanctions of facilities within its jurisdiction, and also manages emission inventory development for such facilities. These facilities include the following:

- Those within 100 km of the Mexican border (La Paz, 1984)
- Those included under Article 111 of the *Ley General del Equilibrio Ecólogico y la Protección al Ambiente* (General Law of Ecological Equilibrium and the Protection of the Environment or LGEEPA) (DOF, 1998)
- Public transportation terminals
- On- and off-shore federal lands (e.g., federal coastal zone, federal islands, reefs, and keys)
- Federal government facilities
- Mexico City Metropolitan Area
- Facilities or activities in one state that affect another state.

As described in Section 3.1.3, submission of annual operating reports (called *Cédula de Operación*

Anual – COA) is compulsory for these facilities. These reports include basic information on fuel consumption, operating conditions, and emissions and are compiled either at SEMARNAT's central offices or at its state *Delegaciones*. Additionally, State Environmental Authorities collect information on point sources not under federal jurisdiction through reports which may contain similar information as that required by federal COAs.

4.4 EMISSION INVENTORY MODELS

Inventory models (or emission factor models) are used to estimate emissions for source categories in which the conventional approach of multiplying an emission factor by an activity factor cannot adequately represent the complexity of the source category. Inventory models are most often used for nonpoint sources such as agricultural and biogenic emissions, or for mobile onroad and nonroad sources. These models can be simple or complex, depending upon the needs of the applications for which they have been developed.

4.4.1 MOBILE6

U.S. MOBILE6

MOBILE6 is an emission model developed by the U.S. EPA (http://www.epa.gov/otaq/m6.htm) for estimating emissions from onroad motor vehicles. The model provides criteria-pollutant (including PM and NH_3) and HAP emission factors for highway motor vehicles such as passenger cars, trucks, and buses. MOBILE6 calculates emission factors for 28 individual vehicle types in low- and high-altitude regions of the United States (U.S. EPA, 2002a; U.S. EPA, 2002b). MOBILE6 emission factors depend on conditions such as ambient temperatures, travel speeds, operating modes, fuel volatility, and mileage accrual rates. Many of the variables affecting vehicle emissions can be specified by the user through the use of an input file. MOBILE6 will estimate emission factors for any calendar year between 1952 and 2050. Vehicles from the 25 most recent model years are considered to be in operation in each calendar year. Emission factors generated by MOBILE6 are multiplied by VMT estimates to produce emission estimates.

MOBILE6 (and the latest release, MOBILE6.2) uses statistical relationships based on thousands of emission tests performed on both new and in-use vehicles. In addition to standard testing conditions, many vehicles have been tested at non-standard temperatures, with different types of fuels, including gasoline oxygenate/alcohol blends, and under different driving cycles. Relationships have been developed for vehicles at varying emission control levels, ranging from no control to projections of in-use performance of new technology vehicles.

Even though systematic emission measurements have been performed on the in-use vehicle fleet in the United States, substantial uncertainty remains regarding the applicability of these results. The primary sources of uncertainty are the sensitivity of vehicle emissions to the driving cycle, the wide variety of driving patterns, and the effects of sampling error. Remote sensing surveys indicate that a small fraction of high emitters in the fleet produce a large fraction of total vehicle emissions. Inclusion of one or more high emitters in a survey sample has a substantial influence on resulting emission rates/ factors.

Since MOBILE6's release in January 2001, there have been two studies sponsored to evaluate and validate the model—one sponsored by the Coordinating Research Council (CRC – a cooperative research effort of the American Petroleum Institute and automotive industry in the United States) and U.S. EPA, and another sponsored by the American Association of State Highway and Transportation Officials (AASHTO).

The CRC/U.S. EPA project (ENVIRON, 2004) compared MOBILE6 HC, CO, and NO_x emission estimates with various real-world data sources, including tunnel studies, ambient pollutant concentration ratios, emission ratios from remote sensing devices, and heavy-duty vehicle emission data based on chassis dynamometer testing. Compared with tunnel studies, the CRC/ U.S. EPA study found that MOBILE6 over-predicts fleet average emissions, with the over-prediction being

most pronounced for CO (and, in particular, newer vehicles). Estimates of NO_x emissions most clearly matched the tunnel data. Compared with ambient data, the HC/NO_x ratios developed from MOBILE6 appear to be reasonably accurate, and the CRC/ U.S. EPA data generally supported the HC deterioration rates in MOBILE6.

AASHTO (Sierra, 2004) evaluated several components of MOBILE6 including (1) PM emission factors, (2) toxic air pollutant emission factors, (3) assessment of emission factors when compressed natural gas is the fuel, and (4) methods to estimate CO_2. It was found that MOBILE6 appears to overestimate exhaust PM emissions from newer vehicles. For pre-1990 model years, MOBILE6 predictions fall within the range of recent test program expected values. The AASHTO study also found that MOBILE6 may be underestimating PM_{10} emissions from heavy-duty diesel trucks. The study also found that MOBILE6 brake-wear emission factors likely underestimate brake-wear emissions from the heavier vehicle classes.

Canadian MOBILE6

Environment Canada has developed a Canadian version of the U.S. EPA's MOBILE6.2 model. The Canadian model was based on reviewing the underlying MOBILE6.2 method and documentation, reviewing current and past Canadian inventory methods, modeling documentation and other related studies, and discussing the differences between U.S. and Canadian vehicle fleets with Canadian vehicle manufacturers.

The Canadian model does not change the functionality of MOBILE6.2 or its commands. Certain data needed to be changed from the U.S. default to properly reflect Canadian conditions, and those data are handled in two ways: either through available MOBILE6.2 input commands (the preferred method) or through code modifications (when input commands can not be used). In this manner, the model is designed to allow for the continued use of the U.S. MOBILE6.2 User's Guide and all commands in MOBILE6.2 are executed similarly in Canadian and U.S. versions. Input files may be more elaborate in Canadian modeling, as the pre-existing defaults in the U.S. version of the model are not always reasonable for Canadian conditions. Code changes also were implemented to address the differences in the light-duty U.S. and Canadian fleets prior to the 1988 model year. All code changes are invisible to the user. A full report on the Canadian conversion of the model is available (Air Improvement Resource, 2004).

The MOBILE6.2C model and all available data and resources, along with a graphic user interface in both official languages of Canada, will be made freely available from Environment Canada's website. The data resources are currently being updated, and when complete, may be accessed at http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm.

Mexican MOBILE6

The basic structure of the MOBILE6-Mexico model is based upon the U.S. EPA's MOBILE6 model (ERG, 2003b). MOBILE6-Mexico estimates emission factors for 28 gasoline- and diesel-powered onroad motor vehicle types. Emission factors include hydrocarbons, CO, NO_x, PM, and CO_2. The specific emission factor estimates depend upon conditions such as ambient temperatures, average travel speed, vehicle operating modes, fuel volatility, and mileage accumulation rates. Nearly all of the required input variables can be specified by the user; however, default values are provided that should be appropriate for most areas of Mexico. MOBILE6-Mexico can be used to estimate emission factors for any calendar year between 1952 and 2050. For each calendar year, the overall vehicle fleet consists of the 25 most recent vehicle model years.

In its first application the MOBILE6-Mexico emission-factor model will be used to develop onroad motor vehicle emission estimates for the Mexican NEI (ERG, 2004).

4.4.2 EMFAC2002

California is the only state in the United States that has the authority to establish its own motor vehicle emission standards. California's emission standards are of equal or greater stringency than the federal standards for the other 49 states. In order to properly account for the effects of California's emission standards, the CARB has developed its own

emission factor model -- EMFAC2002. The model produces emission-rate estimates for exhaust and evaporative hydrocarbons, CO, NO_x, as well as for PM associated with exhaust, tire wear and brake wear. Hydrocarbon emission estimates are produced for total hydrocarbon, total organic gases, and reactive organic gases. PM estimates are made for TSP, PM_{10}, and $PM_{2.5}$. The model also estimates emissions of sulfur oxides, Pb, and CO_2. The CO_2 inventory is used to estimate fuel consumption. Although the estimation of toxic air contaminants is currently performed outside of EMFAC2002, efforts are underway to include this capability in the next version of the model. The model, as well as information, can be obtained at http://www.arb.ca.gov/msei/onroad/latest_version.htm (ARB, 2002).

4.4.3 NONROAD

U.S. NONROAD

The NONROAD emission model, currently in draft form, predicts emissions for nonroad equipment ranging from lawn and garden equipment to heavy-duty commercial vehicles. The model includes more than 300 basic and specific types of nonroad equipment that use gasoline, diesel, compressed natural gas, and LPG. NONROAD estimates emissions for hydrocarbons, NO_x, CO, CO_2, SO_x, and PM (U.S. EPA, 2004b; U.S. EPA, 2004c). Even in draft form, the U.S. EPA considers it the best tool available currently for estimating nonroad emissions.

The geographic extent of each model run is user-defined and ranges from national total emissions to subcounty emissions. The subcounty level requires the user to supply the necessary input to distribute the emissions. NONROAD can estimate emissions for the current year, as well as project for future year emissions out to 2045 and backcast past-year emissions to 1970. The model includes growth and scrappage rates for equipment. Emissions are calculated for annual, seasonal, or monthly time periods, with estimates reported for the total period or for a typical day of the week. The NONROAD model and associated documentation can be obtained at http://www.epa.gov/otaq/nonrdmdl.htm.

The OFFROAD model, developed by CARB, has been used to develop nonroad vehicle emissions of hydrocarbons, CO, NO_x, and PM throughout California. More information about the model can be obtained at http://www.arb.ca.gov/msei/nonroad/updates.htm.

Canadian NONROAD

Environment Canada has developed Canadian nonroad engine population databases for use with the U.S. EPA's draft NONROAD 2004 model. At present, no sub-region or district-level data are incorporated into the Canadian engine population database. However, to provide for compatibility with these and other aspects of the model, Canada, the provinces and territories are mapped to certain American states and Federal Information Processing Standards codes. Environment Canada has also created modified spillage factor files, NO_x deterioration files, and technology files to reflect the difference in Canada and the United States. Full details of the changes to these files are outlined in the report by Vaivads (2004).

All available data, resources, modified files and documentation are available from Environment Canada's website at http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm.

Mexican NONROAD

The U.S. EPA's NONROAD model was used to estimate construction and agricultural emissions (only) for the 1999 Mexican NEI. However, a current project is underway to develop a Mexico-specific version of this model for future use. NONROAD-Mexico will incorporate information on Mexican construction equipment population and usage obtained from field surveys conducted in Monterrey, Nuevo León, in January 2005. Updated agricultural equipment population information has been obtained from *Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación* (SAGARPA, Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food).

4.4.4 MOVES

To keep pace with new analysis needs, new modeling approaches, and new data, the U.S. EPA's Office of Transportation and Air Quality (OTAQ) is currently working on a new modeling system termed the Motor Vehicle Emission Simulator (MOVES). This new system will estimate emissions from onroad and nonroad sources, cover a broad range of pollutants, and allow multiple-scale analysis, from fine-scale to national inventory estimation. The foundation of the multi-scale approach is a common set of modal emission rates disaggregated by driving mode. These modes are then re-aggregated based on representative activity data to estimate total emissions at any scale over any driving pattern. The MOVES model uses a binning approach to define modal emissions. Vehicle-specific power and instantaneous speed are used to identify driving modes. This method produces 17 bins that segregate idle and deceleration, and splits the remaining cruise and acceleration operation into 15 bins defined by combinations of speed (less than 25, 25 to 50 and greater than 50 mph) and vehicle-specific power (U.S. EPA, 2002c).

The current draft version of MOVES (MOVES2004) only models energy (i.e., fuel consumption), methane, and NO_x. The U.S. EPA's plans call for adding hydrocarbons, CO, NO_x, and PM to the draft MOVES2006 model. The MOVES2007 model is expected to be considered "final" for criteria pollutants and will likely be the replacement for MOBILE6 in 2007 (Landman, 2005). Additional information regarding the MOVES model can be obtained at http://www.epa.gov/otaq/ngm.htm.

4.4.5 BEIS

First developed in 1988, the Biogenic Emissions Inventory System (BEIS) estimates VOC emissions from vegetation and NO emissions from soils. Because of resource limitations, recent BEIS development has been restricted to versions that are compatible with the Sparse Matrix Operational Kernel Emissions (SMOKE) system. There have been multiple releases of BEIS, with the most recent being version 3.12.

Characteristics of the various versions of BEIS (U.S. EPA, 2004c) are listed below:

- BEIS 3.12: This is the most recent version of BEIS. It is assembled as a stand-alone module to the SMOKE system for generating gridded, hourly emissions in a format consistent with air quality modeling.
- BEIS 3.11: This is a forerunner to version 3.12 of BEIS. BEIS 3.11 is a stand-alone module to the SMOKE system for generating gridded, hourly emissions in a format consistent for air quality modeling. BEIS3.11 revises the soil NO algorithm in BEIS3.10 to better distinguish between agricultural and nonagricultural land, and to limit adjustments from temperature, precipitation, fertilizer application, and crop canopy to the growing season and to areas of agriculture. A leaf-shading algorithm is added for estimating methanol emissions from non-forested areas.
- BEIS-2: This is an older version of BEIS. It calculates emissions from vegetation using 75 tree genera, 17 agricultural crop types, and urban grasses. Several data requirements are necessary inputs to the BEIS-2 model, including spatially gridded land-use and plant cover data, vegetation-specific emission factors for VOC and NO, and hourly gridded temperature data.

Documented physicochemical effects remain largely unaccounted for in the BEIS models. For example, the effects of plant stress and dew on biogenic emission rates are not accounted for in the model. Because the effects of these conditions are accounted for in existing dry-deposition models, these data are available for incorporation into BEIS models. Relative humidity and CO_2 concentrations also affect biogenic emission rates. Data to support these physico-chemical effects are available for incorporation into the BEIS models. The model and further information can be obtained at http://www.epa.gov/asmdnerl/biogen.html.

4.4.6 GloBEIS

The Global Biosphere Emissions and Interactions System (GloBEIS) is based on a collaboration between the U.S. EPA and the U.S. National Center for Atmospheric Research. GloBEIS allows users to estimate biogenic emissions of VOC, CO, and soil NO_x for any scale and domain. GloBEIS runs in Microsoft Access on a PC platform. Emission rates are a function of landcover and environmental conditions, which are characterized from user-supplied data using the most updated emission algorithms. The developers of GloBEIS identify its attributes as:

- Uses high resolution land use data, GIS data, or Biogenic Emissions Land Cover Data, Version 3 (BELD-3).
- Provides updated emission factor algorithms. The GloBEIS3 algorithms reflect the latest science compared to the BEIS2 algorithms.
- Compares different emission factor algorithms in the same model.
- Provides VOC speciation for atmospheric chemical mechanisms.
- Bases isoprene emissions on solar radiation data supplied from GOES satellite images. This accurately represents the impacts of clouds on biogenic emission inventories with hourly temporal resolution.
- Models effects of drought and prolonged periods of high temperature.
- Uses satellite-based leaf-area index data to determine the spatial distribution of emission and/or leaf age.
- Includes a leaf temperature model.

GloBEIS 3.1 has been adopted by Environment Canada to estimate Canadian biogenic emissions. Environment Canada uses the GIS-based Spatial Emissions Distribution Information System for integrating, processing, and calculating the geographic distribution of CAC emissions from the inventories. This system generates the various input files required to run the GloBEIS 3.1 model such as:

- Domain definition and specification of geographic units; including the identification, latitude, longitude and total area of each geographic unit (grid system or administrative regions)
- Land use distribution by geographic unit and by land use code; including land-use and land-cover information based on an advanced very high resolution radiometer land cover map of Canada
- Hourly temperature data for all stations across Canada
- Hourly cloud opacity data for all stations across Canada.

Some of the emission factors and other related information in the GloBEIS 3.1 model were also updated to reflect the Canadian information available. Information regarding the GloBEIS model can be obtained at www.globeis.com/. More Canadian meteorological data can be found at http://weatheroffice.ec.gc.ca/canada_e.html.

The GloBEIS 3.1 model was used to estimate biogenic emissions for the Mexican NEI (ERG, 2004). The following input data were compiled for use with GloBEIS:

- Land use data sets from the National Forestry Inventory for Mexico developed by the National Autonomous University of Mexico (UNAM) and SAGARPA (for agricultural crops).
- Hourly temperature data from *Servicio Meteorológico Nacional* (SMN, National Meteorological Service) for 15 sites in Mexico, augmented with data from the U.S. National Climatic Data Center (NCDC) for 116 sites in Mexico.
- Hourly cloud cover data from SMN.

4.4.7 BEIGIS

California has proposed developing a biogenic emission-estimation program that incorporates data on the specific vegetation in California and extensive land-use data. The proposed Biogenic Emission Inventory Geographic Information System (BEIGIS)

model is described in further detail at http://www.arb.ca.gov/ei/ccosbeigis2.pdf.

4.4.8 TANKS

TANKS estimates VOC and HAP emissions from organic liquid storage tanks. It models emissions by simulating them as evaporation processes. The American Petroleum Institute developed the underlying equations to TANKS and licensed their noncommercial use to the U.S. EPA for the software and AP-42 documentation. Required inputs include tank size, structure and condition; environmental conditions; and physicochemical data describing the mixture of liquids contained in the tanks. The TANKS software, as well as user's guide can be obtained at http://www.epa.gov/ttn/chief/software/tanks/index.html.

4.4.9 WATER9

WATER9 is a Windows-based computer program developed by the U.S. EPA to estimate emissions from wastewater treatment. WATER9 includes a graphical user interface that allows the user to outline wastewater treatment processes present at a facility. The program can also generate reports of constituent fates, including air emissions and treatment effectiveness.

WATER9 contains a set of representative treatment components that can be used together in a project to provide a model for an entire facility. The model is able to evaluate a full facility that contains multiple wastewater inlet streams, multiple collection systems, and complex treatment configurations. WATER9 provides separate emission estimates for each individual compound identified as a constituent of the waste. The emission estimates are based upon the properties of the compound and its concentration in the wastes. To obtain these emission estimates, the user must identify the compounds of interest and provide their concentrations in the wastes. The identification of compounds can be made by selecting them from the database that accompanies the program or by entering new information describing the properties of a compound not contained in the database.

WATER9 uses site-specific chemical-property information and estimates missing chemical-property values. Estimates of the total air emissions from the process are obtained by summing the estimates for the individual compounds. The model, as well as documentation, can be obtained at http://www.epa.gov/ttn/chief/software/water/.

4.4.10 Emission Dispersion Modeling System

The U.S. Federal Aviation Administration has developed a program to estimate emissions from airports which is called the Emission Dispersion Modeling System (EDMS). The original version of EDMS was released in 1997, and it has since been further developed. The most current version of EDMS is version 4.2. EDMS 4.2 provides emission data for the following pollutants: total hydrocarbons, non-methane hydrocarbons, volatile organic compounds, PM_{10} and $PM_{2.5}$ (there are no PM_{10} or $PM_{2.5}$ emission factors for aircraft). EDMS 4.2 interfaces with the U.S. EPA's latest version of AERMOD and its supporting weather and terrain processors. The latest version of EDMS also integrates the U.S. EPA's MOBILE software for estimating emissions from vehicles at parking lots and feeder roads. In addition, beginning with version 4.1, EDMS integrated the U.S. EPA's draft NONROAD program for estimating emissions from aerospace ground equipment/ground service equipment. EDMS allows users to build and customize aircraft, vehicle, and GSE fleets for individual airports. Subsequently, EDMS calculates emissions by airport. EDMS software can be obtained for a fee at http://www.aee.faa.gov/emissions/EDMS/EDMShome.htm.

4.4.11 Carnegie Mellon University Ammonia Model

The Carnegie Mellon University Ammonia Model is an emission factor model and database of activity data for NH_3 emissions based in part on AP-42 estimates. This model is frequently used in the United States, including in the NEI, for compiling NH_3 emission data. It stores county-specific activity data at the national scale and emission factors for a

variety of NH_3 emission sources, including livestock, fertilizers, wastewater treatment facilities, mobile sources, natural biogenic sources, etc. Examples of stored activity parameters include livestock populations by animal type, fertilizer consumption rates, wastewater plant process rates, VMT by vehicle class and technology types, and land coverage by land use categories. This model and associated documentation can be retrieved at http://www.cmu.edu/ammonia/.

4.5 EMISSION PROCESSORS

Emission processing tools are used to prepare and manipulate existing emission estimates and related data (e.g., temporal profiles, chemical speciation profiles, and control strategies) for input to air quality simulation models. The principal emission processors are described below.

4.5.1 SMOKE

SMOKE processes emission data using matrix-vector multiplication. It performs the core functions of emission processing including spatial allocation, temporal allocation, chemical speciation, control-technology application, and generation of biogenic emission estimates. SMOKE implements the MOBILE6 model and also uses a reorganized version of the Urban Airshed Model – Biogenic Emissions Inventory System (UAM-BEIS-2). Alternative mobile-source models such as EMFAC2002 and biogenic models such as BEIS-3 may be run external to SMOKE and their results incorporated into the SMOKE processing stream. SMOKE can be obtained at http://www.cep.unc.edu/empd/EDSS/emissions/.

4.5.2 Emission Processing System

One of the most widely used emission processing tools is the Emission Processing System (EPS)2.0/2.5 developed under U.S. EPA sponsorship as a FORTRAN-based emission processing system. EPS was designed to prepare county-level seasonal or annual emission inventories for use in urban models and was released as version 1.0. As a result of the 1990 Clean Air Act Amendments, a growing emphasis on the use of urban models led to a series of enhancements. EPS2.0/2.5 provides expanded capabilities to handle the 1990 Clean Air Act Amendments requirements with all the necessary modules to prepare spatially, temporally, and chemically detailed emission inventories. EPS2.0/EPS2.5 is publicly available and allows the development of emission inventory inputs for urban models with a minimum of additional data because it comes with a set of national defaults for many of its required inputs.

Canada has developed its own emission processor, based on the U.S. EPA's EPS2 and on BEIS2. The CEPS1.0 was developed to process current Canadian and U.S. annual national inventories of criteria air pollutants and to generate emission input files for each air quality model as required. CEPS1.0 differs from its U.S. counterpart mainly in the form of regional and country-specific modifications. Areas where the U.S. EPS2.0 and BEIS2 were changed include: data structure, input files for the accommodation of different map projections, and arbitrary grid windows, grid orientations, and grid increments. Further changes were required to the base programs as follows: chemical mechanisms other than carbon bond IV, multiple time zones, updated and enlarged spatial allocation factor fields, various major/minor point-source partitioning options, and the use of gridded meteorological fields in calculating mobile and biogenic emissions.

4.5.3 Emission Modeling System

The Emission Modeling System versions (EMS-95 and EMS-2000) compute model-ready emission estimates for point, nonpoint, mobile, and biogenic sources. Both EMS versions are based on the Geocoded Emission Modeling and Projections (GEMAP) system developed for CARB during the early 1990s and include a number of enhancements and extensions to the original GEMAP system. EMS is composed of six primary modules: the Grid Definition Model, the Point Source Model, the Area Source Model, the Motor Vehicle Emissions Estimates Model, the Biogenic Model for Emissions Estimates, and the Speciation Model. While its approach to generating emission inventories for regional scale air quality modeling is flexible and

comprehensive, the software requirements (SAS, ArcInfo, and a FORTRAN compiler) make EMS an expensive system to use. EMS is specifically designed to perform the following activities:

- Modify emission parameters and inputs efficiently
- Define a modeling grid
- Process point and nonpoint source emission estimates, based on annual average or day-specific emissions
- Calculate onroad mobile source emission estimates
- Calculate biogenic emission estimates
- Calculate crude oil storage tank emission estimates
- Spatially distribute, temporally allocate, and speciate emissions for use in photochemical modeling
- Develop projected emission inventories for future-year scenarios.

EMS-HAP, designed initially to process the 1996 National Toxics Inventory (NTI), is a system of computer programs that process toxic air pollutant (or HAP) emission inventories for use in the Assessment System for Population Exposure Nationwide (ASPEN) or the Industrial Source Complex (ISC3) Dispersion Models (ISCST3) air quality models. EMS-HAP differs from EMS-95 in that it is specific to the NTI and ASPEN/ISCST3. It also is capable of estimating future year emission data for these models. EMS can be obtained at http://64.27.125.175/tech/emis/index.html.

4.6 EMISSION PROJECTIONS

Emission projections are performed in support of several goals, such as providing a basis for developing control strategies for SIPs, conducting attainment demonstration analyses, tracking progress towards meeting air quality standards, and evaluating future-year impacts associated with national rulemakings. Emission projections are a function of change in activity (growth or decline) combined with changes in the emission rate or controls applicable to the source. Changes in emission rates may occur via air pollution regulations and standards or through technological change that occurs with time. The methodologies, tools, and data sources that are used to prepare future-year emission inventories are specific to the inventory sector.

It should be recognized that uncertainties in projection inventories are significantly greater than uncertainties in current (or baseline inventories). These added uncertainties are due to the difficulty in projecting future economic activity by sector and projecting the consequences of unforeseeable actions, such as the decline of the U.S. steel industry in the 1980s or the dot.com bust in the San Francisco Bay area in the 1990s. Thus, it is especially critical for projection inventories to include measures of uncertainty and variability, and to bound projections when possible. In order to characterize the robustness of projections, it is critical that projection models be transparent so that the underlying assumptions can be understood and modified as necessary. The best check on the accuracy of emission projections is the comparison of periodic inventories with projections.

The following discussion identifies key emission projection concepts, and tools and data sources that have been developed and used in preparing emission projections. Additional background projection information is available on the following websites developed in support of the EIIP: http://www.epa.gov/ttn/chief/eiip/techreport/volume10/x01.pdf and http://www.epa.gov/ttn/chief/eiip/committee/projections/evaltools.pdf.

4.6.1 Emission Activity Forecasts

Because source-specific future year emission activity forecasts are difficult or impossible to obtain, projection-year inventories are typically based on forecasts of population, industrial activity, or other surrogates for emission activity changes. In the United States, the U.S. EPA has developed the Economic Growth Analysis System (EGAS) to support emission activity level forecasting. The latest version of EGAS (4.0) provides default emission-activity growth factors for the period 1996-2020

(Pechan, 2004). This Windows-based software tool provides growth factors for nearly 10,000 source classification codes for each county in the continental United States based on forecasts for surrogate emission activity growth indicators such as output by industry sector. Growth factors in EGAS are defaults and forecasters should rely on more specific information whenever it is available. The following link on the U.S. EPA's Emissions Modeling Clearing House provides the EGAS 4.0 installation files, reference manual, and user's guide: http://www.epa.gov/ttn/chief/emch/projection/egas40/index.html.

U.S. EPA is currently developing EGAS 5.0, which will extend projection capability through at least 2025, and include activity growth indicators for all 50 states and the District of Columbia. Some state and local agencies have their own emission forecasting systems. For example, in California, CARB as well as the two of the largest air districts (South Coast Air Quality Management District and the Bay Area Air Quality Management District) develop their own emission forecasts.

Although EGAS provides emission activity growth factors for every emission sector, the NONROAD model has been developed in the United States to support emission projections for most nonroad source categories. The NONROAD model and associated documentation is available from http://www.epa.gov/otaq/nonrdmdl.htm#model. EGAS projections and growth factors can potentially be incorporated into future NONROAD releases.

For fuel combustion sectors, EGAS 4.0 incorporates energy consumption projections prepared by the EIA in Annual Energy Outlook 2001 (EIA, 2004a; EIA, 2004b). Because EIA updates its energy consumption projections annually, emission forecasters can obtain EIA's current energy consumption projections from http://www.eia.doe.gov/oiaf/aeo/index.html. The two main methods that have been used to prepare VMT projections are through travel demand forecasting (preferred) and extrapolation of historical VMT trends. MOBILE6 makes future year projections using changes in future technology and increases in VMT. MOBILE6 uses a 2 percent compounded annual growth rate for VMT.

The importance and complexity of the EGU sector has led to the development of computer models to evaluate the effects of air pollution control strategies and other important changes influencing this sector (Pechan and Wilson, 1984). These models seek to represent generation, transmission and pricing of electricity subject to fuel prices, the costs of capital and domestic investment, and electricity load shape and demand. Such models also typically include a linear programming component to allow evaluations of the cost and emission impacts of proposed policies to limit EGU sector emissions of SO_2, NO_x, CO_2, and mercury via trading programs. In the United States, the Integrated Planning Model (IPM) has been developed for preparing EGU emission projections (ICF, 2004). The IPM is a proprietary model. Information on recent U.S. EPA IPM modeling runs is available from the following U.S. EPA Clean Air Markets Division link: http://www.epa.gov/airmarkt/epa-ipm/.

4.6.2 Emission Rate/Control Forecasts

In the United States, future year emission rates for most source sectors are maintained in sector-specific models (e.g., EGU emission rates in IPM; onroad mobile source rates in MOBILE, and nonroad mobile source rates in NONROAD). These models produce emission forecasts that incorporate the impact of equipment turnover on the emission rates of new vehicles/equipment.

Because no emission estimation model has been developed for the non-EGU stationary point and nonpoint sectors, no single resource provides future-year emission rates for these sectors. To assist in identifying future-year stationary-source emission rate/control assumptions, forecasters can obtain emission-inventory forecast documentation prepared in support of rulemakings. This documentation generally includes estimates of the emission reductions associated with the mandated control for one or more future implementation years. The percent emission reduction then can be calculated and applied in preparing non-EGU stationary source emission forecasts. A potential source of emission reduction information for some stationary sources

is AirControlNET (Pechan, 2003), a U.S. EPA relational database that contains emission reduction and cost information for a series of mandatory and discretionary point and nonpoint source emission control strategies. Information on AirControlNET is available from http://www.epa.gov/ttn/ecas/AirControlNET.htm.

Also, no tool is available in the United States for modeling the impact of equipment turnover and technology changes on future non-EGU stationary source emission rates. Although this is not likely to have a significant impact on short-term projections, emission forecasters should consider incorporating the impact of stationary source equipment turnover whenever possible. A recent example of a stationary point source emission projection effort that modeled this effect is the WRAP 2018 year forecast. More information on the WRAP emission projections methodology can be found at http://www.wrapair.org/forums/ef/documents/2002-12_PECHAN_FinalReport_Base-Annex-Bart.pdf.

4.6.3 Canadian Emission Projections

Like the U.S. EPA, Environment Canada compiles emission projections on a regular basis to support the development of federal and provincial emission-control strategies (federal and provincial implementation plans), to evaluate their future impact on air quality, and to support the reporting requirements of domestic and international programs and agreements. Using the latest emission inventory available, the Canadian projections for industries and power-generating utilities are developed using annual growth factors, which are calculated from surrogate data or indicators obtained from the energy outlook compiled by Canada's ministry of natural resources, NRCan. The projections also take into account changes in technology and equipment turnover for different industries.

NRCan has adapted the U.S. National Energy Modeling System (NEMS) for developing the Canadian energy outlooks. NEMS is an energy-economy modeling system, designed and implemented by the U.S. EIA. NEMS projects the production, imports, consumption, and prices of energy, subject to various assumptions such as macroeconomics, resource availability and costs, costs and performances of energy technologies, behavioral and technological choice criteria and demographics.

Emission projections for onroad vehicles are developed using the Canadian emission estimation model, MOBILE 6.2C. Emission projections for nonroad transportation vehicles (excluding aviation, marine and rail) are calculated using the U.S. NONROAD model. This model takes into account the VKT each year, the turnover of vehicle fleets, and the characteristics of the gasoline and diesel fuel being used, as well as future impacts of current energy policies and emission reduction programs.

A base case forecast is developed using the provincial and territorial projections compiled by Environment Canada. The base case forecast is a "business/policy as usual" projection, in the sense that all current energy, environment and related policies are held constant over the projection period. The impacts of modified or additional control regulations that have not been officially implemented (at the time the forecast is prepared) are not included in a base case. The base case is thus a reference case, against which control scenarios can be built to compare the impacts of potential emission reduction measures. A review of the base case forecast is performed through consultations with industrial sector experts, provincial and territorial governments, industry associations, and other interested parties.

Environment Canada is currently validating and improving the Energy 2020 Model to project the emissions for both CACs and GHGs. Energy 2020 is an integrated energy system that calculates the energy demand, the energy supply and the associated emissions. The model projects end-use energy demands in major sectors (residential, commercial, industrial, agriculture and transportation) based on macroeconomic assumptions. It also dynamically simulates the supply of various types of energy (electricity, oil, gas, biomass) to meet these end-use demands. Finally, it calculates the CAC and GHG emissions associated with these demands and supplies of energy. As an integrated model, Energy 2020 can estimate how changes in energy demand behaviors in one sector can impact other sectors via fuel consumption, fuel supply and fuel prices.

The Energy 2020 model is widely used in Canada, the United States, Europe, and around the world, with each region or jurisdiction configuring the model to meet the detail levels specific to the country. Environment Canada has adapted the model to cover the 10 provinces and 3 territories. Other enhancements to Energy 2020, which take into account the particularities of Canada, include additional categories in the transportation sector, the regulate/deregulate supplies of electricity, disaggregation of fuel types, and CAC emission factors.

The Canadian version of the Energy 2020 model will be used as a starting point for future emission projections. It will become a policy tool to analyze the impacts of current and future environment policies, energy options and control measures to reduce future CAC and GHG emissions. It will be calibrated to the energy outlooks prepared by NRCan on a regular basis.

The latest emission projections available for Canada are based on the 2000 emission inventory and cover the period from 2001 to 2020.

4.6.4 Mexican Emission Projections

Methodology for Projecting the Border Baseline Emission Inventory (1999) to 2002 and 2012

The Mexican emission-inventory base year is 1999. Inventories for the years 2002 and 2012 were estimated in order to characterize the impact of growth and existing control strategies on future emissions within the Mexico/U.S. border region (defined by the La Paz Agreement as the area within 100 kilometers either side of the international border). This section describes the methodology used to project the 1999 baseline inventory to the years 2002 and 2012 (ERG, 2005).

Point Sources

Because the U.S. EGAS model is not applicable to Mexican point sources, point-source projection factors were developed by extrapolating existing industrial statistics. Mexican industrial production statistics from 1995 to 2000 were obtained from the Organization for Economic Co-operation and Development, or OECD (OECD, 2004). The production statistics were aggregated to the 3-digit NAICS level and then extrapolated to 2002 and 2012 to develop appropriate projection factors. The industrial statistics did not provide any information for mining and waste management activities (NAICS codes 212 and 562); for this reason the projection factors for these sectors were set to 1. Information regarding future projections for electric utilities activity was obtained from SENER (2003a). Emissions for electric utilities were projected using estimates of electricity generating capacity (projections of future electricity use were unavailable). Projected emissions from utilities were assigned only to existing facilities (as of 1999) even if future electricity generating capacity was planned for a new location.

Nonpoint Sources

Projection factors for future year Mexican nonpoint sources were based upon a variety of published data. These data included the following:

- Regional energy forecasts (*Prospectivas*) from 2003 to 2012 for four energy sectors (i.e., electricity, petroleum liquids, natural gas, and LPG) were obtained from SENER (SENER, 2003a; SENER, 2003b; SENER, 2003c; SENER, 2003d). Projection factors were derived directly from the specific energy forecasts and applied to all nonpoint source fuel combustion and distribution nonpoint source categories for 2002 and 2012.

- Annual state-level agricultural and livestock statistics from 1993 to 2002 were obtained from SAGARPA (2003). Projection factors for agricultural sources (e.g., Technical Memorandum – Draft Final September 30, 2004 Page 10 livestock ammonia, fertilizer application, agricultural tilling, etc.) were developed by extrapolation of 10-year statistics.

- The industrial point-source statistics described under the Mexico point-source section were used to develop projection factors for four industrial nonpoint sources (i.e., bagasse combustion, coke production, industrial surface coating, and degreasing).

- Future-year population forecasts through the year 2030 at the municipality level were obtained from Mexico's National Council on Population (*Consejo Nacional de Población* – CONAPO) (CONAPO, 2003). Projection factors were derived directly from the specific population forecasts for 2002 and 2012.

Because of difficulties in projecting future levels of wildfires, wildfire activity was assumed to be constant in 1999, 2002, and 2012. Because future-year control information was not available, the projection factors only include the effects of growth.

Onroad Motor Vehicles

Unlike the other Mexican source types, the future-year projection factors for Mexican motor vehicles included both growth and control factors. The growth factors were based upon the future-year SENER regional fuel forecasts. Control factors were estimated by running future-year MOBILE6-Mexico scenarios. Because of the large number of MOBILE6-Mexico runs that were necessary for development of the base year Mexico NEI, it was not feasible to rerun all possible scenarios for 2002 and 2012. However, scenarios representing a typical vehicle speed (i.e., 30 mph) were run for summer and winter conditions at low and high altitude (i.e., >1,400 meters) for the northern portion of Mexico for 1999, 2002, and 2012. The results from these scenario runs were then used to develop the control factor part of the projection factors.

Nonroad Sources

Projections for nonroad sources were based upon regional fuel forecasts (for nonroad equipment including construction and agriculture) as provided by SENER for 2002 and 2012.

Methodology for Projecting the MCMA Baseline Emission Inventory (1998) to 2000, 2006 and 2010

The following is a brief description of the methodology used in the projection of the 1998 emission inventory for the MCMA (GDF, 1998) to the years 2000, 2006 and 2010.

Point Sources

The projection of emissions from point sources was conducted assuming the existence of a direct relationship between emission growth rates and the Gross Domestic Product (GDP) by federal entity and economic activity. In this case, the growth rates used were: 0 percent for the electric sector in the Federal District and 3.7 percent for the municipalities of the State of Mexico; for other point sources (industrial, manufacturing, etc.) a GDP growth rate of 4.2 percent was used for the Federal District and 4.5 percent for the State of Mexico. These values correspond to the annual average growth rates of the GDP for the period 1993-1999 and assume constant growth rates until 2010.

Nonpoint Sources

To estimate emissions from nonpoint sources for the years 2000, 2006 and 2010, projection factors were obtained from a relationship between the activity level during the base year and the activity level for the projected year. The activity level for the projected years was obtained from local behavior studies or projections of the population growth (CONAPO, 2003), as well as growth trends in fuel consumption (gas, diesel, industrial diesel, LPG and natural gas) (SENER, 2000b).

Given the difficulties encountered in projecting the behavior of certain sectors, such as forest fires or structural fires, these activity levels were assumed to remain constant for the projection. The factors used in the projection only include the effect of growth and do not take into account any planned control measures.

Mobile Sources

Net growth of the private auto fleet was estimated based on historical data on the vehicle fleet composition and on new car sales in the metropolitan area. These classifications were used to estimate survival and growth rates, respectively. For the rest of the fleet, projections were based on estimates from the Energy Secretariat (SENER, 2000a). Once the growth of the vehicle fleet for the years 2000, 2006 and 2010 was defined, emissions were calculated for

each type of vehicle. Emission factors for NO_x, HC and CO for private autos 1998 and older are derived from the 1998 inventory. After 1999, all automobiles are assumed to have TIER I technology. Emission factors for other types of vehicles are the same as those reported in the1998 emission inventory, only shifted for the year of projection. For instance, for the projected year 2010, an emission factor for 1974 and older vehicles in the 1998 inventory would correspond to vehicle model years 1986 and older. Likewise, a vehicle model year 1975 would correspond to model year 1987 for the 2010 projection. Each model year is shifted successively with 1998 corresponding to model year 2010.

Methodology for Projecting Mexican Greenhouse Gas Emissions

Projections of energy demand from 1995 to 2010 were estimated using a primary and final energy-demand model. This model considers a population scenario based on the average projection from INEGI (1.42% annual growth throughout the study period) and three economic growth scenarios. The first two scenarios correspond to high and low economic growth, with average annual growth rates of 4.81 and 2%, respectively. The third scenario corresponds to the reference scenario, which assumes an average annual growth rate of 3.4%.

In addition, two options were included for energy intensities (energy used for each Mexican peso produced): a constant, based on average values in agreement with available historical data, and an expert opinion. Under these assumptions the model showed CO_2 emissions for the year 2010 increasing by between 50% and 100% over 1990 emissions, depending on the scenario (INE, 2004). Further information may be obtained at http://www.ine.gob.mx/dgicurg/cclimatico/mycc/mycc2_4a.html.

4.6.5 Projection Coordination

In the United States, Canada, and Mexico, consistent tools have been developed or adapted for developing sector-specific emission projections for onroad, nonroad, and EGUs. Previous sections in this chapter have described how the U.S. EPA's MOBILE6 model has been adapted for use in estimating current and future Canadian and Mexican motor vehicle emissions. Similar efforts are planned, or are underway, for nonroad vehicles using the U.S. EPA's NONROAD model. EGU modeling efforts in the United States have been dominated by the IPM. As part of the joint projects announced in June 2003 by U.S. EPA and Environment Canada under the Border Air Quality Strategy, a Canadian module intended to provide representation of the Canadian electric power sector has been developed for the IPM model. The new module will allow the two countries to conduct joint analyses of the feasibility of cross-border trading of capped emissions of NO_x and SO_2, and explore opportunities for coordinated air quality management. Mexican EGU emission projections do not use a simulation model. U.S. efforts for non-EGU point and nonpoint sectors have recently focused on using growth and control factors within emission processors for making future-year emission estimates for these sectors. However, this approach does not capture some of the important long-term influences on emissions such as international competition and technological changes/advances. These factors have produced significant emission changes for some industries in the past 20 years – most notably for copper smelters and iron and steel production. Therefore, more sophisticated tools are needed for non-EGU point and nonpoint sectors, so that when North American emission estimates are developed for forecast years, emission estimates are comparable among countries. Development of such tools needs to take into account the differences in data sources and data availability.

Other practical issues affecting the ability of the United States, Canada, and Mexico to use each other's emission projections are the need to agree on the specific projection years of interest and on common approaches to providing consistent future information. Achieving this agreement will require coordination of control and economic scenarios. Within the United States, such coordination needs to involve the RPOs, states, and the U.S. EPA, because all will be involved in the regional modeling efforts for ozone, fine PM, and regional haze that take place this decade. At present, U.S. EPA regulatory analysis projections are made in 5 to 10 year increments, while RPOs and the states focus on attainment years (2009, 2018).

Canada's most recent emission projections cover the period 2001 to 2020 to support the reporting requirements of domestic programs and international agreements. The 2010 forecast was included in the 2004 progress report of the United States-Canada Air Quality Agreements. Canada has developed 2010 and 2020 emission estimates for both a base case and a control case that have been used recently in joint transboundary air quality modeling studies with the United States. The Mexico 2012 border emission estimates, when available, can serve as a reasonable proxy for 2010 emission estimates in U.S.-Mexican transboundary studies for that time period. The U.S. EPA has 2010 emission databases available from its national regulatory analyses. These data can be used to establish a representative 2010 North American criteria pollutant modeling inventory. The U.S. EPA efforts may be improved by ongoing RPO projection efforts. These efforts should update the U.S. EPA's work by accounting for how states are implementing new rules/regulations, in practice.

A worthwhile longer-range objective is to have each country develop a set of 2018 emission projections. The RPOs have established 2018 as a common year for evaluating progress in meeting U.S. regional haze rule goals. Because these 2018 emission estimates will be used in regional modeling efforts, it is important that Canadian and Mexican emission estimates for the same time period are developed and made available in consistent formats. Inter-country coordination to produce 2018 emission forecasts should include information exchange about economic and control scenarios.

4.7 EMISSION TEST METHODS

4.7.1 U.S. Emission Measurement Methods

Over the past 30 years, the U.S. EPA has developed emission test methods to ensure compliance with New Source Performance Standards (NSPS), National Emissions Standards for Hazardous Air Pollutants (NESHAPS), and Maximum Achievable Control Technology (MACT) standards. These methods provide the basic emission data for inventories, emission factors, compliance determinations, state data collection requirements, and control technology research and development. Table B.2 in Appendix B lists the U.S. EPA's promulgated, proposed, and conditional test methods and alternative approved methods by criteria and hazardous air pollutant. Links to these methods can be found at http://www.epa.gov/epahome/index/.

All methods include specific QA/QC requirements that must be met, and they provide estimates of method precision. The pollutant-specific methods are generally applicable to multiple categories of stationary source categories. Methods specific to a particular source category are given a letter suffix.

A major limitation to using U.S. EPA test methods for inventory or emission factor development is that each test is conducted at a specific set of operating and ambient conditions. It is therefore difficult to assess the representativeness of the test results. In particular, emission tests are generally not conducted during periods of startup, shutdown, process changes, or malfunctions, when emissions may be higher than during steady state operation.

It is also important to note that the applicability, precision, detection limits, and accuracy of a method developed for a specific pollutant and source category are not necessarily applicable to other categories that have different emission stream characteristics (e.g., temperature, humidity, concentrations, interferences). Also, because many of the test methods are two or more decades old, they were derived to measure emissions characteristic of that period. For example, U.S. EPA Method 7E was developed to measure NO_x emissions from combustion turbines when typical levels were 300 ppm. The best controlled modern combustion turbines emit less than 5 ppm NO_x making the precision and accuracy stipulations of Method 7E inappropriate for modern turbines.

4.7.2 Canadian Emission Measurement Methods

Most of the Canadian measurement methods for stationary emission sources are similar to those used in the United States. Some, like those for vinyl chloride, arsenic, total reduced sulfur (TRS),

and SVOCs, preceded or were developed in parallel to their U.S. EPA counterparts, and retained some significant differences.

The mercury method developed by former Ontario Hydro has been adopted by ASTM as D6784-02 Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal–Fired Stationary Sources.

Some Canadian methods were developed as companions to specific regulations (such as the Ontario total hydrocarbon regulation for incinerator and the ambient odor guideline) or programs (such as Method EPS 1/RM/15 as companion to the National Emission Guidelines for Commercial / Industrial Boilers and Heaters).

Environment Canada's reference methods for stationary sources are summarized in Table B.1 in Appendix B. The Alberta and Ontario methods are also included in Appendix B.

Environment Canada is currently working on the following emission measurement methods:

- Update EPS 1/PG/7 (CEMS for NO_x and SO_2 budgets)
- Revision of RM/15 (addition of low-level SO_2 and NO_2)
- Ethylene oxide control efficiency from sterilizers
- Integrated NO_x sampling method
- Dilution sampling method for condensable particulate matter
- Mercury emissions from landfills
- Ozone depleting substances from low pressure chillers.

Environment Canada's measurement methods for mobile sources are identical to U.S. EPA methods. Currently Ontario is evaluating methods for isocyanate emissions from automotive coating (manufacturing and repairs), in cooperation with stakeholders.

4.7.3 Mexican Emission Measurement Methods

A listing of Mexico's reference methods for stationary sources is provided in Appendix B.

4.7.4 Continuous Emission Monitoring Systems (CEMS)

U.S. CEMS

CEM systems perform continuous measurements of pollutants emitted to the atmosphere from point sources. Typically, a CEMS combines a pollutant analyzer with a manual or software calculation tool that calculates and reports the mass, concentration, or rate of pollutant emissions. Primary driving forces for the use of CEMS are to support the acid rain allowance trading program and to demonstrate continuous compliance with emission limitations established at the federal and state level. The advantage of CEMS over stack testing is that emissions are measured under all operating conditions, including startup and shutdown, not just during a one steady-state operating condition. CEMS typically record and report emissions on an hourly basis. The data can be summed to calculate daily, weekly, monthly, seasonal, or annual emissions, or used as recorded for air quality modeling. While opacity monitors fall under the category of CEMS, they do not provide quantitative emission data and are thus not considered in this section. Table 4.5 provides an overview of representative CEMS technology.

The largest users of CEMS in the United States are EGUs, which are mandated by Title IV of the *Clean Air Act* (the Acid Rain Program or ARP) to reduce emissions of SO_2 and NO_x. The ARP uses an allowance-trading program (each allowance is equal to one ton of SO_2 emitted during a year) to ensure compliance with the emission reductions. Hourly CEMS data from EGUs provide the assurance that each allowance represents one ton. The ARP requires each EGU larger than 25 megawatts (with certain exceptions) to install CEMS for SO_2, NO_x, volumetric flow, and either O_2 or CO_2. The CEMS are subject to stringent certification requirements,

Table 4.5. Representative CEMS Technologies. Proven technologies exist for SO_2, NO_x, CO_2, CO, flow, PM, and opacity.

Pollutant	Measurement Principle	Status
SO_2	UV Absorption	Mature technology
NO_x	Chemiluminescence	Mature technology
CO_2	NDIR[a]	Mature technology
CO	NDIR	Mature technology
Flow	Various	Mature technology
PM	Light Scattering/Beta Attenuation	Mature Technology
Opacity	Light Transmission	Mature Technology
Hg total	Carbon tubes/CVAF[b]	Under development
Hg, total, speciated	Aqueous/AF[c]	Under development
NH_3	UV Absorption	Under development
Carbon Black	Multi-angle absorption	Under development

[a]NDIR = non-dispersive infrared absorption
[b]CVAF = cold vapor atomic fluorescence
[c]AF = atomic fluorescence

QA/QC procedures, and record keeping rules (40 CFR Part 75). The U.S. EPA's Clean Air Markets Division (CAMD) receives hourly data from over 2,600 units each quarter. These data are summed to calculate annual mass emissions of SO_2 for the ARP allowance trading program and used to provide annual emissions for the NEI, state, and RPO inventories from EGUs. The hourly data are available for use as inputs for atmospheric dispersion and deposition models.

The U.S. EPA has recently established the NOx Budget Trading Program to reduce ambient ozone levels in the eastern United States. This program, which affects EGUs and industrial boilers and turbines with fuel inputs greater than 250 mmBtu/hr (and cement kilns in New York), receives hourly NO_x emission data from more than 1,000 units each quarter. These hourly data can be used in the same manner as ARP hourly data for SO_2.

On March 10, 2005, the U.S. EPA issued the Clean Air Interstate Rule (CAIR) intended to assist states in meeting NAAQS for ozone and $PM_{2.5}$ by significantly reducing emissions of SO_2 and NO_x from electric utilities in 28 states in the eastern United States and the District of Columbia. This rule relies on a cap and trade program similar to that used in the acid rain program. It is expected that the CAIR rule will increase the number of electric utility sources that use CEMS for SO_2, NO_x, CO_2, and flow. In addition, the March 15 Clean Air Mercury Rule designed to reduce emissions of mercury from electric utilities also relies on a cap and trade approach. When implemented this rule will require the use of mercury CEMS.

CEMS are also required for 20 NESHAPS categories under 40 CFR 63 and four NSPS source categories under 40 CFR 60. Pollutants monitored under these standards are SO_2, NO_x, CO, TRS, VOCs, and THC. Performance specifications for these CEMS are specified in Appendix F to 40 CFR 60. In addition, many states require continuous emission monitoring of sources in addition to the federal requirements. For example, Pennsylvania requires the operation of about 500 CEMS in addition to those required under the federal ARP, NESHAPS, and NSPS programs. Because CEMS installed for NESHAPS, NSPS, and state mandates are used to monitor continuous compliance with emission standards, they generally measure pollutant concentrations, not mass emissions. Although the concentration data, in many cases, could be used to calculate mass emissions, this is generally not done and these data are not typically used in calculating emission factors or in emission inventories.

Canadian CEMS

CEMS implementation in Canada is generally specified by the certificate of approval or permit of the facility, which is issued by provincial regulatory agencies. The majority of CEMS are required to monitor process conditions linked to emissions, such as ozone and CO at municipal solid waste incinerators, wood waste combustors, cremators, and other sensitive sources. Mass emission-rate CEMS are installed at major sources such as thermal power stations, primary smelters, and cement plants.

Technical guidance for CEMS installation, certification, operation and data reporting in Canada is provided by the federal "Protocols and Performance for Continuous Monitoring of Gaseous Emissions from Thermal Power Generation" Report EPS 1/PG/7. Although this is a guideline for thermal power stations, the general principles can be adapted to other processes and have been referenced on numerous permits for other sectors. 1/PG/7 is currently under review, to update QA/QC provisions associated with SO_2 and NO_x budget programs.

At the provincial level, Alberta has developed guidelines similar to 1/PG/7, named "CEMS Code," and expanded their scope to include in-stack opacity, TRS, and CO. Alberta and Ontario require generating units with greater than 73 MW to report SO_2 and NO_x emissions on the basis of CEMS measurements.

Mexican CEMS

Currently, Mexican specifications pertaining to monitoring frequency are included in a standard called NOM-085-ECOL-1994 (DOF, 1997). According to this standard, only those facilities with combustion equipment larger than 110,000 MJ/hr are required to perform continuous emissions monitoring of NO_x emissions. Other regulated pollutants are monitored either one, two or three times per year, depending on the fuel used, the size of the combustion equipment and the nature of the pollutant. This standard is currently being revised and is expected to be updated soon.

4.7.5 Other Emission Measurement Methods

Several agencies in the United States and worldwide have developed additional emission measurement methods. Some of the first U.S. source testing methods were developed by the American Society of Mechanical Engineers (ASME). These and other ASME methods are called Performance Test Codes (PTCs). One of the first PTCs related to the abatement of atmospheric pollution was PTC 21, "*Dust Separating Apparatus*." PTC 21 was published in 1941. That was followed in 1957 by a stack testing method, PTC 27, "*Determining Dust Concentration in a Gas Stream*." PTC 27 and the similar Western Precipitation WP 50 procedure collected particulate matter isokinetically using a ceramic (alundum) thimble filter medium. These methods were used for performance evaluations of particulate removal equipment and for determining PM emission concentrations and mass emission rates. In 1965, ASME published PTC 28, "*Determining the Properties of Fine Particulate Matter*." This method included procedures for characterizing the properties of the particulate matter.

ASTM International (ASTM), originally known as American Standards for Testing and Materials, was formed over a century ago. It is one of the largest voluntary standards development organizations in the world. ASTM has developed stack-testing methods for a number of years, and continues to do so today. Some of the more recent ASTM stack testing methods are:

- D6331-98 Standard Test Method for Determination of Mass Concentration of Particulate Matter from Stationary Sources at Low Concentrations (Manual Gravimetric Method)
- D6348-03 Standard Test Method for Determination of Gaseous Compounds by Extractive Direct Interface Fourier Transform Infrared (FTIR) Spectroscopy
- D6420-99 Standard Test Method for Determination of Gaseous Organic Compounds by Direct Interface Gas Chromatography-Mass Spectrometry

- D6522-00 Standard Test Method for Determination of Nitrogen Oxides, Carbon Monoxide, and Oxygen Concentrations in Emissions from Natural Gas-Fired Reciprocating engines, Combustion Turbines, Boilers, and Process Heaters Using Portable Analyzers
- D6735-01 Standard Test Method for Measurement of Gaseous Chlorides and Fluorides from Mineral Calcining Exhaust Sources – Impinger Method
- D6784-02 Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro Method)
- D6831-02 Standard Test Method for Sampling and Determining Particulate Matter in Stack Gases Using an In-Stack, Inertial Microbalance.

These methods are produced by the ASTM D22 Subcommittee. The D22 Subcommittee has Work Groups that are assigned to specific methods. The U.S. EPA has been involved on some of the ASTM D22 Work Groups and has adopted some of the most recent methods as Reference or Alternative Methods. In addition to the published methods, ASTM D22 Work Groups are currently working on:

- Practice for Certification of Opacity Monitors for Low Level (<10%) Applications
- Continuously Monitoring Low Levels of NO_x, Carbon Monoxide and Ammonia
- Test method for Determination of $PM_{2.5}$ Mass and Species Emissions from Stationary Combustion Sources by Dilution sampling.

In addition to the consensus groups, ASME and ASTM, several U.S. state and local agencies have developed their own stack testing methods. Examples are the CARB, the Commonwealth of Pennsylvania, and the SCAQMD. Other states adopt U.S. EPA methods with some variation such as Maryland that requires the use of 70º F as standard temperature instead of 68º F as used by U.S. EPA. Many states have guidelines for stack testing and although they may not have specific methods, some of the state guidelines apply the U.S. EPA methods.

Section 12(d) of Public Law 104-113, the *National Technology Transfer and Advisory Act of 1995* directs federal agencies to use voluntary consensus standards, such as the ASME and ASTM standards noted above, in lieu of government-developed standards where possible. This law is implemented by Office of Management and Budget.

4.7.6 Predictive Emission Models (PEMS)

PEMS can be used in certain applications as a less expensive alternative to CEMS to provide hourly emission data. PEMS were developed as an outgrowth of process-control software that monitors and adjusts operating parameters to maximize process efficiencies. For environmental applications, the software can be modified to predict emissions of pollutants of interest from the same parameters monitored for system performance. In 2001, over 75 PEMS had been installed, the vast majority on gas-fired combustion turbines, with the remainder on gas-fired boilers and internal combustion engines. The majority of approved PEMS have been installed in Texas which allows PEMS to be used to report NO_x emissions from combustion turbines. To date, 80 percent of all approved PEMS across the United States have been used to measure NO_x.

PEMS can be classified as first-principles, statistical regression, and neural network models. A first-principles model calculates emissions based on the chemical kinetics and thermodynamics of the combustion or other process using the operating parameters of the system. Uncertainty analysis is generally not a part of a first-principles method. Regression models establish the relationship between emissions of a pollutant of interest, process operating parameters, and ambient conditions such as temperature and humidity based on a probability model. An error structure for the model is assumed (usually based on a normal distribution), allowing the estimation of error in the coefficients in the model and the propagation of error through the model into predictions made with the model. The method consists of two steps: (1) a model-fitting step that estimates model coefficients, and (2) a prediction step, where the model is used to estimate emissions. This

method facilitates conducting an uncertainty analysis at different levels, including model prediction error, parameter error, and random error. A neural network method infers emissions based on an established set of logic commands and causal linkages between emissions, operating and ambient parameters. Some neural-network applications involve statistical techniques. In a network, emissions are inferred from a set of linkages (defined by the user) that establish the relationship between how a combustion source is operated and the expected emissions. Unlike first-principles methods, neural networks require the user to establish "fault trees" or "event trees" consistent with standard engineering techniques. Uncertainty analysis is not generally performed in a neural network framework, but is conceptually possible.

The U.S. EPA's OAQPS and CAMD, the Texas Council on Environmental Quality, and SCAQMD have established or are developing PEMS performance requirements. All protocols require comparison of PEMS predictions to measured emission tests, relative accuracy tests, sensor drift limitations, and QA procedures.

Technical issues related to the accuracy, precision, and reliability of PEMS predictions include: the amount of paired PEMS/CEMS (or manual test) data to be collected at each condition for accuracy determinations; the definition of the operating envelope over which PEMS predictions are reliable; the startup, shutdown, and transient conditions (PEMS are designed for predicting emissions at steady state); the duration and timing of the demonstration period (e.g., combustion turbine operations differ by season); the frequency of relative accuracy testing.

4.8 DATA MANAGEMENT

Emission inventory data-management systems have changed dramatically over the last 20 years from older mainframe systems (such as the U.S. EPA's National Emissions Data System [NEDS] which later became the Aerometric Information Retrieval System [AIRS]) to simple spreadsheets (used initially to develop the U.S. EPA's National Emission Trends). AIRS can be accessed at http://www.epa.gov/Compliance/planning/data/air/afssystem.html. The NEDS data format was used to store U.S. EPA emission data including data developed for the 1985 NAPAP emission inventory. Current emission inventory data-management-system development efforts revolve around issues of database size, data usage, data accessibility, resources, and to a certain extent, the familiarity of the user/developer with certain database management software systems. Most of the large database management systems currently in use or in development are based on relational approaches that use structured query language (SQL) to retrieve, store, sort, and provide overall data handling and management. These systems typically reside on client/server networks. However, emission data are still managed with smaller systems including spreadsheets and smaller relational systems such as Microsoft Access.

The Canadian emission inventories are maintained in two different databases for storage, retrieval, and processing. The CAC emission data collected annually from industrial and commercial facilities through Environment Canada's NPRI are stored into the NPRI database. The NPRI database is a relational database available in Microsoft Access and in Microsoft SQL server for main storage. Copies of this point-source database, which includes information for more than 323 pollutants including CACs and heavy metals, can be downloaded at the following location: http://www.ec.gc.ca/pdb/npri/npri_dat_rep_e.cfm. The database can also be accessed using online querying and mapping tools available at the following locations: http://www.ec.gc.ca/pdb/npri/npri_online_data_e.cfm, http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm.

The comprehensive emission inventories for CACs, heavy metals, and persistent organic pollutants compiled to support the development of emission reduction policies, air quality modeling, and emission trends are stored in a separate relational database system called the Residual Discharge Information System. This database system was designed in 1998 and incorporates many of the features available from provincial and state database systems available at that time. This Microsoft SQL database was designed to handle multi-media emissions and provincial emission inventory information, which are submitted in various file formats. The database is not publicly available owing to confidentiality of the historical point-source information. Efforts are currently

underway to export the Canadian emission inventory data in the latest NEI Input Format (NIF).

A new Microsoft SQL database called OWNERS is currently being developed in Canada. This new database will provide one window for the Canadian industries to report their releases and other information required under different regulations online using a new electronic reporting form. The database will also merge the information from the NPRI and the Residual Discharge Information System databases, and is expected to be ready in 2005.

A National Emission Inventory Database System is being created in Mexico as a tool to help in the development, use, management and update processes of national inventories. This system will compile emission information from the Mexican NEI, the Mexican PRTR (*RETC*), and the GHG inventory, as well as inventories developed for the air quality management programs (PROAIREs) from cities throughout the country.

Development of the Emission Inventory Database System will facilitate

- Concentrating emissions information in a single source
- Providing user-friendly access to emissions inventories for environmental officials, researchers and the general public
- Institutionalizing the maintenance and update processes of the inventories
- Meeting deadlines of international agreements, such as those of the UNFCCC and the CEC.

This system will include data input, manipulation, QA/QC procedures, storage, accessibility, and dissemination. The different areas in SEMARNAT in charge of emission inventories are working together to address significant data management issues such as transparency, applicability, quality, quantity, accessibility, dissemination, and lag time of the stored data. The system is expected to start operations in spring 2006.

4.8.1 Data Transparency

Data transparency refers to the ability to easily access and understand data and the ability to use data in multiple database programs. Several efforts are currently underway to provide data transparency. In most data-management systems, the first step toward understanding data is the development of metadata. Metadata are "data about the data." Metadata describe the data in a database and assist users in understanding what the data elements represent.

Generally the next step is the development of a data dictionary. This step frequently depends upon how formal the database management system will be. If the data are likely to be stored in a spreadsheet or a stand-alone PC-based database management system, this step may not be required. However for relational databases, this step is virtually mandatory.

For example, the U.S. NEI is hosted on an Oracle relational database. Data are entered into the NEI using NIF. The NIF fully defines the data fields and their attributes necessary to submit and store data in the underlying database. The U.S. EPA has developed the NIF format in a precise manner so that data submitted by state, local, tribal and other reporting agencies can be stored in the database management system. Use of the NIF creates a relational, normalized data set that conforms to the relational standards and structure of U.S. EPA's Oracle database that stores the NEI data. This format avoids duplication of information that may otherwise occur in a flat file format, and it reduces the size of the resulting database. This format also provides flexibility to support the changing requirements of the U.S. NEI over time. The NIF is currently one of the most widely used formats by state, local and tribal agencies to report emission data to the U.S. EPA.

The NIF is divided into four source groups – point, nonpoint and nonroad mobile, onroad mobile, and biogenic. The table structure for the current NIF is shown in Table 4.6. The number of fields per table is shown in parentheses. These tables and fields contain the detailed information on emission sources, such as processes associated with the emissions, location, periods of operation, pollutants emitted to

Table 4.6. NIF 3.0 Source Tables.		
Source	**Tables**[a]	
Point	Transmittal (19) Site (20) Emission Unit (15) Emission Release Point (29)	Emission Process (23) Control Equipment (18) Emission Period (21) Emission (33)
Nonpoint and Nonroad mobile	Transmittal (19) Emission Process (21) Emission Period (18)	 Control Equipment (12) Emissions (27)
Onroad Mobile	Transmittal (19) Emission Period (12)	Emissions (17)
Biogenic	Transmittal (19)	Biogenic (13)
[a]The values in parentheses indicate the number of fields in the table.		

the atmosphere, and control technologies. Key fields provide the linkage between the many tables in the relational structure.

While the national data format is precisely defined, state, local, and tribal agencies may maintain their emission databases in formats that meet their own particular needs and still report data to the U.S. EPA using the NIF format. This is an example of data transparency. The format and characteristics of the data are fully described so that either submitters or users of the data may easily and straightforwardly send or receive data from the database management system. Such transparency can be important for entities outside of the United States. For example, data transparency may be of particular importance for Canada and Mexico and their development of national emission inventories. If all three countries used the NIF, it would be possible to develop a tri-national emission inventory. However, the use of the NIF by other countries is subject to each country's regulations and needs.

Other entities have gone different routes to ensure that their data are fully understood and to make sure that the user can readily obtain and use the emission data. For example, the Global Emission Inventory Activity (GEIA) has developed a standard format for storing emission data. Information on that format can be found on the GEIA data website at http://www.geiacenter.org/emits/geiadfrm.html. In addition to a description of the data format, GEIA also provides a tool to read their data into a series of arrays that can be used for pre-processing. Information on that tool is available at http://www.geiacenter.org/emits/geiadfrm.html#Program.

4.8.2 Data Applicability

One of the biggest issues in emission-data management is the applicability of the data. In some situations emission-inventory data management is relatively straightforward because the usage (applicability) is simple. In other cases the usage is multifaceted and complex. For example, the U.S. NEI provides an example of the complexity associated with data management issues of large, complex emission inventories. The NEI database is used for air quality modeling, human exposure modeling, risk assessment, regional compliance strategy development, and emission trends tracking. Because of these many demands on NEI, the data input requirements and data base have become very complex.

Other data applicability issues result from temporal, spatial, and species requirements. For example, the focus of the NEI has largely been on criteria pollutants at either an annual, seasonal, or daily basis. More recently HAPs have been added to the NEI, resulting in modifications to the database structure because the original structure was not designed to include HAPs in the database. Emissions in the NEI are limited to the U.S. states and territories, with point sources specifically located using latitude/longitude (or UTM) coordinates and nonpoint and mobile sources located within counties.

For GEIA, the focus is on global emissions of a wide variety of compounds/species that are available on a one-degree grid for the entire world. The data are reported with annual, seasonal or monthly resolution. Most data are provided for the surface level, but there is vertical resolution for some chemical emissions.

Recent evaluations of the use of the NIF for specifically locating wildfire emissions have shown some limitations of the format for these types of emissions. While the NIF as currently structured will largely work for most aspects of fire emissions, current thinking is that these emissions should be treated more like point sources than nonpoint sources. This shift has created issues with the current NIF structure, particularly the way that the NIF structure deals with plume characteristics of fires.

Other entities have found other limitations to the NIF structure. WRAP has recently embarked on the development of an Emission Data Management System, which is largely based on the NIF structure. However, in that effort, WRAP has developed modifications to the NIF structure to handle fires, meteorological and geographic information.

As another example, the current NIF structure is not particularly well suited for handling link-based mobile source data. Most mobile-source inventory data stored in the NIF currently are housed at the county level.

Under most current regional air quality modeling systems, emission data must be "pre-processed" for use in the model. Thus, most data management systems are not currently set up to handle "model-ready" data. To some degree, this is a consequence of the different input requirements of the air quality models.

Clearly, the application of the emission data plays a large role in determining the overall requirements of an emission data-management system. However, even when most of the applications of the data are known, the data may frequently be used in applications different from those originally intended. This can be clearly seen from the changes that the NIF has undergone over the last few years.

4.8.3 Data Quantity

The total amount of data that a database management system must store will frequently determine the characteristics of the system. Data requirements depend upon the types of data being stored, the period of time the emissions cover, and the data usage. For example, the amount of data received by the U.S. EPA from submitters to the NEI can be significant. A decade's worth of emission inventory data in the NEI requires approximately 50 gigabytes of storage space. This amount of data requires advanced data-management systems and capabilities. Local inventories for a county or municipality, on the other hand, can be housed effectively in a spreadsheet or a Microsoft Access (or similar) database management system, especially if the use of the data is limited to simple inventory needs rather than for air quality modeling.

Current trends have been toward larger and larger datasets. There are three reasons for this: First, the amount of computing power and data storage capacity that an individual or group has at their disposal has significantly increased over the last decade. Second, the tools with which to manage larger amounts of data have significantly improved. Third, the uses of the data have typically expanded. These factors have generally led to a significant increase in the quantity of data that many emission database management systems must handle.

4.8.4 Data Quality

Data quality has become an issue of increasing concern for emission inventory developers and users. Estimates of uncertainty and an understanding of the lineage of the data have become increasingly important for current inventory practices. This trend is particularly true for the NEI. For the NEI, state/local/industrial/tribal agencies frequently either do not collect the necessary data or do not have access to it. In those cases, the U.S. EPA may use surrogate data or use default values to fill in missing data. For example, for HAPs toxic release inventory data are often used to fill in missing or incomplete information. Data used for the development of

MACT standards have also been used as inputs for the NEI HAP data. Growth factors are sometimes applied to old NEI data in order to calculate emissions for more current years for NEI submittals. This data mix has resulted in inconsistent data of uncertain quality and inconsistent lineage.

Several attempts have been made to improve the understanding and the actual quality of emission inventories. For example, the U.S. EPA developed the Data Attribute Rating System, designed to assign qualitative numerical rankings to the various aspects of inventory development (such as emission factors or activity data) so that the overall quality of individual data elements could be ascertained. Specific guidance for applying the numerical ratings to these data elements was developed and the results were typically used to characterize which sectors of the inventory were of higher or lower quality than others.

Since implementing the NIF, the U.S. EPA has also attempted to provide QA tools for the actual data submitted to the U.S. NEI. As part of this attempt, the U.S. EPA has developed a program called the Basic Format and Content Checker. Based on ASCII text or Microsoft Access database inventory files, the program generates multiple reports identifying missing and invalid information in the submitted inventory. This check allows the submitter to make necessary data corrections early in the process, when the information is more readily available. After submittal, work is done to conduct additional quality checks on the data, fill in data gaps, and prepare the data for loading into the NEI database. Thus, the majority of state submittals still require extensive data manipulation efforts in order to be placed in the NEI. While the Basic Format and Content Checker provides a significant mechanism for ensuring that the data submitted are within likely bounds, and that the data are amenable to use in a relational database system (e.g., by checking for widowed and orphaned records), it does not address the lineage of the data received, nor does it address the mixture of data levels that can be submitted to the inventory. In addition, it is intended only for the NIF format and does not provide QA tools for other inventory data.

Environment Canada does not provide a quantitative estimate of the uncertainty for its emission inventories. Qualitative estimates are available and were included in the NARSTO PM Assessment (NARSTO, 2004).

Different QA/QC tests are performed on the information contained in the NPRI and Residual Discharge Information System databases. For example, the information collected through the NPRI is verified using a series of validation functions which are triggered within the electronic reporting form used by the industries. Similar validation functions are also applied to the information reported by the industries before it is transferred into the main database for storage and querying. These validation functions include:

- Verification of all required fields
- Verification of reported values to ensure that they are within expected ranges
- Comparison of new data to previously reported data for each facility.

Data outliers are identified and facilities are contacted to correct the data anomalies.

Verification of the information contained in the Residual Discharge Information System database is also performed on a regular basis. The provincial information received usually includes process-level information and undergoes the same validation functions as the NPRI data. Additional validation performed on this information includes:

- Verification that all CAC contaminants were estimated or reported
- Verification that emission levels are within the expected levels and ratios
- Verification that emission methodologies and emission factors reflect the most up to date information available.

4.8.5 Data Accessibility

In current systems, accessibility (including data dissemination) is largely an issue of making emission data more readily available on a quicker schedule than in the past, to a wide variety of users, and in

a format that is relatively transparent (or at least easily understood). However, there are other issues regarding data accessibility that may be important to specific user groups. For example, one user group may want to access emission data to make comparisons across geographical regions, whereas another user group may wish to obtain detailed emission data to be used in modeling applications. Consequently, data accessibility has varying definitions depending upon user needs.

Under current capabilities, the primary mechanism for data access and dissemination is the Internet. The U.S. NEI data and documentation are made available through the U.S. EPA's website: http:/www.epa.gov/ttn/chief/eiinformation.html. NEI data files on this website are in Microsoft Access format, and can therefore be used by people having access to the Internet and a PC. The amount of data present in the NEI requires the use of a robust PC and knowledge of Microsoft Access. The data are also available using file transfer protocol (FTP) sites. For large data sets, this is the quickest means of accessing complete data sets.

The U.S. EPA has also developed a series of programs with which NEI data can be accessed over the Internet. For example, the U.S. EPA has developed a user-friendly web-querying tool called NEON (NEI on the NET). This system allows users to access data down to the process level from the NEI. For example, NEON allows users to select the information that they wish to see, and the data can be output on screen or downloaded in Microsoft Excel spreadsheet format. In coordination with the SAS Institute, the U.S. EPA has developed the AirData system that provides color-coded geographic maps displaying varying intensities of air pollution. The SAS software allows users to map air pollution to the county level for all states for which data is present in the NEI. However, NEON is currently only available internally via the U.S. EPA intranet to EPA personnel. Future plans include providing public access to this information. In the meantime, a number of State and local agencies provide access to data they collect on their own websites.

The California Air Resources Board makes emission data available at http://www.arb.ca.gov/ei/emissiondata.htm. Emission data included on this website are onroad, offroad, stationary, area wide and top-25 source categories. In addition, data can be obtained on a statewide, air basin, county, or neighborhood geographical scale. Finally, the website also allows a user to search individual facilities for emission data.

As was stated in Chapter 3, there are numerous ways in which the U.S. EPA's TRI database can be accessed. For example, TRI data can be obtained by geographical area, industry type, or individual facility at http://www.rtk.net. TRI data can be obtained at varying levels of detail. For example, a user can select to obtain either low, medium, or high levels of detail when obtaining facility specific TRI data.

In Canada, accessibility and dissemination of emission information is also largely done through the internet on Environment Canada's Greenlane. The national emission summaries for CACs (with provincial and territorial breakdown) are accessible in tabular format at the following location: http://www.ec.gc.ca/pdb/cac/cac_home_e.cfm. Copies of the point-source database (in Microsoft Access format), which includes information for more than 323 pollutants including CACs, heavy metals, and persistent organic pollutants, can be downloaded from the following location: http://www.ec.gc.ca/pdb/npri/npri_dat_rep_e.cfm. Facility specific releases and the emission the summaries for various air pollutants are also accessible at various resolutions (national, provincial/territorial, postal code, major urban centers, community, user defined areas) using online querying and mapping tools available at the following locations: http://www.ec.gc.ca/pdb/npri/npri_online_data_e.cfm, http://gis.ec.gc.ca/npri/root/main/main.asp. The Canadian provinces also provide access to their emission summaries on their respective Internet sites.

4.8.6 Data Dissemination

While the NIF defines a particular format, agencies may submit the inventory in one of several different electronic formats: flat file, Access database, and eXtensible markup language (XML). XML is designed to store any kind of structured information and improve the functionality of the Internet by providing more flexible and adaptable information

identification. XML makes it possible for diverse computer systems (and data applications specifically) to share data stored in different formats across multiple computer platforms in a convenient fashion. XML makes it easy for a computer to generate data, read data, and ensure that the data structure is unambiguous across platforms, formats, and applications. XML enables a user to define a custom markup language for transferring data.

4.8.7 Data Lag Time

A major issue facing emission inventory data management is data lag time. As usage of the Internet and other "data now" capabilities increases, the expectation is that emission inventory data should also be available in real time. Current practices within the U.S. EPA generally show a lag time of several years between the actual date and the most recent inventory year of record. For example, in 2005 the most current version of the U.S. NEI was a draft emission inventory for calendar year 2002, a lag time of more than two years. This concurrency issue is perhaps one of the biggest problems facing inventory data management. Building the infrastructure necessary to successfully collect and calculate emissions from various sources in a time frame that is close to real time is a major challenge. Real-time emission data management is unlikely for many types of sources. However, the availability of real-time emission estimates for some point sources is becoming an increasing reality. The use of CEMs provides one example of the potential for real-time reporting of emission values. They also provide further support for the increase in the amounts of data being reported to regulatory and other agencies.

Legislatively imposed data-quality requirements in the United States may also limit the reductions in lag times. Data used in significant regulatory actions must undergo adequate QA/QC procedures, including external peer review. An evolution toward faster data accessibility may be possible, although users must recognize that immediately accessible data are more likely to contain errors. "Official" inventories that have been adequately validated and reviewed will likely continue to include significant processing delays.

These features -- data transparency, data applicability, data quantity, data quality, data accessibility, data dissemination, and data lag time -- prevent simple solutions to data management issues. However, over time, significant progress will be made toward addressing these future needs.

4.9 QA/QC METHODS

The IPCC provides definitions for both QA and QC as these activities relate to emission inventories. The IPCC defines emission inventory QA as follows:

> *Quality Assurance (QA) activities include a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process. Reviews, preferably by independent third parties, should be performed upon a finalized inventory following the implementation of QC procedures. Reviews verify that data quality objectives were met, ensure that the inventory represents the best possible estimates of emissions and sinks given the current state of scientific knowledge and data available, and support the effectiveness of the QC program) (IPCC, 2000).*

The IPCC provides a rigorous definition for QC as it pertains to emission inventories. Specifically, the IPCC definition sets forth three goals for QC systems:

> *Quality Control (QC) is a system of routine technical activities, to measure and control the quality of the inventory as it is being developed. The QC system is designed to:*
>
> 1. *Provide routine and consistent checks to ensure data integrity, correctness, and completeness;*
> 2. *Identify and address errors and omissions;*
> 3. *Document and archive inventory material and record all QC activities.*
>
> *QC activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardized procedures for emission calculations,*

measurements, estimating uncertainties, archiving information and reporting. Higher tier QC activities include technical reviews of source categories, activity and emission factor data, and method (IPCC, 2000).

In June 1997, the EIIP (IPCC, 1997) published a guide of QA/QC methodologies that can be employed for emission inventories (EIIP is a jointly sponsored effort by STAPPA/ALAPCO and the U.S. EPA; see Section 4.1 for more information). EIIP methodologies include, in order of decreasing complexity, reality checks, peer review, sample calculations, automated checks, sensitivity analysis, statistical checks, independent audits, and emission estimation validation.

The format of the emission inventory is a key driver in determining how QA/QC routines are applied. For example, an emission inventory built on the basis of a spreadsheet will have different QA/QC requirements than an emission inventory built around a database. The size of the emission inventory is also a driver to the type of QA/QC routines that are used. For example, automated routines may not be necessary for small inventories but are essential for regional or national ones.

Large emission inventories contained in databases are of particular concern due to their size and complexity. Three useful QA/QC methods for assessing the quality of an emission inventory are (1) examining the content of supplemental fields, such as SIC and NAICS codes, geographic location, and pollutant, (2) if there are multiple tables in a relational database, checking that correct parent-child relationships exist, and (3) evaluating the emission numeric values.

In the first method, one can check that those fields in the inventory that are required to have an entry do have an entry, whether it is valid or invalid. As a second step for those fields that are restricted to certain values, the entry can be compared to values in a lookup table. For example, the NAICS codes, SIC codes, and pollutants in the inventory can be compared to an acceptable list of codes or names. For locational data, the x- and y-coordinates of a point source can be checked to see if they lie within the boundaries of a geographic entity such as a county or state.

If the inventory is defined in terms of relationships between tables, in which there is an association between common fields in two tables, then the second method is used to check these relationships. For example, if there is a relationship between a table with geographic information for point sources and a table with emission values for those point sources, one can check that for each record in the table of geographic information there is at least one record in the emission table.

The third method of assessing an emission inventory is to examine the actual emission data by filtering the data with different criteria. These methods can be simple lists, statistical comparisons, or graphical methods. Lists of top emitters (facilities or sources at facilities) by pollutant can be compiled to determine if any of the emissions appear to be too large relative to the emissions of other facilities or points. Similar lists can be compiled by geographic region to determine if one region's emissions exceed those of other regions. If this appeared to be the case, then the list of top emitters, as described above, in that region could be examined. Emissions by a specific classification group, such as the NAICS, can be examined. Not only can the emission values be checked, but if specific pollutants are known to be associated with a classification, then the inventory can be checked to be sure there are no pollutants that do not belong to the classification. Graphical methods include frequency histograms to provide graphical representations of the distribution of the emissions that illustrate the distortion and spread of the data, as well as the presence of outliers. Another graphical aid displays emission density maps to see where the majority of the emissions occur. These ideas can be applied to a single inventory or comparing two inventories, such as one year to another, or one region (e.g., county) to another.

The U.S. EPA has developed two programs that perform varying QA/QC checks on incoming state NEI submittals. The first program, called the Basic Format and Content Checker is designed to QA/QC MS Access or ASCII submittals in Version 3 of the NIF. This program checks to ensure that mandatory fields are filled, that tables and field names are correct, and it also checks for duplicate data records. In addition, the program performs referential integrity checks to ensure that relationships between tables are

correct. Finally, as an option, the program can also perform contents checks. In this case, it compares reported values against those provided by lookup tables.

The U.S. EPA has also developed the Extended QA tool which is designed to review hazardous air pollutant and criteria air pollutant related data in NEI submittals. The Extended QA tool is used to examine actual emission data contained in NEI submittals. The tool can be used to identify top emitting facilities by geographic region or by NAICS/SIC code. Depending upon the availability of data, the tool can also analyze multi year emission data. This tool is particularly useful for identifying outliers within data submittals.

While objective methods for assessing an emission inventory can be developed, the analysis of the results from those methods require the intervention of someone familiar with the inventory to ultimately decide whether or not the data in the inventory are valid or need to be modified. Consequently, QA/QC tools are of importance, but the ultimate checks must be performed by those familiar with the sources and magnitudes of emissions.

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CHAPTER 5

STRENGTHS AND WEAKNESSES OF CURRENT EMISSION INVENTORIES

This chapter provides a qualitative assessment of the strengths, weaknesses, and uncertainties of current emission inventories. It provides a bridge between the first four chapters of this Assessment and the remainder of the report. Chapters 1 and 2 describe the issues that are forcing change in the content and structure of North American emission inventories, and they provide a vision of what these future inventories should look like. Chapters 3 and 4 describe the current status and content of North American emission inventories, and they review the tools and methods that have been used to develop them. The final four chapters focus on the future. Motivated by the shortcomings summarized in this chapter, the remainder of the assessment reviews new technologies for improving emission inventory content, discusses methods for assuring their quality and for quantifying their uncertainty, and provides a set of recommendations for achieving the standard of data quality, documentation, and accessibility that will be needed in the future.

Emission inventories are subject to substantial (and typically unspecified) levels of uncertainty, and this uncertainty affects the confidence one can place in the air quality management strategies that are based on them. Better knowledge of these uncertainties, as well as better characterization of the basic strengths and weaknesses of emission inventories in general, provides the basis for developing targeted and cost-effective strategies for improving inventories and, for improving air quality management.

Over the past 40 years, emission inventories have improved dramatically in terms of accuracy and completeness in Canada, the United States, and Mexico. Air quality managers have a good understanding of the major sources of emissions that affect air quality, and they have turned this

Chapter 5 Objective: ***To provide a qualitative assessment of the strengths, weaknesses, and uncertainties of current inventories so that emission inventories can be used with the appropriate level of confidence and areas needing improvement can be identified.***

Strengths

- The major sources of emissions that affect air quality are well characterized.
- North American emission inventories and models can provide quantitative estimates of emissions at national, state, or provincial, and county levels.
- Confidence is high in data on emissions of SO_2, NO_x, and CO_2 from electric generating units as the result of the development and deployment of CEMS at these facilities.
- Emission trends over time can be used to evaluate the effectiveness of control strategies and projects.

Weaknesses

- Quality assurance and quality control procedures are not strictly applied in the development of most emission models and inventories.
- Emissions for mobile sources and many important stationary nonpoint source categories are uncertain and inadequately characterized.
- Emission estimates are frequently based on a small number of emission measurements that may not be representative of real world activity.
- Insufficient information is available on chemical composition – of both PM and gases – for many sources.

knowledge into effective programs for reducing these emissions. In Canada and the United States, for example, significant reductions in emissions have been achieved over the past 30 years in spite of increases in population, gross domestic product, and energy consumption (see Figures 3.4 and 3.5 and the supporting references in this Assessment). Two major source categories, stand out in terms of improvement. Characterization of emissions of SO_2, NO_x, and CO_2 from electric utilities has improved significantly as the result of the development and deployment of CEMS that are the backbone of the successful acid rain cap and trade program (Werner and Mobley, 2005). Likewise, the characterization of mobile source emissions has improved as a result of the research that underlies models such as the MOBILE series of emission models developed by the U.S. EPA. Most current inventories or models can provide quantitative estimates of emissions at national, state, and county levels;and these inventories and models can be used to compare the significance of different source categories. Emission estimates from current inventories and models can provide insights regarding air quality trends over time, they can be used to track pollution, control efficiency, and they can help decision-makers develop air quality management strategies.

5.1 STRENGTHS OF CURRENT EMISSION INVENTORIES

While much of this chapter focuses on shortcomings of emission inventories and the tools used to construct them, it is important to place the weaknesses in perspective by recognizing some of the key strengths of modern inventories and tools. For example, an analysis of the U.S. NEI provides a big-picture view of the importance of various sectors to air quality in the United States by showing that: (a) stationary sources contribute the largest portion of total NO_x and SO_2 emissions and a considerable portion of VOC emissions, but a relatively smaller portion of total CO emissions; (b) mobile sources are the largest contributor to the total CO emissions and a considerable contributor to total NO_x emissions; and (c) biogenic sources contribute the largest portion of total VOC emissions (U.S. EPA, 1996; Placet et al., 2000). For the most part there is a high degree of confidence in these major insights.

Current emission inventories estimate emission trends over time and give some indication of the effectiveness of particular control strategies and projects. Emission inventories are also key inputs for air quality modeling, and they can be used to evaluate the effect of different pollution strategies on the ambient air quality. There is a high degree of confidence regarding some major changes in total emission inventories at the national level, such as reductions in SO_2 and NO_x from electric utilities in the United States associated with acid rain provisions of the *Clean Air Act Amendments of 1990*.

Inventories help decision-makers allocate resources and develop air quality management strategies. Knowledge of emissions contributed from different source categories helps decision makers set priorities for air quality improvement in allocating limited resources to those sources with the greatest potential to reduce emissions (Frey et al., 1999; Frey and Zheng, 2002). For example, in urban areas facing ozone problems, the relative importance of NO_x versus VOC control can be assessed taking into account both urban scale and regional geographic scales, and the key source categories that should be the focus of control efforts can be broadly prioritized.

Mobile-source emission inventories can be used as inputs to air quality models to simulate regional and urban dispersion of pollutants. They are also used in developing national, regional and urban emission inventories for criteria pollutants and toxic air pollutants. The MOBILE models are useful in evaluating regulatory strategies and state implementation plans, because they utilize an aggregate approach for wide areas under average conditions (NRC, 2000). The NONROAD model predicts exhaust emissions for HC, CO, NO_x, SO_x, PM, CO_2, as well as diurnal and refueling evaporative HC emissions, and the volume of fuel consumed by nonroad equipment except locomotives, aircraft, and commercial marine vessels. The level of detail from NONROAD includes fuel type (diesel, gasoline, LPG, and compressed natural gas), individual source category classification, power range, geographic area (nationwide, state, or county), and temporal (annual,

seasonal, monthly, weekday/weekend) for calendar years 1970 to 2050 (Harvey et al., 2003).

The success of past and ongoing emission control programs means that maintaining and improving future air quality will require emission reduction programs that are more focused on specific sources and pollutants. Developing these programs will require accurate and detailed knowledge of emissions from sources that are smaller, more widely dispersed, and more difficult to characterize. These needs will require improved inventories that fill information gaps and reduce emission uncertainties that have been less important in the past.

Table 5.1, which is based on a previous review of emission inventories (NARSTO, 2004), provides a qualitative overview of the level of confidence of these experts in emission inventories in Canada, the United States, and Mexico for four important pollutant classes: SO_2, NO_x, VOCs, and HAPs. This type of assessment is a useful starting point for summarizing the current state of knowledge regarding key components of emission inventories and for identifying the principal weaknesses that must be attacked if confidence in current emission inventories is going to be increased.

5.2 WEAKNESSES OF CURRENT EMISSION INVENTORIES

Qualitative assessments of emission inventory uncertainties, such as the one summarized in Table 5.1, have revealed a number of specific shortcomings and information gaps in the inventories of Canada, the United States, and Mexico. These problems are summarized below.

5.2.1 Quality Assurance and Uncertainties

Quality assurance and quality control procedures often are not strictly applied in the development of emission models and inventories, and the documentation of uncertainties and data sources in emission inventories is not adequate.

Strict quality evaluation during the development of emission inventories can reduce errors such as misclassification of sources or their mislocation. Many different agencies and stakeholders may contribute data to an inventory, and QA/QC procedures for evaluating emission data and key assumptions are not uniform or uniformly followed. In addition, uncertainties that can arise from measurement or sampling error are rarely characterized and reported. These problems are typical for all source categories whether the emission data are based on direct measurements or are estimated from emission models using activity and emission factors that are not always well documented in terms of uncertainty or pedigree.

Uncertainties are rarely or not rigorously quantified in emission inventories and models (NRC, 2004; NARSTO, 2004; Frey et al., 1999; Frey and Bammi, 2002). For example, almost no emission estimation models, including the widely used MOBILE and NONROAD models for mobile source emissions, and BEIS3 for biogenic emissions, contain a component that can assess uncertainty in model inputs and structure. Emission inventories developed based upon these models rarely quantify uncertainty in emission estimates. Although there are some examples in which uncertainties had been quantified for an emission inventory (e.g., Frey and Zheng, 2002; Zhao and Frey 2004; Hanna and Wilkinson, 2004), most of these examples are demonstrative case studies. In routine practice, uncertainties are typically ignored. The most readily available, and best known, information regarding uncertainty is the quality ratings of stationary-source emission factors listed by U.S. EPA in AP-42 (U.S. EPA, 2005).

5.2.2 Mobile Source Inventories

Significant uncertainties exist in mobile source inventories with regard to the magnitude of CO emissions, the temporal trend of NO_x emissions, the representativeness of the emission projections from MOBILE6, and the accuracy of emission estimates for nonroad sources. There are significant uncertainties in mobile source inventories particularly regarding the speciation of VOCs, the magnitude of CO emissions, and the temporal trend of NO_x emissions.

Table 5.1. Estimated Relative Confidence Levels of Emission Inventories.				
Pollutants	**Source**	**Estimated Confidence Levels in Overall Inventory**		
		Canada	**U.S.A**	**Mexico**
SO_2	Utilities	high	high	high
	Other point sources	medium	medium	low-medium
	On-road mobile	medium	medium	low
	Nonroad mobile	low-medium	medium	low
	Stationary nonpoint sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources (non-combustion)	low	low	low
NO_x[a]	Utilities	medium-high	high	medium
	Other point sources	medium	medium	medium
	On-road mobile	medium-high	medium-high	medium
	Nonroad mobile	medium	medium	low
	Stationary nonpoint sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources (non-combustion)	medium	medium	low
VOC[a]	Utilities	medium-high	medium-high	medium
	Other point sources	low-medium	low-medium	medium
	On-road mobile	low-medium	low-medium	low
	Nonroad mobile	low-medium	low-medium	low
	Stationary nonpoint sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources (non-combustion)	medium	medium	low
HAP	Utilities	medium	medium	medium
	Other point sources	low-medium	low-medium	low
	On-road mobile	low-medium	low-medium	low
	Nonroad mobile	low-medium	low-medium	low
	Stationary nonpoint sources	low	low	low
	Biogenic source	low	low	low
	Other man-made sources (non-combustion)	low	low	low
[a]NARSTO PM Assessment (NARSTO, 2004)				

MOBILE6 may under- or over-predict onroad emissions for certain pollutants from certain vehicle types. MOBILE6 is not user-friendly and requires users to research and write detailed input files. Even though this enables users to create highly detailed and specific input files, the process is time consuming, tedious, and error prone. The problems with CO emissions and NO_x trends are discussed in some detail in Chapter 7.

Existing onroad emission factor models, such as MOBILE, are not well suited to deal with mesoscale

or microscale emission estimates that take into account local effects of specific transportation control measures or highly resolved (both temporally and spatially) characterization of emission hotspots, such as at intersections. As such, these models are poorly suited for analysis of the impact of specific transportation improvement projects or for conducting corridor-level analysis. This shortcoming introduces substantial uncertainty in the assessment of future transportation improvements or controls with respect to air quality management (NRC, 2000). Mobile-source tailpipe emissions are also typically estimated based upon test procedures that are of limited duration (e.g., 10 to 40 minutes in many cases). These short-term tests may not be representative of emissions over a longer time period.

Other concerns with emission estimates for onroad mobile sources are:

- Standard test procedure measurements made using dynamometers, whether chassis or engine, may not adequately capture the effects of real-world conditions that could substantially affect emissions.
- Treatment of the effects of emission spikes that come from variability in engine loads and the importance that such spikes have in overall emission inventories are not adequately addressed (Barth et al., 1997; NRC, 2000; Hallmark et al., 2001).
- A disproportionate amount of emissions are typically attributed to a relatively small percentage of high-emitting motor vehicles (NRC, 2001); however, high emitters are probably not adequately treated by current mobile source emission models. High emitters are typically conceived to be older vehicles as well as newer vehicles that are malfunctioning in some manner.

Although nonroad sources are becoming an increasingly important part of total emissions, nonroad models are suspected of not accurately estimating emission inventories. There is also little information about the accuracy or uncertainty of such models (Frey and Bammi, 2002; NRC, 2004b).

5.2.3 Nonpoint Stationary Sources

Emissions for many important categories such as PM and their precursors, biogenic emissions, toxic air pollutants, NH_3, fugitive emissions, open biomass burning, and many other area sources are uncertain and inadequately characterized

Emissions from nonpoint stationary sources are much more uncertain than for criteria pollutants from stationary sources. The individual sources may be smaller and widely dispersed (Placet et al., 2000, Hanna and Wilkinson, 2004; Zhao and Frey, 2004; TNRCC, 2003; NARSTO, 2004). Or, as in the case of fugitive emissions, they may result from unknown sources or from offnormal operating conditions. In some cases, such as biogenic emissions, agricultural-related ammonia, or biomass burning, emissions may be from processes or activities that contain considerable inherent variability and are difficult to measure, characterize, and express in emission models.

The CMU Ammonia Model's activity data and emission factors for agricultural sources are uncertain. As described in Section 4.4.11 of Chapter 4, the CMU Ammonia Model is a database containing activity data and emission factors for NH_3 emissions. Agricultural operations are particularly large emitters of NH_3, and the identified weaknesses make emission estimates uncertain. However, as noted in Section 7.5, recent work has made progress in reducing this uncertainty.

Compared to other source categories, nonpoint stationary-source emission inventories have the highest uncertainty in emission rates (NARSTO, 2004). Because direct measurement of nonpoint stationary emission sources is resource-intensive (Placet, et al., 2000), nonpoint stationary-source inventories are constructed generally through calculations. In some situations, surrogates for emission and activity factors are used for emission estimates. The quality of the estimates depends on how well the surrogate activity factor correlates with the emission rate for the source.

5.2.4 Measurements

Emission estimates are frequently based on a small number of emission measurements that may not be representative of real world activity. Accordingly, the precision and accuracy of estimates developed from these measurements will be limited.

Because the number of measurements used either to represent a class of sources or to develop emission and activity factors is always limited, the sample data set may not be large enough to provide a statistically robust estimate (NRC, 1991; 2000; 2001; 2004b; GAO, 2001; Placet et al., 2000; Mangus, 1997; Barth et al., 1997; NRC, 2000; Hallmark et al., 2001). Even for CEMS-based emission estimates, CEMS are not available for all pollutants (e.g., less than 1 percent of the CEMS at large point sources measure hydrocarbon emissions or toxic air pollutants). In addition, some CEMS do not record measurements during startup, shutdown, or upset conditions. Moreover, bias errors can be introduced when CEMS are temporarily out of service or if there are missing data (typically a default maximum emission estimate is used to fill in for missing data).

Uncertainties arising from measurement error are often ignored. Because of imperfections in instruments and procedures, measurement errors inevitably appear in emission data. However, current emission inventories rarely report how measurement errors affect emission estimates. Even when some types of errors are acknowledged, such as detection limits, the methods used in practice are often simplistic and subject to bias. This is especially important for pollutants such as HAPs that are emitted at very low concentrations. Uncertainty arising from measurement error is typically not characterized or systematically reported, and yet is a key component of uncertainty especially for these pollutants.

Emission factors typically should not be used to estimate emissions for individual sources because they are based upon averages from multiple sources. The use of emission factors for estimating emissions of a single source could occur when estimating emissions for a permit or when dealing with a geographic area that has only one emission source of a particular type. Because of inter-individual variability among sources, which implies that the emissions of any individual source could be much smaller or larger than the average, the use of an average emission factor applied to a particular source could be subject to a large error.

Most emission inventories generally do not include emissions from startup, shutdown, malfunctions, or accidental releases. For some facilities in some areas (e.g., Houston), these emissions can dominate the emissions from typical or normal operations.

5.2.5 Spatial and Temporal Allocations

The process for developing information on emissions with the degree of spatial and temporal resolution needed for location-specific air quality modeling is problematic, and it is a source of unquantified uncertainty in model results

Emission inventories do not provide emission data at the spatial and temporal scale needed for air quality modeling (NRC, 2000; Sawyer et al., 2000; NARSTO, 2000; 2004). Emission estimates with the required spatial detail and temporal resolution are provided by emission processors that are based on a variety of assumptions. Emissions from smaller point sources, stationary nonpoint sources, and mobile sources are a particular problem. As mentioned previously, emission factors, for example, are typically based upon averages of many representative sources. They are not intended to be used to estimate emissions from individual sources, and doing so can result in significant errors. In addition, the averaging times used to generate emission factors are typically different from the time resolution required by air quality models. This mismatch is a source of additional error and uncertainty. Finally, current mobile source models are not designed to provide the kind of mesoscale and microscale source distribution needed to account for emission hotspots, such as intersections or high-traffic corridors. Similar problems exist for emissions of toxic air pollutants.

Emission factors should not be used to estimate emissions for averaging times that are substantially different from the temporal or activity basis of the measurements upon which the factors are based. For example, using emission factors based upon the average of a few days of operation can be problematic

when applied to estimating annual average emissions. Allocation of mobile source emissions both temporally and spatially, such as required for gridded air quality models, involves assumptions for which data may be lacking and thus introduces additional uncertainty (Sawyer et al., 2000; NARSTO, 2000).

5.2.6 Speciation

Insufficient information is available on chemical composition – for both PM and gases – for many sources. Methods used to estimate emissions of individual chemical species in many emission models are out of date and produce estimates that are not reliable.

It is well known that many speciation profiles in the U.S. EPA's SPECIATE program date back to the 1980s. U.S. EPA has identified VOC and PM on- and offroad chemical speciation profiles as being the most out-of-date and the most likely to have changed. This is an especially serious problem in all three countries.

Many emission factors contained in the U.S. EPA's FIRE program are out of date. In addition, no guidance is provided to developers of emission inventories regarding the applicability of an emission factor to specific sources.

5.3 CONCLUSIONS

From the preceding overview of the reliability and shortcomings of current emission inventories and tools, Several important conclusions can be drawn from the preceding overview of the reliability and shortcomings of current emission inventories and tools

First, in using emission inventories to develop air quality management policies and control strategies it is critical to evaluate the robustness and reliability of the conclusions drawn from the emission inventory data. In general, criteria pollutant emission data from large stationary sources are more accurate than emission data from smaller sources or emission data on individual toxic chemical species.

Second, most of the low-hanging fruit has been picked. Whereas there are large quality assured databases of criteria pollutant emissions from stationary and mobile sources, few reliable data are available for fine PM, toxic air pollutants, and NH_3. The data that do exist for these pollutants are generally derived not from direct measurements, but from models that frequently rely on limited out-of-date data, and which are rarely subject to analyses of uncertainty.

Third, although mobile source emission models are useful in evaluating regulatory strategies and state implementation plans, they are not accurate enough to provide the kind of information needed to characterize emissions on the local scale or to provide accurate information on VOCs, fine PM, and toxic air pollutants.

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CHAPTER 6

INNOVATIVE TECHNOLOGIES AND APPLICATIONS

Chapter 6 Objective: ***To examine evolving and prospective future methodologies for emission measurement, data analysis, and data archival.***

Chapter 5 described strengths and weaknesses of current emission inventories. Addressing the weaknesses of inventories and of the methodologies used in developing them has been an important technical activity for at least two decades. It has led to major advances in measurement and observational capabilities, as well as improved modeling and interpretative methods. In addition to these advances, modern information-management techniques offer the opportunity for greatly improved inventory accessibility and transparency. Chapter 1 noted that contemporary research offers new and evolving techniques that are potentially applicable for developing and/or verifying emission inventories, and that these methodologies should be considered for broad application in the future. This chapter provides a brief overview of these techniques.

Three general aspects of these techniques and methodologies are noteworthy: First many, if not all, of the methods discussed here are not really "new;" indeed, most have been in existence in one form or another for a number of years. Receptor modeling and plume measurement by ground-based optical remote sensors, for example, have been evolving for some time. Other techniques, including satellite remote sensing and inverse modeling, are relatively new to air pollution analysis, though the latter has experienced extensive application in other fields. Key points to note in this respect are that the selected methodologies are evolving in application, leading to new approaches for emission inventory analysis. It is important that workers in the emission inventory field monitor these developments, and take advantage of their capabilities to address weaknesses in the historical approaches to inventory development.

The second noteworthy aspect is the fact that the potential for innovative application often lies more in a combination or integration of two or more of these technologies, rather than in isolated deployment of a single technique. Creative combinations of aircraft remote-sensing measurements, ambient concentration observations, and demographic or source data from a well-designed field campaign with an inverse-modeling analysis, for example, can reveal substantial information regarding specific emission sources.

Third, many of the technologies discussed in this chapter were not developed specifically for emission inventory application, but subsequently have proven useful for emission analysis. The emission inventory community needs a process that is more direct and focused than this largely happenstance approach. Accordingly, an active dialog between emission inventory developers and scientists involved in adopting measurement and interpretive methodologies is vital. Inventory developers need to increase their awareness of technological developments related to their field; but more importantly, they also should think creatively about their future requirements and communicate these requirements to their counterparts so that future development occurs less by chance and more by intentional design. A dialog between emission inventory scientists and those developing sensors for satellites is a prime example of such an interaction. The sections of this chapter discuss examples of these evolving methodologies as a starting point for developing better inventory-development techniques.

6.1 OBSERVATION AND MEASUREMENT METHODS

Advanced measurement capabilities can address many of the weaknesses in current emission inventories described in Chapter 5. Important applications for new observational opportunities include:

- Seeking complementary and efficient approaches to conventional stack and effluent testing, including compositional data
- Expanding the use of a variety of ambient concentration data to cross-check inventory estimates and provide quality-control options
- Establishing a linkage with "real world" sources, including vehicle fleets, compared with idealized emission conditions
- Expanding spatial and temporal data for mobile and area sources to improve emission models
- Providing direct measurements of biogenic and fugitive emissions for incorporation into emission models
- Providing a basis for determining whether long-term, estimated emission trends are consistent with ambient concentrations.

This section describes a number of evolving observational and measurement techniques having emission inventory applications, summarizing them in sufficient detail to give the reader a basic idea of their measurement principles, their future potential, and their limitations. As is readily apparent in the following sections, some of these methods are much more complex than others, and require more extensive descriptive detail to convey their features. These differences are reflected by the selected lengths of the individual descriptions presented below, which are arranged in descending order of complexity and attendant descriptive detail.

6.1.1 Remote Sensing

Remote-sensing techniques (cf. Stephens, 1994; Finlayson-Pitts and Pitts, 2000) fall into a number of classes depending on the type of sensing signal applied (e.g., electromagnetic or sonic), electromagnetic wavelength range (ultraviolet, visible, infrared, or microwave),[1] whether the method in question observes spectrally disperse or broadband radiation, whether it has ranging capabilities, and the type of signal detected (e.g., absorption, light scattering, fluorescence, . . .). Several systems within these categories have been deployed to determine emissions from both stationary and mobile sources, using surface, aircraft-based, and satellite-mounted sensors.

In general, remote-sensing chemical measurements sense path-integrated loadings, or at best (in the case of ranging measurements), ambient concentrations. Deriving actual emission rates from these data requires either knowledge of concentration distributions along a sight path and a direct or indirect indication of flow velocity, or else the use of index species (such as CO_2) in conjunction with process-stoichiometric calculations. In some cases, such as satellite or aircraft surveillance, an air quality model is required to infer emission rates. Although these deficiencies may be resolved during future years by application of advanced techniques such as tomography for path-measurement reconstruction and laser, microwave, and/or sonic anemometry for flow measurement, they should be borne in mind as significant issues in the present context.

Electromagnetic radiation remote-sensing applications fall into several categories, the most important of which are summarized as follows:

Absorption Spectroscopy. Open-path, absorption-spectroscopy techniques produce path-integrated measurements, and monitor attenuation of a light beam as it transects the sampled atmosphere. As

[1] Light absorption and emission by molecules and atoms occurs as a consequence of energy transitions between quantum states, and thus individual pollutants have characteristic spectroscopic signatures, which can be used for their identification and measurement. Individual "signatures" often dictate which portion of the electromagnetic spectrum is most appropriate for measuring a specific pollutant. Because of its comparatively high photon energy, the ultraviolet/visible portion of the spectrum is associated mainly with transitions between electronic energy levels. Lower-energy infrared radiation is associated with energy transitions between various molecular vibrational and rotational energy states; microwave radiation, which has even lower photon energy, interacts mainly with rotational transitions. These features usually dictate the choice of one technique versus another for observation of a specific pollutant. One should note that besides these molecular-level interactions, radiation can be scattered physically through interactions with atmospheric density fluctuations, airborne particles and precipitation elements.

such they require a sensor viewing a remotely located radiation source, or else a source co-located with its sensor, viewing a remote reflector.

Variants of absorption spectroscopy include non-dispersive infrared (NDIR) techniques, which measure the attenuation of a broadband radiation source by the sampled medium. This approach is applicable to pollutants such as CO, whose broadband absorption spectrum dominates those of other gases in specific spectral regions. Dispersive techniques, in contrast, typically deploy a continuous light source and a detector incorporating a diffraction grating to disperse the incoming radiation according to wavelength, or else a laser light-source which may be tunable over a limited wavelength range. Variants of these methods include Fourier transform infrared (FTIR) methods, which use an interferometric sensing approach to generate a Fourier transform of the spectral signal, and thus can monitor the entire spectral range essentially simultaneously. Because of its spectrally resolved approach, FTIR can measure emissions of a large variety of compounds. Yokelson et al. (1997), for example, applied FTIR to measure formaldehyde, ethanol, acetic acid, ethene, propane, propanol, HCN, CO, CO_2, CH_4, and NH_3 emissions from combustion processes. Another technique, differential optical absorption spectroscopy (DOAS), applies a broadband light source, disperses the incoming signal into a resolved spectrum, and applies an interpolation process to estimate the spectral background, which is subtracted from the total spectral signal to obtain the pollutant-induced component. Both FTIR and DOAS can operate in a passive mode, using natural light sources such as the sun or moon. Positioning requirements, however, generally dictate the use of active techniques in the case of pollutant emission analysis.

Tunable diode laser spectroscopy is another absorption spectroscopic technique with a high potential for application in emission assessment. As its name implies, this technique employs an (infrared) laser light source, whose frequency output is adjustable over a specific wavelength range. Tunable diode laser spectroscopy offers the advantage of very highly resolved spectral resolution but has the disadvantage, compared to FTIR, of limited wavelength ranges attainable by the tunable sources.

Fluorescence Spectroscopy and Raman Spectroscopy. Fluorescence-based methods transmit a light beam through the sampled atmosphere to induce electronic excitation of pollutant molecules, which emit radiation when transitioning back to their ground states. The emitted radiation is monitored by a sensing device, providing a measure of pollutant concentration or pathway loading. Excitation of specific molecules, as well as their resulting fluorescence, is wavelength-specific; thus single- or dual-wavelength lasers, selected for the specific pollutant of interest, are applied most often for this purpose. In their simplest form, open-path fluorescence-based methods produce path-integrated results, but can incorporate ranging when applied in conjunction with lidar systems (see below). Raman spectroscopy operates in a manner somewhat similar to standard fluorescence spectroscopy. Here, however, the frequency of the incident light beam is shifted to a (usually) lower value by extraction of a portion of the photon energy through interaction with the sampled medium.

Light Detection and Ranging (lidar). Lidar is based on projecting a coherent light beam through the sampled air volume and monitoring the return signal, which results from light scattering by the target pollutant material. In contrast to the methods described above, lidar has a range-gating capability, which allows generation of pollutant-profile information at relatively fine intervals (down to about 3 m). Single-wavelength lidars have been applied since the 1960s to remotely sense PM concentrations, and more elaborate, multi-wavelength lidars (e.g., differential absorption lidar) have been applied increasingly to measure spatial distributions of trace gases. A Raman spectroscopy lidar variant also has been applied during recent years.

All of the techniques described above must address issues of sensitivity and specificity, which are highly species- and technique-dependent but of some concern in practically all cases. The associated equipment tends to be expensive and in many cases requires highly experienced operators. Moreover, and as discussed above, these detection methods generally depend on ancillary effluent flow measurements or on inferred flows based on modeling or stoichiometric ratioing techniques to determine actual emission rates. The following sections, which discuss remote

sensing from satellite-, aircraft-, and surface-based platforms, provide some examples of these issues and their resolution.

6.1.1.1 Satellite Remote-Sensing Applications

Measurement and Interpretive Bases

Although satellite measurements of surface features such as vegetative ground cover,[2] surface temperature, and ocean activity are of some interest in an emission inventory context, actual pollution loadings are of more direct utility and provide the most difficult challenges. Consequently these applications will be emphasized here. Up to now satellite observations of trace gases and PM in the troposphere have been confined largely to passive, downward-looking, spectrally resolved techniques. These techniques observe energy emanating from the surface or the atmosphere and derive concentrations and/or column densities from the amplitudes of spectral lines at specific wavelengths associated with the pollutant molecules of interest. Currently operational (and most planned) measurements are made from low Earth orbit, providing a swath of data during each orbit with individual measurements on spatial scales of tens to hundreds of kilometers (cf. Figure 6.1).

Perhaps the best known applications of satellite measurements for emission estimation involve the imaging of the planet surface to identify the location and intensity of smoke sources, ship plume tracks, major industrial plumes, and incidents of dust storms or regional haze. These visual images have aided in identifying potential source areas of interest for smoke and haze emissions and transport. However, they are extremely limited in their ability to provide quantitative data. Important progress has been made recently in using the satellite data to infer pollutant column concentrations or densities, and continental-scale emissions.

Although satellite applications for determining trace-gas and PM emissions must deal with numerous

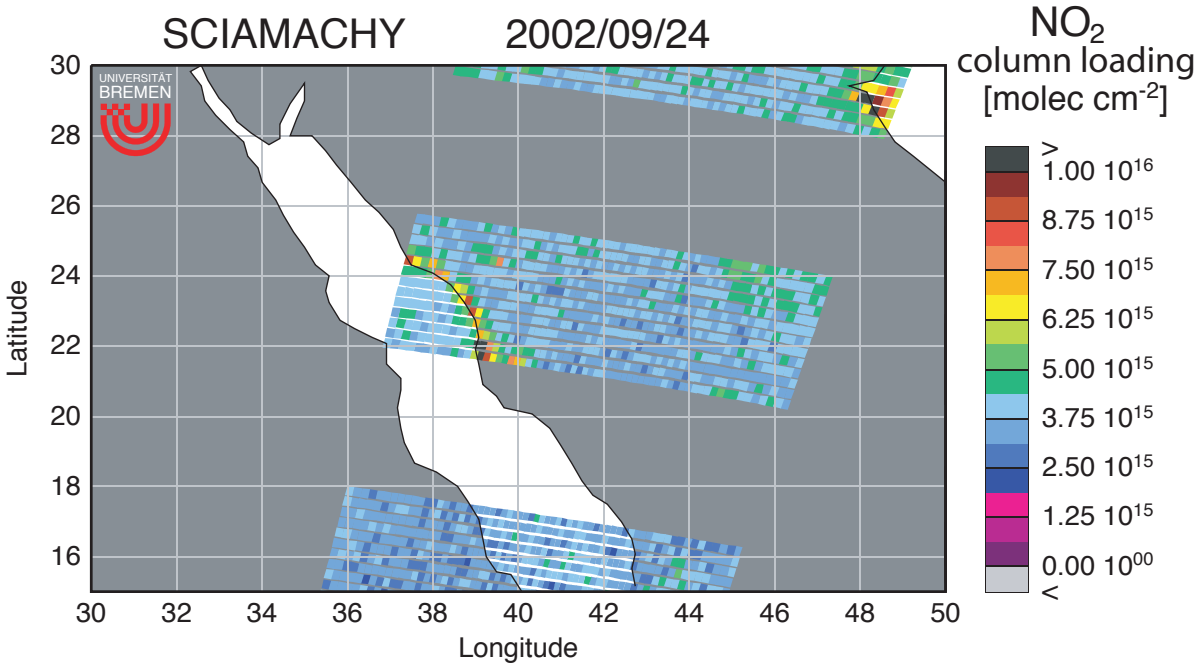

Figure 6.1. Tropospheric NO_2 column densities in the Red Sea/Arabian Gulf area derived from SCIAMACHY data for September 2002 (after Richter, in Borrell, et al. 2004). Emissions of NO_x from isolated, individual cities such as Jeddah, Mecca, Medina, and Kuwait City are easily identified, based on the conventional assumption that NO_2 is a surrogate for NO and NO_2.

[2] LANDSAT data have been used on a regional scale, for example, to support evaluation of changes in biogenic emissions in central California (Tanner et al., 1992).

technical challenges, their ability to cover large, typically global, spatial domains provides a major advantage not shared by other approaches. This global coverage encourages the application of European, as well as North American satellite observations for emission evaluations over large areas of the NARSTO domain.[3] The European research community is making considerable progress in this field (Borrell et al., 2004), and indeed data from European satellites are being applied currently for interpretation of North American emissions (e.g., Palmer et al., 2003a).

Many of these observations are based on UV or visible light reflected or backscattered from the surface or from clouds, and derive vertical-location estimates from the spectral-line widths, which result largely from pressure broadening. These techniques are available only during daylight hours and provide no information at night. Other passive techniques operate in the infrared portion of the spectrum, which is available continuously throughout the day and night. Usually, vertical location is derived from infrared (IR) measurements based on the variation of radiative properties with atmospheric temperature, thus vertical temperature structure is an important data-processing consideration. Satellite PM observations have been demonstrated using lidar, an active technique which can provide detailed vertical information under most conditions. Lidars produce sparser horizontal data sets than passive systems because greater instrument energy is required.

Typically, the inference of emission rates from satellite measurements is derived in two general steps: (1) retrieval of lower-atmosphere pollution concentrations from the raw satellite data and (2) estimation of emissions on the basis of this near-surface information, usually in conjunction with ancillary data and interpretive calculations. Substantial processing is required in the retrieval stage to convert raw satellite data into useful products, such as concentration patterns, column densities, and optical depths, and the retrieval algorithms applied for this purpose tend to be complex. Estimation of emission rates from retrieved satellite products also requires substantial processing and interpretive effort. The following subsection gives several examples of different approaches in this general area.

Satellite-based measurement of tropospheric pollutants presents several technical challenges. These include compensating for variations in the air chemistry matrix, aerosol burden, cloud cover, surface albedo, and temperature, as well as dealing with masking effects of the stratospheric overburden, which can be dominant. Satellite measurements beneath cloud cover are virtually impossible with present technology. Moreover – with the exception of lidar – attempts to resolve measurements vertically typically depend on interpretation of secondary effects such as pressure broadening and temperature influences, thus limiting the resolution of vertical structure. In fact, satellite-based trace-gas measurements have not yet resolved even two separate layers in the troposphere. Further, satellite instrument sensitivity is often a strong function of altitude. Thus, each instrument has its own characteristic averaging kernel for each species, which defines the altitude dependence of its sensitivity. As a result, retrieval of integrated concentration profiles requires information regarding the species' vertical distribution, and leaves a significant uncertainty regarding the derived quantities. These features combine to result in highly species-specific retrieval algorithms, and limit the number of tropospheric pollutants that can be observed reliably; however, this limited set includes important pollutants such as PM, and a number of key secondary-pollutant precursors.

Table 6.1 summarizes existing, planned, and feasible satellite-based tropospheric trace-gas and PM measurements by the U.S. National Aeronautics and Space Agency (NASA) and the European Space Agency (ESA). Future measurement systems that are feasible with current sensor technology include geostationary trace-gas measurements, which can provide essentially continuous coverage (many observations per day over the same location) at high horizontal resolution. As indicated by Table 6.1, satellites currently in use revisit portions of the globe only periodically, usually at the same time of day, and thus provide less temporal coverage than is usually desired. This issue may be resolved during

[3] More comprehensive information on North American and European satellite programs is available on the NASA and European Space Agency (ESA) websites: www.earth.nasa.gov/ese_missions/satellites.html and envisat.esa.int.

Table 6.1. Selected Past, Current, and Future Remote Sensing Instruments used to Determine Amount and Distribution of Constituents in the Troposphere.

Instrument	Name	Vertical extent of measurement	Horizontal resolution, domain	Temporal revisit	Target Constituent/Property for Air Quality	Platform
Current and past instruments						
GOME	Global Ozone Monitoring Experiment	Troposphere and Stratosphere	40 x 40 km^2, 40 x 320 km^2 swath	Once every 3 days	Tropospheric columns for O_3, NO_2, BrO, SO_2, HCHO, clouds and aerosols	ESA-ERS-2 (1995-present)
MODIS	Moderate Resolution Imaging Spectroradiometer	Surface to space	0.25 - 1 km , 2330 km wide swath	Once 1-2 days	Aerosol column optical thickness, aerosol type (sulfate, biomass burning) over land	NASA Terra (1999) NASA Aqua (2002)
MISR	Multi-angle Imaging SpectroRadiometer	Surface to space	0.275 -1.1 km, 141 x 563 km^2 swath	Once every 9 days	Aerosol properties (angular radiance dependence)	NASA Terra (1999)
MOPITT	Measurement of Pollution in the Troposphere	Tropospheric columns, layers	22 x 22 km^2, 22 x 640 km^2 swath	Once every 3 days	Total column of CO, CH_4 ; CO layers	NASA Terra (1999)
SBUV-2	Solar Backscatter Ultraviolet Ozone Experiment 2	Stratospheric profiles	200 x 160 km^2	Daily	Stratospheric O_3	NOAA-9 (1985-1998) NOAA -11 (1989-94, 1998-present) NOAA-14 (1996-present) NOAA-16 (2000-present)
SCIAMACHY	SCanning Imaging Absorption spectrometer for Atmospheric ChartograpHY	Tropospheric columns	30 x 30 km 960 km swath	Once every 3 days	Tropospheric columns for O_3, NO_2, N_2O, CO, CH_4, SO_2, HCHO, clouds and aerosols	ESA Envisat (2002)
OMI	Ozone Monitoring Instrument	Stratospheric profiles, Tropospheric columns	48 x 48 km^2	Once per day	Tropospheric columns for O_3, SO_2, HCHO, NO_2, and aerosol	EOS Aura (2004)
TES	Total Emission Spectrometer	Stratospheric profiles, Tropospheric layers	26 x 42 km^2	~ once every 2 days	Tropospheric columns for O_3, NO_y, CO, SO_2, CH_4	EOS-Aura (2004)

Table 6.1. Concluded.

Instrument	Name	Vertical extent of measurement	Horizontal resolution, domain	Temporal revisit	Target Constituent/Property for Air Quality	Platform
Future instruments scheduled to be launched						
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	Stratospheric profiles, Tropospheric profiles	0.3 x 0.3 km^2	Not operated continuously	Aerosol column loading and radiative properties	NASA CALIPSO (2005)
Geo-TRACE	GEostationary Observatory for TROpospheric Air ChEmistry	Tropospheric layers	4 x 4 km^2, 8000 x 4000 km^2 (entire North American continent)	Once per hour	Tropospheric columns for O_3, NO_2, SO_2, HCHO, CH_4, , clouds and aerosols: tropospheric columns and layers for CO	Potential future NASA Earth probe
Geo-SCIA-MACHY	Geostationary SCanning Imaging Absorption spectrometer for Atmospheric ChartograpHY	Tropospheric layers	25 x 25 km^2, entire Earth disk, European view	Twice per hour	Tropospheric columns for O_3, NO_2, H_2O, SO_2, HCHO, CH_4, CO, clouds and aerosols	Potential future ESA mission

future years for both North America and Europe by the deployment of sensors on geostationary satellites, providing almost continuous temporal coverage (see Geo-TRACE and Geo-SCIAMACHY in Table 6.1). Finally, satellite observations typically report data in terms of average concentrations, column densities, or derived quantities such as optical depth; thus, any inference of emissions from such products necessarily depends on the application of inverse modeling, or some other interpretive technique.

Example Applications

The objective of this section is to provide the reader with an initial appreciation of available satellite products, and to demonstrate these products' potential applicability for emission assessment. Figure 6.1 provides a simple example for an initial approach to this objective. Here, observation swaths from ESA's SCIAMACHY show tropospheric NO_2 column densities observed in the vicinities of some Middle Eastern cities. Because of these cities' isolation from confounding sources, this image immediately suggests that local NO_x emission rates could be inferred from these data in conjunction with observed winds and using chemical-transport model analysis to simulate NO_x chemistry.

Figure 6.2 shows tropospheric column densities of selected pollutants obtained from a variety of North American satellite sensors (Neil, Fishman, and Szykman, 2003). Such data provide a more complicated (but also more typical) example of large-scale burden patterns. If these burdens are confined to the planetary boundary layer, for example, they can be used with an air quality model for semi-quantitative, large spatial-scale source allocation. These plots indicate the potential complexity of inferring emission rates from continental data, which reflect long-range transport and multitudes of individual sources. The following paragraphs present some examples of studies where inroads are being made in this area.

Given the measurement challenges noted above, emission assessments using satellite-derived products are currently at a relatively nascent, but evolving, state. Interpretive work has consisted largely of studies wherein satellite-based column loadings of a pollutant or its reaction product are observed and

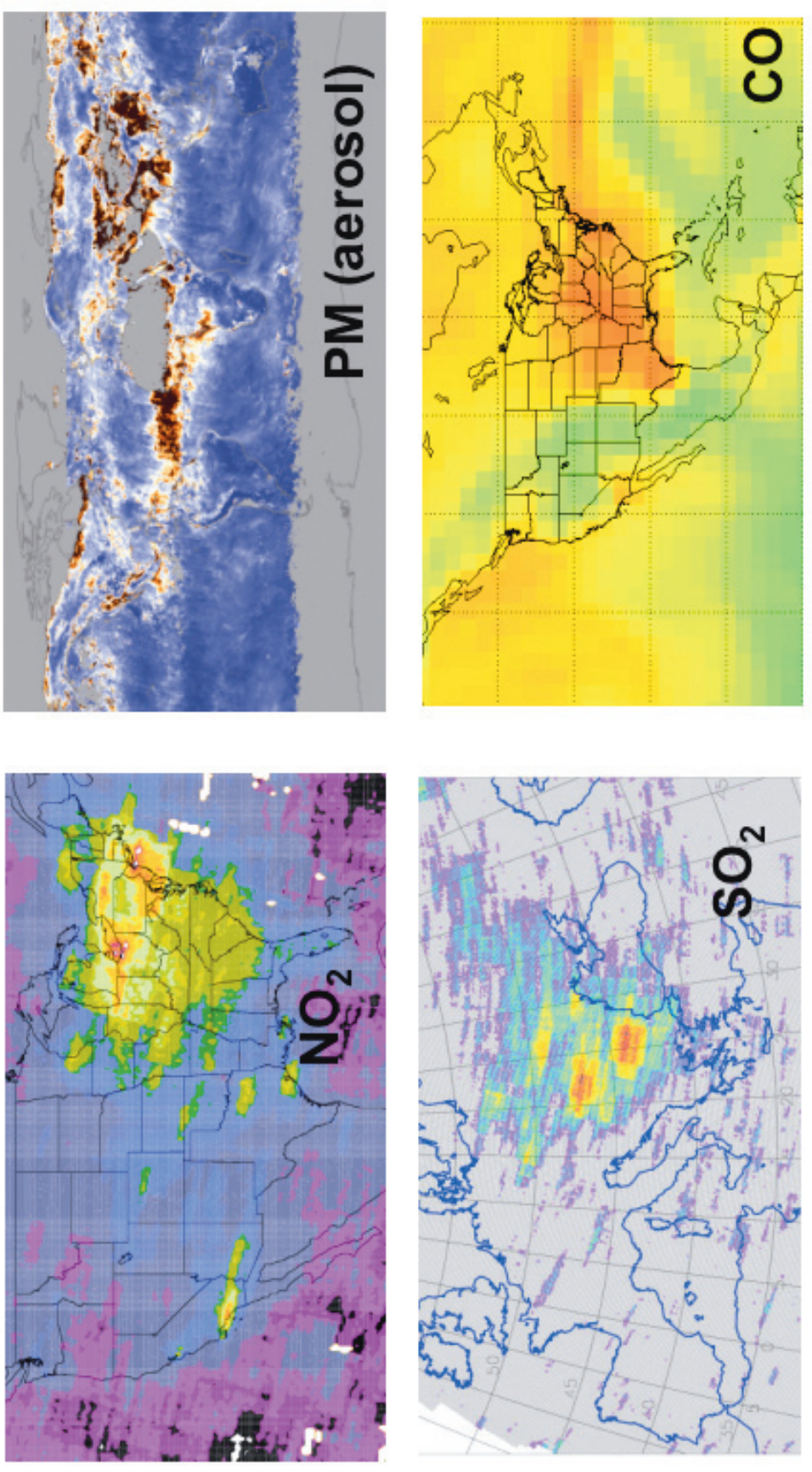

Figure 6.2. Typical satellite-derived tropospheric column loadings of selected pollutants, which are confined mainly to the planetary boundary layer. In the NO_2, PM, and SO_2 displays bluer or more yellow hues qualitatively indicate regions with relatively low emission rates. In all displays the orange to red or darker hues qualitatively indicate higher column loadings, identified with areas of higher emission density. Data obtained from a variety of satellite sensors (Neil, Fishman and Szykman, 2003).

compared with model-derived column loadings based on an assumed emission inventory. Subsequently the model is executed repeatedly, adjusting the emission inventory until a match between the model- and satellite-derived values is achieved. For cases involving multiple sources this can be viewed as a rather broad-brush approach, providing coarse estimates of overall emission magnitudes. These estimates are perhaps most useful (a) for large-scale geographical regions, where little or no quantitative information exists, or (b) for estimating natural vs. anthropogenic emissions.

Examples of this approach include the work of Petron et al. (2004), who applied MOPITT CO data in conjunction with the NCAR Model for OZone And Related chemical Tracers (MOZART) to infer CO emissions from western U.S. wildfires occurring during August 2000. Similarly, Palmer, et al. (2003b) applied formaldehyde column data derived from GOME measurements to infer North American emissions of the biogenic formaldehyde precursor, isoprene, using the GEOS CHEM chemical-transport model as an interpretive tool. As can be noted in Figure 6.3, comparison of GOME data with GEOS CHEM simulations based on two existing isoprene emission inventories suggests significant biases in these inventories.

A third example of this approach is the work of Martin et al. (2003), who applied GOME-derived NO_2 column data to reduce errors in the global NO_x emission inventory. In some respects model applications of this type can be considered an elementary form of inverse-modeling applications. More formal inverse-modeling approaches, described in Section 6.2.2, involve a substantially more detailed mathematical treatment, but offer the possibility of increased resolution of individual pollution sources. To date this more formal approach has been limited to a few special applications, such as global CO_2 emissions (e.g., Kasibhatla et al., 2003), but one can expect extended application in the future.

The current evolutionary state of satellite measurements should be expected to expand in at least three general areas. The first of these involves the realization of more highly specific measurements with regard to chemical species, vertical and horizontal resolution, and temporal coverage, which will be provided by platforms and sensors currently planned or envisioned. Progressively higher-quality satellite-based measurements of O_3, NO_2, SO_2, HCHO, CO and PM will be available over the next five years from the recently deployed ESA SCIAMACHY and NASA's EOS Aura (http://eos-chem.gsfc.nasa.gov/project). Moreover the geostationary platforms noted in Table 6.1, if deployed, will substantially improve spatial/temporal coverage of the North American and European continents.

The second important development involves interpretation of quantitative emissions. This has a somewhat longer time horizon, and depends strongly on the ability of scientists working in the emission inventory field to envision new satellite-derived products desired for their specific purposes and to communicate these ideas to their counterpart scientists in the satellite community.

Finally, as demonstrated by the example applications described above, considerable development can be expected in inverse-modeling applications and other innovative interpretive techniques, often using satellite measurements in conjunction with surface-based measurements. With developments in these areas, satellite applications can be expected to attain significantly greater source-resolving power, which may be a complement to conventional estimation methods.

6.1.1.2 Aircraft Remote-Sensing Applications

Both surface- and aircraft-based remote-sensing applications to evaluate pollutant emissions have relied almost totally on open-path optical techniques, and share considerable commonality with sensors currently deployed on satellite platforms. In contrast to most satellite-based approaches, a majority of surface and aircraft-based sensors deployed for emission assessment observe radiation emitted by the measurement device, and thus are classified in the "active" category.

Aircraft remote sensing provides a useful complement to in-situ emission measurements from aircraft, which are described in Chapter 7. As with their in-situ counterparts, aircraft remote sensing is usually applied for determining pollutant fluxes through vertical planes encompassing the plumes being

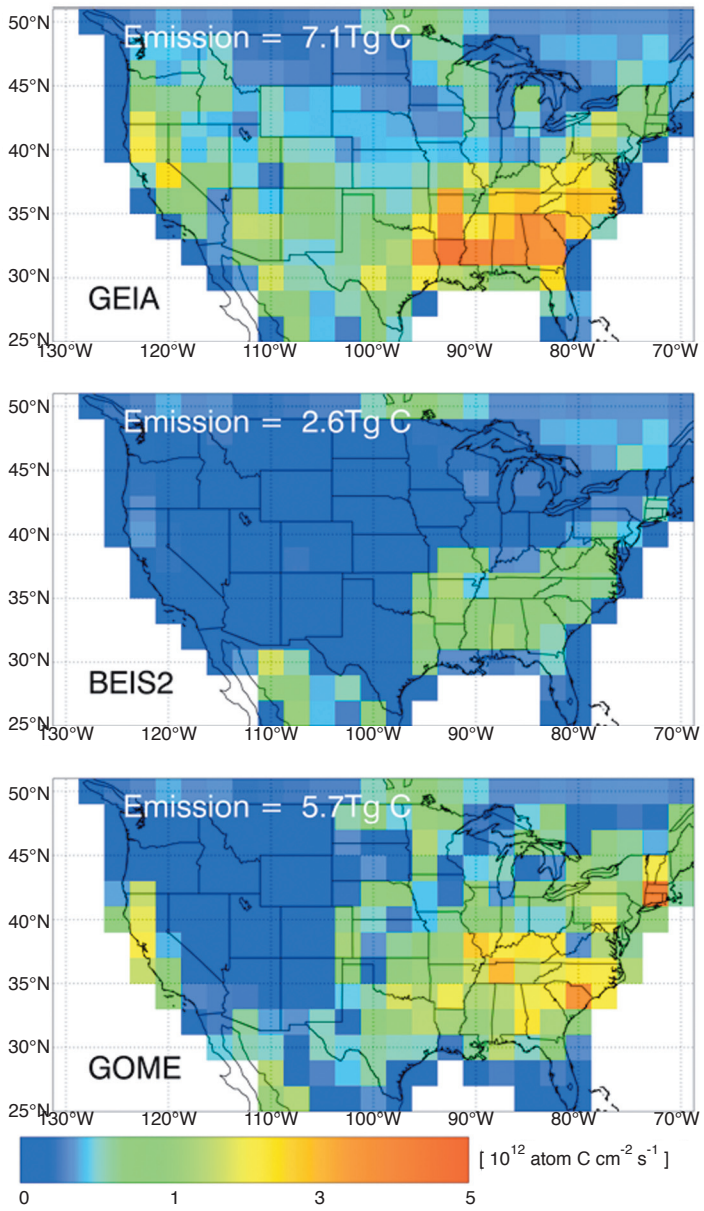

Figure 6.3. Comparison of North American isoprene emissions derived from GOME formaldehyde data for July 1996, with those estimated by the GEIA and BEIS2 inventories. From Palmer et al. (2003a,b).

observed. Typically, such measurements are made by DOAS (Melamed et al., 2002 and references therein), infrared spectroscopy (Stearns et al., 1986), or by lidar.

Remote sensing has several advantages in aircraft applications. Most importantly, these methods provide a measure of the vertical column of the concentration through the plume, thereby directly evaluating an integral of pollutant concentration over the vertical dimension. The evaluation of integrated plume concentration is then reduced to integrating the column measurement across the plume. The plume flux can be determined using the average wind speed [See Equation (7.1)]. A second advantage is that the column measurement is insensitive to variations in the height of the planetary boundary layer (PBL) and vertical inhomogeneities of concentrations. Finally, the required cross-sectional measurement is accomplished in a single aircraft transect that can be

carried out above the PBL. It is thus more suitable for determining plume-wide fluxes from extended sources, such as urban areas. One disadvantage of the technique is that the species that can be measured are presently limited; plume fluxes have been reported only for DOAS measurements of NO_2 (which allows the calculation of corresponding NO_x fluxes) and for SO_2. The reported precisions for these measurements are near plus or minus 30 percent. In intense biomass burning emission plumes, molar ratios of a variety of species have been determined (Worden et al., 1997).

As previously mentioned, current aircraft-deployed, remote-sensing applications for emission analysis are limited mainly to DOAS measurements of NO_x and SO_2 fluxes and IR spectroscopy determinations of emission factors for species released in biomass burning. DOAS techniques could potentially be extended to some VOC species including formaldehyde, alkenes and aromatics. There is also potential for lidar instrumentation to be applied to measured primary PM emissions. It is possible to remotely measure wind speeds using Doppler lidar techniques; application of this instrumentation would be a useful advance. The limiting factor in these possible projections will be the ultimate signal-to-noise ratios that can be achieved.

6.1.1.3 Ground Based Remote Sensing Application

Stationary Sources

For discussion purposes it is convenient to subdivide surface-based remote sensing of emissions into two categories, depending on whether the source in question is mobile or stationary. Remote-sensing evaluations of stationary-source emissions have applied several of the optical methods summarized in the introduction to this section. While having significant potential, they are limited for stationary source applications because of detection limits, especially for toxic gases at very low effluent concentration. Often used more for pollutant concentration studies not directly related to emission inventory evaluation, these techniques are currently much more limited for stationary sources than their mobile source counterparts. North American applications, for large point sources at least, have been superseded by the reliance on standard reference methods and CEMS, which often provide the most straightforward and direct approaches to emission measurement. On the other hand, remote sensing is often attractive in situations (such, for example, as petroleum refineries) involving complex source configurations and/or detection of fugitive emissions. The availability of commercial, off-the-shelf equipment for this purpose is limited, although a few organizations – particularly in Europe – offer services applying remote sensing for emissions from sources such as refineries and feedlots (e.g., www.spectrasyne.ltd.uk/; www.kassay.com/kfshome.htm; www.erg.com/services/environ_meas_source.htm).

Several examples of successful application of remote-sensing technology for stationary-source emission assessment can be cited. Apart from the previously cited application of FTIR by Yokelson et al. (1997) to determine combustion-process emissions, these include the work of Schröter et al. (2003) who applied lidar measurements of a power plant plume to remotely sense SO_2 concentration, and processed the results with co-located sound detection and ranging (sodar) flow measurements to estimate SO_2 emissions. Schäffer et al. (2004) applied simultaneous upwind and downwind DOAS measurements to determine emissions from automobile service stations and from tanker filling operations, using a small-scale dispersion model to back-calculate emissions. Galle et al. (2001) applied active FTIR to monitor CH_4 emissions from landfills and NH_3 emissions from agricultural manuring applications. They also applied passive FTIR (using the sun as a radiation source) to determine emissions from petroleum-processing complexes and harbor operations. Haus et al. (1998) applied FTIR analysis of CH_4, CO_2, CO, NO, and water to determine emission rates by natural-gas flares.

A survey of this subject indicates that remote-sensing technology has large future potential for evaluation of emissions from complex sources, such as refineries or chemical plants, which are not amenable to standard single-stack treatment. Reflecting this future potential, the U.S. EPA is currently supporting research and demonstration programs applying remote sensing to a variety of fugitive emission sources (www.epa.gov/ORD/NRMRL/scienceforum/thoma_e.htm), and a number of innovative techniques

– such as the application of tomography to FTIR path measurements for determining spatial distributions (Hashmonay and Yost, 1999; Hashmonay et al., 1999) – are currently in a development stage. Although it has received little application to date, remote sensing of effluent velocity fields in conjunction with pollutant measurements has a large potential for emission quantification, and can be expected to expand considerably during future years.

Mobile Sources

As noted in the previous subsection, mobile-source remote sensing has received significantly more application for emission analysis than its stationary-source counterpart, and several commercial applications are currently in operation. The most important of these is cross-road sensing using electromagnetic radiation, which performs a series of light-absorption measurements intercepting exhaust plumes behind moving vehicles. The initial implementation of this technology involved NDIR measurements of CO and CO_2, with CO_2 serving as the internal plume tracer. Stoichiometric ratios of excess (above background) plume CO/excess plume CO_2 can be used to compute the fraction of CO in the exhaust at the vehicle's tailpipe (Bishop et al., 1989; Stedman, 1989). The measured excess target pollutant/excess CO_2 ratio also can be used along with a combustion equation to provide a target pollutant emission index (g pollutant emitted/kg fuel consumed). This system has been extended to measure HC and NO_x emissions using NDIR absorption, and, with greater selectivity and sensitivity, using UV spectroscopy (Guenther et al., 1995; Bishop and Stedman, 1996; Popp et al., 1999). Similar NDIR cross-road instruments were also successfully developed by General Motors Research Laboratories to monitor CO and HC exhaust emissions (Stephens and Cadle, 1991; Cadle and Stephens, 1994). Commercial instruments based on this technology and methods of exploiting advances in software and computer hardware for improved instrument control and signal processing are currently produced by Environmental Systems Products, Inc. (ESP, 2003a).

Advanced cross-road remote-sensing systems based on tunable IR laser differential absorption spectroscopy (TILDAS) have been developed and deployed by Zahniser and co-workers (Nelson et al., 1998; Jiménez et al., 1999; Jiménez et al., 2000a,b). These systems have the advantage of longer measurement path lengths, more easily manipulated light paths, and greater sensitivity for a range of individual exhaust species, allowing more pollutants to be quantified more specifically. TILDAS measurements of exhaust NO, NO_2, N_2O, and NH_3 have been reported and calculations show measurements of other species such as CO, H_2CO, CH_3OH, C_2H_4, and CH_2=CH-CH=CH_2 are feasible. Although still in the development stage, sensitive remote sensors for mobile-source PM emissions using lidar backscatter (Moosmüller et al., 2003; Barber et al., 2004; Kuhns et al., 2004; Mazzoleni et al., 2004a,b) are currently receiving research application.

Dispersive IR spectroscopy also can be used to quantify exhaust emissions from moving vehicles, although cross-road path lengths and vehicle speeds may be restricted, especially compared to the TILDAS systems. Baum et al. (2000) have demonstrated a prototype onroad vehicle emission measurement system combining IR and UV spectrometers. This system can quantify exhaust CO, NO, NO_2, N_2O, HONO, NH_3 and as well as some light aldehydes, aromatics, and aliphatic hydrocarbons, and has been used to measure NH_3 emission distributions on a Los Angeles freeway onramp (Baum et al., 2001). Finally, instruments to measure exhaust PM are currently being developed and demonstrated (Moosmüller et al., 2003; ESP, 2003b). ESP's latest commercial remote-sensing technology includes a UV spectral measurement to generate a smoke index (g particles emitted/kg fuel consumed).

Cross-road remote-sensing studies have been extremely valuable in characterizing onroad emissions for light duty gasoline-powered vehicles. A critical finding from these fleet-emission measurements indicates that a small fraction of the vehicles emits a large fraction of a given pollutant, demonstrating that emission factors do not follow a normal distribution. Ten to 20 percent of the vehicles tested account for 50 to 80 percent of the emissions. These high emitters constitute a large part of the inventory, which is not well reflected by average emission factors. Onroad tests show that inspection and maintenance (I/M) programs often do not identify the highest emitters.

This highly skewed distribution was recognized by Zhang et al. (1994) for CO and HC emissions, and is also reported for CO and HC by Stephens (1994). The same distribution also has been shown to characterize NO (Jiménez et al., 1999) and N_2O emissions (Jiménez et al., 2000a). This fact has a large impact on the sample size of light-duty vehicles whose emissions must be evaluated to determine statistically valid inputs for mobile emission models. Referring to enforcement practice, other studies have qualified the measurement of specific gas components as independent measures guiding vehicle inspection and maintenance surveillance (e.g., Mazzoleni et al., 2004).

Relatively long time-series of remotely sensed emissions for light-duty vehicles are now available for a number of North American and European cities, allowing a determination of how well new cars meet regulatory standards and assessments of emission changes with vehicle age (Pokharel et al., 2003; Sjödin and Andréasson, 2000). Comparable data are available from enough cities around the world that the impacts of variations in maintenance practices can be recognized (Zhang et al., 1995). Data on vehicle emissions from several Mexican cities have been compared and contrasted with similar data from U.S. cities (Bishop et al., 1997). Studies like these are important to inform mobile-source emission models about expected temporal and geographic variations of mobile-source emissions from evolving light-duty vehicle fleets. However, ongoing studies will need to be maintained to keep such projections valid as new vehicle technology is introduced and older vehicles age.

While the great bulk of remote-sensing data available are for light-duty vehicles, emissions from heavy-duty diesel vehicles have been characterized, even though many North American heavy-duty diesel vehicles have substantial exhaust emissions that are not well sensed by normal low-level cross-road optical technology. Both traditional non-dispersive systems (Bishop et al., 2001a) and TILDAS systems (Jiménez et al., 2000b) have been deployed to reliably characterize onroad heavy-duty diesel trucks. These vehicles have emission distributions that are much closer to normal than the γ-distributions found for light-duty vehicle emission distributions. The same technology also has been used to characterize significant offroad mobile sources, such as snowmobiles (Bishop et al., 2001b). Measurements on a wide variety of offroad vehicles are underway and will help inform offroad mobile emission models.

It is possible to construct light-duty vehicle emission inventories directly from cross-road remote sensing data. Singer and Harley (2000) have used remote-sensing data to construct a fuel-based inventory for mobile emissions in Los Angeles, California, and Stedman and co-workers have recently published one such inventory for the Denver, Colorado metropolitan area (Pokharel et al., 2002). If more continuous and comprehensive remote-sensing data sets become available, the derivation of mobile emission inventories directly from these data may become widespread. However, because remote-sensing measurements typically sample each vehicle for less than a second, thus sampling a very small segment of each vehicle's operating range, Wenzel et al. (2000) caution that it is necessary to sample a very large number of vehicles to estimate valid mobile-source emission inventories.

Remote-sensing measurement data have demonstrated utility for evaluating the effectiveness of air quality control programs. One of the earliest uses of remote-sensing data was to assess the impact of using oxygenated fuels to reduce mobile CO emissions (Bishop and Stedman, 1990). Systematic analyses of multi-year data sets have been used also to evaluate the effectiveness of I/M programs (Stedman et al., 1997). A recent extensive roadside pullover study that stopped vehicles which remote-sensing instruments had identified as high emitters and subjected them to conventional tailpipe emission inspections has confirmed that remote sensing does generally correctly recognize vehicles with excessive emissions (BAR, 2001). A recent report by the NRC concluded that remote-sensing measurements are an excellent source of onroad CO and HC emission data, that they also can be a useful screening tool to identify vehicles likely to pass or fail conventional I/M program tests, and that remote sensing is underutilized in current I/M programs (U.S. EPA, 1998; NRC, 2001). Since the impacts of control strategies must be factored into mobile-source emission inventories, remote-sensing data can play a key role in updating current emission inventories and projecting future emissions.

From a mobile-source standpoint, remote-sensing technology is now sufficiently developed that routine operational deployment as part of state or provincial I/M programs is feasible. The potential adoption of operational "clean screen" and/or "gross emitter" onroad I/M programs may provide nearly continuous and real-time remote-sensing data sets, which can be incorporated to keep mobile emission inventories much more current and provide better spatial resolution. Several large studies of commercial cross-road remote-sensing technology of ongoing I/M and other clean-air initiatives have been concluded recently (McClintock, 2002; ESP, 2003a; McClintock, 2004), opening up the prospect of more widely distributed and more continuous data sets gathered on a daily basis. For instance, a recent program sponsored by Missouri to test a clean-screen component for the I/M program for the St. Louis metropolitan area operated 20 to 26 days per month, collecting 300,000 to 500,000 vehicle-emission records per month for a total of nearly 5 million over the course of a year (McClintock, 2002).

Traditionally focused on VOCs, NO_x, and CO, future mobile-source sensing technology can be expected to address additional chemical species during future years. There is an increasing concern about mobile sources of airborne toxic air pollutants, with particular emphasis on possible carcinogens including formaldehyde, acetaldehyde, benzene, acrolein, and 1,3 butadiene, as well as the organic portion of exhaust fine PM. Advanced remote sensing systems employing dispersive spectrometers (Baum et al., 2000) or tunable lasers (Nelson et al., 1998) have the capability to quantify some exhaust toxic air pollutants directly and may well be able to quantify related indicator compounds for others. Advanced remote sensing systems also have the capability to quantify mobile emissions of greenhouse gases beyond CO_2, including N_2O and CH_4 (Baum et al., 2000; Jiménez et al., 2000a). Both types of advanced systems have demonstrated the ability to quantify the production of NH_3, an important PM precursor, on overactive NO reduction catalysts (Baum et al., 2000; McManus et al., 2002).

Remote sensing data for mobile sources are primarily reported on a fuel-use basis (g emissions/g fuel used). To be compatible with the current vehicle emission models, the fuel-based estimates are converted to g/VMT using estimated relationships between driving patterns and fuel consumption. Fuel-based emission estimates are preferred by some workers for evaluation of mass emissions and for speciation profiles for emitted PM. Fuel-based methods also offer important opportunities to evaluate transportation sources on a comparable basis with nonroad sources, which may become increasingly important for some applications.

6.1.2 Alternate Methods for Mobile-Source Characterization

Mobile-source emissions continue to represent one of the more challenging aspects of emission rate estimation. Typical mobile-source emission models such as the MOBILE series are idealized, in the sense that they assume standard driving cycles and fleets having uniform characteristics based on certification and dynamometer testing (e.g., Sawyer et al., 2000), leading to serious concerns regarding their "real-world" applicability. The models have received ad hoc adjustments for urban/rural situations as well as for Mexican and Canadian driving conditions, but remain relatively coarsely evaluated. In recent years, testing under real-world driving conditions has increased, using different creative approaches, which attempt to avoid limitations embedded in the existing emission models. One such approach –remote sensing – has been discussed in Section 6.1.1. Several additional approaches are summarized in the following subsections.

6.1.2.1 Roadway Tunnel Studies

Roadway tunnel studies represent an additional method for testing motor-vehicle emission models, at least over limited ranges of conditions. These studies include gas and particle sampling from tunnel entrance and exhaust air using conventional instruments, documentation of driving conditions during sampling, documentation of the types of vehicles passing through the tunnel, and estimation of emission rate distributions expected from the fleet observed in terms of speed (or speed variation) and tunnel length. The first experiment of this type was conducted in the 1970s (e.g., Pierson and Brachaczek, 1983). More recently, several of these studies have been reported in Los Angeles, Baltimore

and Vancouver (e.g., Pierson, et al., 1996; Gertler et al., 1997; Pierson et al., 1996; Sawyer et al., 2000; Graham et al., 2003).

Tunnel studies have been useful in providing data for checking the reliability of models such as MOBILE and EMFAC to calculate traffic aggregate emissions of CO, VOC, NO_x and PM under a limited range of onroad conditions. Historically, these studies raised serious questions regarding the performance of emission models as early as the 1980s.

While the tunnel studies have limitations in themselves, they nevertheless are valuable for identifying ambiguities in model calculations, and have resulted in improved model estimates of gaseous emissions. Tunnel studies have been criticized for not being representative of a wide range of expected onroad driving conditions (including cold starts, and transients—fuel rich operation), for having ambiguities in vehicle operating conditions, and for having only limited representation of traffic mixes. They also give ambiguous results for evaporative emissions. Critics also have questioned whether or not the observed pollutant mixtures are characteristic of open-air conditions, given the constrained air circulation present in tunnels.

Despite these limitations, tunnel studies have been instrumental in providing cross-checks for mobile emission models (e.g., Sawyer et al., 2000). Partly in response to tunnel-study results, considerable effort has been devoted to improving the MOBILE and EMFAC emission models since the 1980s.

6.1.2.2 Mobile Laboratories and Chase Vehicles

The development of robust, fast-response sensors for many gaseous pollutants, as well as PM physical and/or chemical properties, has allowed the deployment of useful instrument suites in a variety of onroad vehicles. This combination enables truly "mobile laboratories" capable of real-time measurements while in motion. In general, modern mobile laboratories can be used to characterize onroad, mobile-source emissions in two distinct modes—vehicle fleet and vehicle tracking, or "chase" measurement.

In the fleet mode, mobile laboratories characterize onroad pollutant emissions in two ways. The most accurate and informative method is by intercepting individual vehicle exhaust plumes and correlating target pollutant enhancements with above-background CO_2 levels. Less quantitatively, elevated onroad pollutant concentrations can be measured and correlated with traffic volume or average elevated CO_2, or CO as an emission marker without resolving individual vehicle plumes. These fleet methods can be thought of as tunnel studies without the tunnel. Like tunnel studies, they yield a sample of fleet-averaged emission indices for individual pollutants. The individual plume-intercept method has the advantage of also yielding a full distribution of emission indices for the target pollutants, since an individual emission index is obtained for each exhaust-plume intercept. Since plume excess CO_2 can be readily related to the fuel consumption rate through the combustion equation, measurements of emission ratios (plume excess pollutant/plume excess CO_2) can be directly converted to emission indices (g pollutant emitted/kg fuel consumed for different driving conditions).

In the chase mode, mobile laboratories are designed to sample exhaust plumes from specific target vehicles repeatedly. This mode can be used to characterize the emissions of either cooperative or non-cooperating "wild" vehicles over a range of operating parameters. The chase laboratory must shadow the target vehicle and must contain fast response (~1-s) sensors, typically measuring CO_2 and the target pollution of interest. Data from fast-response sensors for the target pollutants are correlated with the CO_2 data to yield emission ratios and derive emission indices for target vehicles as a function of operating conditions. The target vehicle's speed and acceleration can be obtained from onboard sensors (for cooperative vehicles), or from the speed and acceleration values of the chase vehicle, plus range-finder measurements providing the instantaneous distance between the chase and target vehicles. Chase-vehicle measurements are similar to onroad dynamometer measurements, but typically may sample a wider range of operating conditions

Fleet emission ratios for N_2O emissions from U.S. vehicles have been reported by Jiménez et al. (2000) and formaldehyde emission ratios for vehicles in Mexico City and Boston by Kolb et al. (2004). Jiménez et al. (2000) demonstrated that

the distribution of U.S. fleet N_2O emission ratios measured using onroad mobile laboratory plume sampling was very similar to that obtained by cross-road remote sensing, using tunable infrared laser differential spectroscopy sensors in both cases. A variety of mobile laboratories has been developed recently and deployed to characterize onroad pollutant levels and mobile emissions in Europe and North America (Seakins et al., 2002; Bukowiecki et al., 2002; Kittelson et al., 2004; Weijers et al., 2004; Gouriou et al., 2004; Kolb et al., 2004), although only the latter group has published fleet-emission ratios and indices based on ensembles of individual exhaust-plume emission ratios (Jiménez et al., 2000; Kolb et al., 2004). A number of groups have focused on characterizing onroad exhaust emissions of PM, with some placing particular emphasis on ultrafine or "nanoparticle" concentrations and properties (e.g., Kittelson et al., 2004, Gouriou et al., 2004; Weijers et al., 2004).

Kittelson et al. (2000) have deployed a "mobile emission laboratory" mounted in a cargo container on a truck chase vehicle to characterize onroad diesel emissions from cooperative heavy-duty diesels. Vogt et al. (2003) have instrumented a chase van to characterize emissions from cooperative light-duty diesel vehicles on a test track. Kolb and co-workers have utilized a large van-based mobile laboratory to quantify a range of gaseous and PM emissions from a range of heavy-duty diesel and heavy- to light-duty gasoline vehicles in Mexico City and several U.S. cities (Shorter et al., 2001; Cangaratna et al., 2004; Kolb et al., 2004). Initial analyses of these measurements indicate that the data are comparable to cross-road remote-sensing data, giving the advantages that individual vehicles can be sampled for a larger range of operating conditions and a much wider range of gaseous exhaust species and fine particle properties can be specified. For instance, the mobile laboratory described in Kolb et al. (2004) is equipped to quantify exhaust emissions of gaseous CO, NO, NO_2, HONO, NH_3, H_2CO, CH_3CHO, CH_3OH, benzene, toluene, C_2-substututed benzenes, and SO_2, as well as a range of PM properties, including number density, size distribution, and mass loadings of $SO_4^{=}$, NO_3^{-}, NH_4^{+}, OC species, and PAHs.

6.1.2.3 Portable Emission Measurement Systems

As their name implies, portable emission measurement systems consist of analytical equipment that is sufficiently compact and field-operable to allow deployment on vehicles under actual operating conditions. This is particularly important for some mobile sources – such as construction and farm equipment – which are difficult and expensive to subject to standardized testing. Portable emission measurement systems provide a way of testing such equipment without having to either remove the machine from service or modify it in any way.

Portable emission measurement systems have been under development for about a decade. The U.S. EPA, for example, recently patented the Real-Time OnRoad Vehicle Exhaust Gas Modular Flowmeter and Emissions Reporting System, better known as ROVER (U.S. EPA, 2003). As the first generation of portable emission measurement system devices, ROVER established a method for measuring mass flow from engines.

U.S. EPA workers have continued portable emission measurement system development and introduced the Simple Portable Onboard Test (SPOT) in 2001. SPOT was designed specifically for nonroad applications. Building on the ROVER system, the SPOT system consists of a rugged, compact package and provides further advances in mass-flow measurement and activity data capture. The technology has been licensed to equipment manufacturers and a competitive market has emerged to design and manufacture portable emission measurement systems that meet stakeholder needs.

Portable emission measurement system-related goals are to encourage and support private industry in equipment development and refinement. The U.S. EPA is also working on developing and demonstrating PM mass measurement. Prototype equipment is under evaluation in U.S. EPA and contractor laboratories to establish correlation between reference methods and prototypes. Development and field adoption of this capability is ongoing, and similar work will pursued for measuring toxic air pollutants in the future.

Currently, portable emission measurement systems are being deployed in a number of ways, such as checking compliance of in-use heavy-duty vehicles. The U.S. EPA is also undertaking an extensive program in Kansas City in 2004/2005 (Baldauf et al., 2004) to evaluate PM emissions from light-duty vehicles. About 500 cars are being tested on a portable dynamometer and most of those also will be equipped with portable emission measurement systems and returned to their owner for real world emission measurement. This will constitute the first large database for real-world, in-use emission measurements ever assembled. In addition, the U.S. EPA plans to launch a test program involving 150 nonroad engines. Plans are also in progress to test heavy-duty trucks.

Portable emission measurement systems enable the testing of motor vehicles in any location, and the cost of testing per vehicle is believed to be a fraction of that for laboratory testing – by an order of magnitude or two in the case of nonroad engines and heavy-duty trucks. These two advantages will allow testing of statistically significant national samples of vehicles. Portable emission measurement systems are believed to be sufficiently inexpensive that state governments can afford to acquire and deploy them to generate local emission and activity data for use in refined local and mesoscale modeling. This will improve the quality of data input for emission models such as MOVES, and transportation inventory projections.

6.1.2.4 Onboard Sensors

A complement to other mobile source measurements has been developed using the monitoring of onboard engine diagnostic (OBD) sensors in contemporary vehicles, such as exhaust-gas oxygen and temperature sensors, and engine-load and fuel-consumption monitors. By using an engine performance model in conjunction with a wireless device to communicate, these sensors can provide an essentially real-time, indirect estimate of CO, NO_x and VOC emissions from equipped vehicles. Tests in California on a fleet of 1000 taxicabs, for example, have provided useful data on a large number of vehicles for comparison with the federal OBD II I/M emission test (e.g., Banet, 2003). Using these data, nonperforming vehicles can be identified, and returned for maintenance to correct failing emission control equipment. The data have not been used extensively as yet for comparison with other onroad measurements. Investigation of their application to emission estimation should yield at least qualitative performance data to check limited sampling data acquired from portable emission measurement systems and roadside monitoring.

In the future, new micro-sensors are under development that can withstand the conditions present in high-temperature, hostile post-combustion environments (e.g., http://www.es.anl.gov/html/sensor.html). The Argonne National Laboratory, for example, is developing prototype "smart" voltammetric/electrocatalytic microsensors combining cermet materials, voltammetry, and neural network signal processing. Tests have been conducted on these prototypes for CO_2 detection, but the sensors also can be "trained' to detect other chemicals, including VOCs. With these sensors, one can foresee opportunities for onboard emission sensing by vehicles far in advance of current practices. Such sensors also should have important applications as CEMs for a variety of industrial applications.

6.1.2.5 Sampling and Dilution Tunnels for Reactive Emissions

Although applicable for evaluating both stationary and mobile sources, sampling and dilution tunnels are of particular interest in the context of transient emissions from diesel-powered roadway vehicles, and thus are discussed here. Determining emission rates from sources whose pollutants transform quickly once emitted to the atmosphere has received increasing attention during recent years, primarily as a consequence of heightened importance placed on ultrafine PM and associated health impacts, as well as the evolution of specific combustion technology categories (e.g., advanced diesel engines), which emit large numbers of particles in this size range. Characterizing PM emissions from combustion systems is difficult because of the high temperatures and moisture content of exhaust gases, as well as the strong coagulative tendency of ultrafine PM in high concentrations. Upon exiting the stack the combustion products cool rapidly and dilute with ambient air, during which time physicochemical reaction processes such as condensation, nucleation, and coagulation change PM size distribution and composition. Measurement of PM in hot exhaust is

further complicated by the presence of semivolatile material, which may either undergo homogeneous nucleation or condense on existing particles, thus changing chemical composition and size distribution. Because particle count is dominated by the small particles, particle-number distributions are especially sensitive to sampling and dilution conditions. Measured particle-number concentrations can be changed many orders of magnitude by varying sampling conditions.

An obvious approach to this issue is to utilize fast-response instruments to continuously measure flow rates and the concentrations of species of interest. Frequently, this is not possible because of sample temperature, humidity, and the lack of suitable instrumentation. Dilution sampling (Lipsky et al., 2002) represents an alternative technique for this purpose. Depending on their design, dilution samplers either quench the physicochemical reactions by rapid dilution and cooling, or else they provide for quantitative examination of these processes by mixing with specified amounts of conditioned air.

Some sampling systems have added residence chambers to increase the time between exhaust dilution and sampling the diluted emission stream (e.g., England et al., 2005). This is done to allow additional time for equilibration between the semivolatile constituents and the PM as well as time for coagulation of some of the fine PM. Additional dilution of the sample immediately before the residence chamber can be done to better simulate the effluent after equilibration with ambient conditions. While dilution tunnels are designed to minimize particle losses, sampler surface interactions between the gases and particles remain problematic. Care has to be taken in the sampling system to determine losses of trace reactive gases and particles. Semivolatile materials tend to slowly adsorb and desorb from tunnel walls, resulting in a variable background contribution from the tunnel itself. Hence, the tunnel must be conditioned carefully if it is used on sources of greatly varying magnitude.

One of the problems associated with the use of dilution tunnels is their lack of portability for source sampling. Many sources are large and involve equipment or stacks that are at substantial heights. Dilution systems designed in the 1980s and later generally are bulky and clumsy to transport. Recently, designs based on these large units have been built, with residence times needed for equilibration much shorter than the larger units. England et al. (2005), for example, have designed a new portable tunnel based on much larger, bulkier units of Hildemann et al. (1989) at the U.S. EPA and the Desert Research Institute. This and other portable dilution tunnels have been demonstrated for sampling of stationary sources. The England et al. design has been used for mass emissions and speciation analysis of $PM_{2.5}$ from a selection of gas- and oil-fired combustors. The results also provide important data and insight into emission behavior, as well as ultrafine PM and semivolatile material from these sources. Based on the performance testing of dilution-tunnel units for stationary sources, an ASTM committee has been formed to codify the sampler and sampling method (ASTM D22.03/W1752 certification). This method will probably replace U.S. EPA standard methods 201A and 202 in 2005.

Tests for PM emissions from stationary sources using dilution samplers have shown significant differences compared with Methods 201A/202 (e.g., England et al., 2002). In testing of effluents from a natural-gas process heater and boiler, for example, the proposed ASTM method indicates that the dilution tunnel samples yield much lower PM concentrations from such combustors compared with Methods 201A/202, and from estimates based on default values in the AP-42 guidelines. Thus, the sampling method for source effluents of PM clearly depends strongly on the suitability of sampler design. This will significantly influence certain published emission factor estimates currently used in practice.

Fast-response sensors, fast-response mass flow controllers, and improved electronics are likely to result in more accurate and reliable dilution samplers in the near term. The impact of semivolatile material on PM measurement, however, will not be solved by improved sampling methods. Standardization of measurement procedures should greatly increase precision of the measurement, but will not resolve the problem of applicability to different atmospheric conditions (i.e., ambient temperature, humidity, dilution, and background PM). Relating sources of rapidly reactive emissions to ambient concentrations will require (a) improved modeling of atmospheric

processes, (b) innovative statistical inferences to relate measurements of a few samples to conventional averaged estimates, and (c) more geographically and seasonally comprehensive source measurements of the appropriate parameters as input to models.

6.1.3 Continuous Emission Monitoring Systems

CEMS have been described in some detail in Section 4.7.4, and are mentioned again here mainly to note that these systems, and their application, can be expected to evolve substantially as newer sensors are developed (e.g., Jahnke, 2000). As discussed in Chapter 4, CEMS for SO_2, NO_x, CO_2, O_2, opacity, and flow have been deployed on large electric utility boilers in the United States since the early 1990s to comply with the allowance trading requirements established by the Acid Rain Program under Title IV of the U.S. 1990 *Clean Air Act* Amendments. Hourly emission data from CEMS are reported quarterly to the Acid Rain Program's Electronic Data Reporting System. This information forms the basis for the annual emission data included in the U.S. emission inventories for electrical generating units and also serves as highly accurate input to modeling inventories. The variations in emissions recorded by CEMS reflect changing boiler and combustion-turbine operating conditions, fuel compositions, meteorological conditions, start-ups, and shut-downs. Additional continuous NO_x monitors will be installed on other sources in the eastern United States in the next several years to comply with allowance trading that is integral to the NO_x budget program. In addition, opacity monitors are commonly installed on incinerator stacks

CEMS for gas-phase constituents typically use optical sensors, based on absorption, emission, or fluorescence, depending upon the species being detected. Pollutant emission rates are calculated by multiplying pollutant concentrations by stack volumetric flow. Table 4.5 contains a representative list of mature and developing CEMS technologies indicating the physical measurement basis for each pollutant species.

Many challenges are associated with demonstrating the accuracy, precision, and reliability of CEMS. Substantial effort will be needed to develop protocols and experience to ensure that their operation provides credible data. For example, interferences, such as those associated with UV absorbance bands of SO_2 and mercury, must be minimized. Precision and accuracy at low emission levels, such as single-digit ppm NO_x levels from state-of-the-art combustion turbines must be demonstrated. CEMS must be maintained and carefully calibrated in hostile thermal and corrosive atmospheres of hot effluent gases. Validation and management of a large body of continuous data from thousands of sources presents a formidable task for the operators and for the U.S. EPA and states as the archivers of these data. In spite of these difficulties, Section 7 demonstrates that CEMS systems on power plants have yielded highly accurate emission measurements for NO_x, SO_2 and CO_2.

CEMS for other pollutants are being developed in the United States and Europe for regulatory compliance, for process-control needs, and to support future allowance-trading programs. Pollutants for which CEMS are currently under development include NH_3, BC, mercury (total and speciated), PM, and VOCs. Most of the development is being conducted by instrument manufacturers with the expectation of growing markets for this technology.

6.1.4 Aircraft Plume Measurements

An important alternative to remote sensing of stationary sources is the use of aircraft, helicopters and even blimps to sample plumes, and characterize near-stack chemical reactions with distance downwind. Plume tracing has been used to characterize, at least qualitatively, gas and PM emissions from large power plants, industrial sources and urban areas since the 1970s (e.g., Easter et al., 1980; Cher et al., 1984).

In the past, emission rate determination using aircraft sampling has been difficult because of large uncertainties in identifying the plume location and the fluxes of pollutants moving through plume cross sections. One of these problems derives from the lack of fast-response instruments compatible with aircraft speeds. Another arises from the imprecise sampling and measurement from an aircraft flying at different altitudes. Yet another is the lack of complete, simultaneous measurements that provide

for estimating a material balance for reactants and products. Recently, plume measurements have become more quantitative with the use of fast-response instrumentation, global positioning system (GPS)-based position measurement, and carefully planned, systematic sampling across plumes (cf. Chapter 7).

Section 7.3.2 discusses an extensive set of plume flux determinations that are used to evaluate inventoried power plant emissions. In general, quite good agreement is found between the aircraft flux measurements and the fluxes derived from CEMS data. Attempts to quantify emissions from urban areas are described by Trainer et al. (1995), Klemm and Ziomas (1998), and Plummer et al. (2001).

A major challenge in these measurements is developing and deploying instruments that can perform fast response (~1-s resolution) measurements of the ambient concentrations of the emitted species with sufficient accuracy and precision. In addition, the wind speed and direction at the time of emission are required to derive a flux from the concentration measurements. Current instrumentation is adequate for fast response measurements of CO, NO_x, SO_2 and CO_2. Biomass burning emissions have been determined by Fourier transform infrared spectrometry and other techniques that often have considerably slower response times. In this case various integrating procedures are utilized (Sinha et al., 2003). However, much of this current instrumentation is heavy and requires a good deal of electrical power and experienced operators. It could be more extensively applied if lighter, lower powered and more routinely operated instruments are developed. There is an important need to develop instrumentation for determination of speciated VOC emissions from intense sources such as petrochemical industrial facilities, as discussed in Section 7.3. Such emissions have been identified as critically important to some outstanding air quality issues, for example, in developing Texas state implementation planning for achieving the ozone standard.

6.1.5 Direct Flux Measurements

In the context of the present section, "flux measurements" pertain to direct or indirect determinations of pollution fluxes (amount of pollution issuing from a unit area of the Earth's surface per unit time) occurring by vertical turbulent transport within the Earth's boundary layer. Measurements of this type typically apply to emissions from sources having relatively uniform spatial distributions (e.g., isoprene emissions from a forest canopy, NH_3 emissions from agricultural land, dimethyl sulfide emissions from an ocean surface) or aggregated sources which can be approximated as uniform in a spatially-averaged context (e.g., urban and suburban areas under specialized conditions). Because pollution fluxes can be either positive (emission) or negative (deposition), measurement technology for emission flux measurements closely parallels that for dry-deposition assessment.

Although several inferential techniques have been applied to estimate pollution fluxes (Hicks et al., 1987), most direct emission flux measurements fall into two basic classes: profile measurements and covariance methods.[4] As their name implies, profile measurements depend on observations of vertical pollutant profiles in conjunction with appropriate meteorological measurements. Typically fluxes are calculated on the basis of these observations using an equation of the form

$$\text{flux} = -K_z \frac{dc}{dz} \qquad (6.1)$$

where $\frac{dc}{dz}$ is the vertical gradient of pollutant concentration c, and K_z is a vertical transport coefficient inferred from meteorological observations.

Covariance methods (Rinne et al., 2001) measure fluctuations in local concentrations and wind-velocities, and calculate fluxes on the basis of fundamental turbulence theory using the form

[4] Enclosure methods, wherein an emitting area is enclosed in a monitored chamber, constitute another class of flux measurements (cf. Baldocchi et al., 1996). This class is of more limited applicability in the context of criteria pollutants and their precursors, and will not be considered further here.

$$\text{flux} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} w'c'\,dt \qquad (6.2)$$

where w' and c' respectively are the fluctuating components of the vertical wind-velocity and concentration, and $t_2 - t_1$ is some appropriate time-smoothing interval. Measurement approaches that observe w' and c' directly and compute fluxes by subsequent integration often are referred to as eddy-correlation techniques.

Eddy correlation instrumentation must be sufficiently responsive to monitor all important components of the turbulence spectrum, typically frequencies of the order of 0.1 Hz and higher; and while modern wind-velocity instrumentation can satisfy this requirement easily, current pollution monitoring equipment often cannot. Eddy-accumulation methods, wherein the w' sensing device operates a fast-response valving system feeding two air sampling reservoirs at rates directly proportional to w', represent one method of overcoming this difficulty. Subsequent concentration measurements of the two chambers leads to evaluation of the integral in Equation (6.2). Additional attempts to overcome the time-response issue have led to various "relaxed" or "disjunct" covariance approaches, wherein the required sampling frequency is degraded in one form or another (Wesely, 1988). Such approaches typically involve additional approximations or limiting assumptions regarding turbulence behavior.

In addition to the obvious challenges posed to measurement instrumentation, both profile and covariance techniques depend strongly on measurement location, meteorology, and pollutant behavior. Equations (6.1) and (6.2) both are single, one-dimensional components of the general relationship describing three-dimensional, transient behavior in the real atmosphere, and their valid application for flux measurement generally requires that the local environment approximate a one-dimensional steady state. This in turn implies a uniform source distribution and a uniform wind fetch. Informed meteorological guidance is essential for determining the presence of these conditions. Moreover, while Equation (6.2) can be considered a fundamental, first-principles relationship, Equation (6.1) is more inferential in the sense that the transport coefficient, K_z, is quasi-empirical in nature and is an estimated entity. This renders profile measurements somewhat more subject to uncertainty - in principle, at least - than their covariance counterparts.

Finally, Equations (6.1) and (6.2) both imply that turbulent transport dominates the total flux term, a situation that will be violated if other mechanisms, such as gravitational sedimentation, are significant. In addition, chemical reaction of the observed component, if sufficiently rapid, can confound both profile and covariance observations.

Direct flux-measurement techniques have been applied for both monitoring and special-purpose measurements. Table 6.2 provides several examples of such observations. As noted above, both profile and covariance methods are limited by applicable source and meteorological conditions. Covariance methods tend to be less demanding in this respect, and this combined with their stronger theoretical basis suggests their preferential use during future years.

The currently rapid development of sensitive, fast-response chemical instrumentation (e.g., mass spectroscopy) will encourage extensive future covariance-method application, both on stationary and aircraft platforms. While the bulk of these applications will focus on relatively ideal boundary-layer situations, some encouraging developments are taking place in less ideal settings, such as urban and mixed suburban areas (Velasco et al. 2005; Fowler et al., 1997). Future results will determine practical applicability and the extent of future use under such situations.

The estimation of fluxes from diffuse ground level sources, for example windblown dust, has proven to be a major challenge for inventory development. Simulations by air quality models, which approximate vertical dispersion in atmospheric surface layers can overestimate dust emissions by a factor of two or more, compared with actual ambient measurements (e.g., NARSTO, 2004). To resolve this issue, substantial effort has been invested recently in developing improved methods for estimating such surface emissions, as reviewed by Watson and Chow (2002). Countess et al. (2002) also have reported

Table 6.2. Examples of Direct-Flux Emission Measurements.				
Pollutants	**Technique**	**Source/Location**	**Platform**	**Reference**
Isoprene, CO_2	Disjunct eddy covariance	Deciduous forest Michigan	Tower	Westburg et al. (2001)
Biogenic organic compounds	Disjunct eddy covariance	Forests, mown croplands	Tower	Karl et al. (2001, 2002)
Ethane	Disjunct eddy covariance	Urban area, Mexico City	Rooftop tower	Velasco et al. (2005)
CO_2	Eddy covariance	Various locations throughout the world.	Tower	Baldocchi (2003)
Suspended dust flux	Eddy covariance	Prototype testing in western United States	Tower	Gillies et al. (2003)

a methodology for estimating windblown dust and resuspended road dust fluxes for application to regional-scale air quality models.

6.1.6 Summary of Measurement Alternatives

Table 6.3 provides a summary of the measurement methods discussed in this chapter and their application, as well as a conceptual summary of their relevance to emissions and activity factors. This listing is intended as a reference point for more detailed examination of the above discussion, as well as contributions to the published literature.

6.2 MODELING AND INTERPRETIVE METHODS

Over the last 25 years, air quality models establishing the relationship between sources and ambient concentrations or receptor exposure have improved dramatically for both nonreactive and reactive pollutants. In principle, the models can be used to estimate ambient conditions for periods of less than a day to multiple years, provided appropriate emission and meteorological data are available. Sufficient testing and evaluation of models has been accomplished over the years that workers have identified emission estimation as one of the major uncertainties in the model results (e.g., NARSTO, 2000; 2004).

Chemical-transport models have offered an important opportunity for checking the reliability of the emission models on which they depend. The methods use two different kinds of models that are readily available: (a) receptor-oriented modeling, and (b) source-based modeling. Recent advances increase the potential for both techniques. The following sections describe recent improvements in the reliability of emission estimation though insights provided by air quality model results.

6.2.1 Receptor Modeling

Receptor modeling is a term describing a variety of (largely) statistically associated techniques for inferring source categories and/or magnitudes on the basis of ambient-concentration measurements. Differences among these various techniques are based on the types of statistical approaches employed and the types of observational patterns (e.g., temporal differences, spatial differences, ratios among specific compounds) considered, as well as whether the specific technique depends on source-profile information in addition to ambient measurements. Although most receptor models are totally statistical in nature, some variants employ limited deterministic calculations as well. Receptor modeling is most applicable to situations where differential attrition of the observed species, by deposition or by reaction, is minimal, although techniques to deal with such issues have been incorporated into some receptor models by adding quasi-deterministic components

Table 6.3. Summary of Alternative Methods for Emission Measurement.

Method	Application	Example Metric	Emission Factor	Activity Factor	Comments
Remote sensing (Ground based-ambient)	Stationary and mobile sources --cross plume observations.	Gaseous spectral absorption or PM light extinction.	EF estimate from process data and emissions as a function of time; short time comparison with direct stack tests.	Direct measurement of emissions as a function of time; with EF convert to activity estimate.	Limited use because of detection limit concerns and ambiguities in best interpretation for PM. Mobile emissions mainly fuel based.
Remote sensing (Aircraft and satellite)	Stationary sources; intermittent-wildfires, dust storms.	Gaseous spectral absorption; PM light extinction.	Emission rate estimates compared with calculated long term EF; interpretation of large scale EF for natural sources.	Capability for estimating time and space variability of natural sources, and testing time variation of stationary sources.	Aircraft plume measurement time and space limited; species detection limit; satellite observations limited by species observations and detection, and by spatial scale resolution.
Roadway tunnel studies	Mobile sources --controlled measurements constrained by the tunnel conditions.	Conventional gas and PM instruments.	Short term, traffic-based emission rates translated into EF.	Limited activity data based on tunnel constraints.	Strong limitations based on narrow range of driving cycle and short term observations relative to long-term estimates; unclear interpretation of exhaust vs. evaporative emissions.
Mobile laboratory and chase vehicles	Mobile sources	Conventional gas and PM instruments; vehicle identification records.	Short term emission rate measures translated into EF from real world fleet.	Activity factors interpreted indirectly from traffic patterns and emission rates for vehicles.	Limited for number of vehicles tracked, and range of driving cycle; unknown data for cold start or evaporative emissions.
Mobile onboard sensors	Mobile sources	New technology relying on link of gas microsensors and vehicle computer system.	Estimate of fuel based EF from detectors, combined with vehicle engine performance.	Time variation in emission rate enables estimate of activity factors given emission rate.	Basically untested for capability of generating a large data base for statistical estimates of EF and activity.

Table 6.3. Summary of Alternative Methods for Emission Measurement (concluded).					
Method	**Application**	**Example Metric**	**Emission Factor**	**Activity Factor**	**Comments**
Dilution tunnel sampling	Stationary and mobile sources (New ASTM reference certification for stationary sources)	Sampling of emissions approximating real world conditions for dilution (gases and PM).	Emission rate determined with speciation for condensed phase, volatiles and semivolatiles; comparison with EF from conventional methods.	Time variation over short term sampling provides estimate of activity factor with emission rate variation.	Limited to short term testing of stationary sources, and dynamometer testing of vehicles; translation into long terms averages for emission estimation not well established - new reference method in process.
Continuous emission monitoring (CEMs)	Stationary sources	In-stack observations of a few key gases; opacity for PM semi-quantitative	Emission rate directly measured with stack flow rate and concentration; infer EF from data.	Activity estimated from time variation in emission rate; gives long term and short term variability.	Major improvement in emission rate of stationary sources based on gas measurements. Limited to large stationary sources.
Airborne plume observations	Stationary sources; intermittent sources like wildfires	Conventional gas and PM observations, with ancillary aircraft speed, location	Emission rate inferred from cross plume tracking; EF inferred if effluent rate known.	Activity factor potentially inferred from emission rate.	Limited in space and time; depends strongly on ability to calculate flux from plume cross-section.
Ground based-direct flux observations	Ground level fugitive sources	Conventional multiple gas and PM instrumentation using vertical stratification.	Emission rate estimated from vertical gradient observation or analogous means. Translated into EF using ancillary meteorological and land surface data.	Activity factor estimate based on time variation in emission rate, and ancillary observations.	Limited by undetermined representativeness of flux conditions for dust rise, or from vegetation; reliability of application to broad range of conditions unknown.

to account for these effects. Receptor modeling should be applied with special caution when such conditions are suspected, especially for regional and larger spatial-scale conditions.

As with inverse modeling, receptor modeling is generally considered more as a verification/reconciliation tool, as well as a means for generating semi-quantitative insights regarding questionable or unknown emission sources. The success of receptor modeling depends heavily on the selection and quality of associated input measurements. Moreover, receptor-model results can be strongly prone to misinterpretation unless treated with appropriate caution: The experience and capability of the practitioner is of considerable importance in this regard.

Receptor-modeling techniques are described in detail in several reviews (NARSTO, 2004; Chow and Watson, 2002; Henry et al., 1984; Henry et al., 1997; Hopke and Dattner, 1982; Hopke, 1999; Moro et al.,

1997; Pace, 1991; Seigneur et al., 1999; U.S. EPA, 1984; U.S. EPA, 1985; Watson, 1984; Watson et al., 2002; Watson and Chow, 2004). Brook, Vega, and Watson (see NARSTO, 2004) provide an informative summary table, which itemizes the various receptor techniques and compares their input requirements as well as their strengths and weaknesses.

From a historical perspective, it is noteworthy that receptor modeling activities were the first to identify the need to extend emission inventories far beyond urban domains to estimate long-range sulfur transport (Hidy, 1994), that fugitive dust was identified as an important emitter (Gatz et al., 1981), that residential wood burning emissions needed to be inventoried (Watson, 1979), that meat cooking emissions needed to be inventoried, that cold-start emissions were not accounted for in inventories (Watson et al., 1998), and that CO and hydrocarbon emissions were underestimated by emission models (Fujita et al., 1992, 1994, 1995). Many of these sources were previously omitted from local emission inventories, so source-oriented modeling existing at the time was incapable of accounting for their contributions.

Emission identification and reconciliation using receptor-model applications for atmospheric pollution source analysis are presently at a relatively mature state. Although such models can expect to experience further development during future years, they can be considered to be a stable cadre of useful tools for emission verification and analysis, which should see continuing and extensive future application.

6.2.2 Inverse Modeling

Inverse modeling involves data-analysis procedures that employ a deterministic source-receptor model to derive information on sources (which are usually considered as independent model variables), based on sampled values of observable, dependent variables such as ambient pollutant concentrations. In a somewhat simplistic sense, conventional atmospheric source-receptor models adhere to the general form

$$c_i(x,y,z,t) = f(Q_1,Q_2,Q_3,...v_1,v_2,v_3,...) \quad (6.3)$$

where the dependent variable c_i represents concentration of pollutant i at some point x,y,z and time t, the Q's denote strengths of associated emission sources, and the v's the remaining ensemble of independent model variables such as winds, solar insolation, and deposition rates. Inverse modeling for source evaluation involves a reformulation of the modeling equations to express the Q variables (usually implicitly) in terms of the observed concentrations, combined with the remaining independent variables. This essentially involves "running the model backwards," hence the term "inverse modeling."

The mathematical details associated with inverse modeling are described in a number of texts (e.g., Bennett, 2002). To date inverse-model applications have been much more extensive in non-atmospheric areas such as ground-water contaminant transport and seismic analysis (e.g., Parker, 1994; Zheng and Bennett, 2002), although significant recent advances have occurred in the atmospheric field (Bennett, 2002; Enting, 2002).

Although inverse modeling is currently considered a potentially useful top-down verification of existing, bottom-up emission inventories, it is not generally viewed as a direct tool for quantifying specific emission sources. There are two major reasons for this. First, the source-receptor models applied for inverse analysis are subject to substantial overall (i.e., global) uncertainty, owing to stochastic considerations as well as to uncertainties in model characterizations of individual contributing phenomena. Emissions calculated from inverse models on the basis of sampled concentration values are typically highly sensitive to this global uncertainty. Second, the sampled concentration data applied for inverse-model analysis must be chosen judiciously, and one must be careful to collect a sufficient number of samples to provide a well-specified mathematical system. Information redundancies between data samples – which are usually difficult to evaluate in a direct manner – add to the complexity of this specification problem. It is apparent that future model improvements combined with accumulated application experience will render inverse-modeling applications more quantitative during future years.

Inverse-model applications for atmospheric source analysis have been confined mainly to large-scale phenomena and disperse sources, such as global

CO_2 emissions (Gurney et al., 2002), global CO emissions (Pétron et al., 2002; Palmer et al., 2003a,b; Kasibhatla et al., 2003), and continental NH_3 and carbonaceous PM emissions (Gilliland et al., 2003; Park et al., 2003).

As noted above, atmospheric inverse-modeling techniques have lagged those in the other geological sciences. Improvements in atmospheric models combined with more general appreciation of the technique's potential for emission analysis, however, will undoubtedly result in significantly increased application during future years. It can be anticipated that future intensive field studies will be designed with direct inverse-model applications in mind, resulting in collection of data specifically intended for this purpose.

6.2.3 Specialized Field-Study Design

The use of models to evaluate emissions, and the application of specialized measurements, are optimized by a careful design for field studies. Experience in developing appropriate designs for verifying emissions from different sources has expanded dramatically in the last decade or so. Field studies have become increasingly expensive, yet there are significant opportunities to conduct meaningful experiments with relatively simple and inexpensive approaches. Perhaps the simplest situation concerns the emissions from a single source. Complexity increases substantially when multiple sources of individual species are present.

Ideally a source-verification design should include:

- At least qualitative specification of the chemical constituents emitted by the source, and identification of similar sources in the surroundings that may confound the emission estimation.
- Specification of the time duration for estimating the emission rate, determination of the expected material input and process variables (e.g., fuel composition), and notation of the availability of test data from this or a similar source.
- Identification of appropriate sampling and instrumentation, including response times, specificity of composition, etc. to determine or estimate the emissions for the period of interest.
- Consideration of ancillary tracer measurements to assist in tracking the plume a posteriori.
- Consideration of the chemical reactions that may take place between the exit point and downstream tens of meters.

Few source-oriented experiments aimed at establishing emissions have taken all these requirements into consideration. However, a number of recent studies have been designed to account for some of the elements listed above. Notable among the design of source-oriented experiments recently are hybrid-source receptor studies including the investigation of the Mojave power plant in southern Nevada (e.g., Eatough et al., 2000), the Hayden and Craig power plants in west-central Colorado (Watson et al., 1996), the Nashville urban and power plant studies (e.g., Ryerson et al., 1998), the BRAVO experiment (Pitchford et al., 2004), and TexAQ2000 (2003). These studies were not designed to obtain emission rates per se, but emission rates were a necessary element for the studies to examine dispersal of the plume and its impact on surrounding areas, including human exposure, and visibility degradation.

6.3 ADVANCED DATABASE MANAGEMENT

In Chapter 2, a vision for improved database management was described. This vision includes applying innovative methods from areas outside of pollution engineering technology. While applying new methods from outside the field will take place over time, there are a number of opportunities to apply conventional database management approachs today. This section summarizes these opportunities.

Emission inventories like the U.S. NEI contain very large data collections. The NEI alone, for example, contains more than 60 million items. Access to the inventories now involves complex manipulations of data, which remain user "unfriendly." A major challenge for managers of emission data, along with producing quantitative uncertainty estimates,

is the development of a means for access that uses contemporary management techniques, accommodates a variety of different data sources, and ensures data quality. This challenge is compounded by the need for efficient access of large amounts of spatially and temporally resolved data for air quality modeling. Access to these collections depends not only on efficiency of entering the tabulations for specific locations and times, but also on the ability to summarize emissions in terms of sources and emission density graphically, or by other visual means.

Most current emission databases are not seamlessly integrated with the other information sources needed to design emission control strategies. For example, the task of de-trending air quality data to isolate the effect of meteorological fluctuations and year-to-year emission changes is made extremely cumbersome by the data architectures currently used by regulatory agencies. The problem is further compounded by the fact that the emission databases typically are not integrated with geographically encoded land-use and urban-planning information systems. There has been an explosion in the use of GIS by urban planning agencies; but these advances are only beginning to be incorporated into the systems used by air pollution agencies. Moreover, there is a distinct need for standardized electronic, possibly Internet-based, data-reporting systems, which will allow industries and state/local/tribal agencies to report data, make emission estimates, and perform quality-control checks online.

When designing the data architectures and reporting systems it must be recognized that inventories serve multiple purposes. One of the reasons why there are no real incentives to improve the quality of the existing data is that the local agencies charged with the permitting process do not derive any real benefits from the current systems that are used to aggregate emissions for air quality modeling studies. Once the local data are aggregated to the state and regional levels, there is no feedback to the permitting officers. Open access to local emission information would provide an incentive for both the public and industry to ensure that the information is correct. As previously discussed, collection and submittal of emission inventory information by agencies might be improved if federal or state funding is explicitly linked to these activities being completed.

In the future, it is expected that a North American emission inventory will be universally available to all who want to access its information. This facility should be capable of handling information that has high temporal and spatial resolution, is source and facility specific, is comprehensive with respect to pollutants and sources, is well documented, and is based on comparable methodologies and factors. North American emission inventories need to be cast in common formats and units, or transparent conversion between metric and English units should be built into the data management software. Advances in information technology and the pursuit of collaboration among emission inventory organizations are paving the way to an inventory that meets these goals.

6.3.1 Distributed Emission Inventory Network

The guiding principles of an integrated emission inventory follow those of distributed databases and distributed computing. The design objectives are to create a network of relevant data, as well as visualization and analysis tools, which is characterized by the following attributes:

Distributed. Data are shared but remain distributed and maintained by their original inventory organizations. The data are dynamically accessed from multiple sources through the Internet rather than collecting all emission data in a single repository. Responsibility for data quality and availability remains with the data providers; however, data users also can make their collated and refined data sets available to other users via this distributed system.

Non-intrusive. The technologies needed to bring inventory nodes together in a distributed network need not be intrusive in the sense of requiring substantial modifications by the emission inventory organizations in order to participate. However, there will need to be some harmonization of existing inventory data and

structures and assignment of certain functions to maintain a fluid system.

Transparent. From the emission inventory user's perspective, the distributed data should appear to originate from a single database to the end user. One-stop shopping and one interface to multiple data sets are desired without required special software or download on the user's computer.

Flexible/Extendable. An emission data network should be designed with the ability to easily incorporate new data and tools from new providers joining the network so that they can be integrated with existing data and tools.

Figure 6.4 depicts an envisioned end state of a distributed emission inventory. Distributed data sources (emission estimates, activity data, surrogates, etc) in a variety of formats (relational database-management systems, text files, etc.) are available through the Internet and registered in one or more data catalogs. These data can be uniformly accessed with the aid of data wrappers (translators) and connected with web tools and services to support a variety of end applications. Mediators are used to find and combine the appropriate mix of data and services to fulfill a user's task.

Information technologies available to develop a distributed emission inventory include web services and related interoperability standards, such as the OpenGIS Consortium Web Map Server and Web Feature Server specifications. An important aspect of many of these technologies is that they can be implemented without requiring substantial modifications of the existing emission inventory databases and data dissemination systems.

6.3.2 Data Sharing and Web Services

Many emission databases are already accessible through Internet-based methods either through direct data-file download or through web query tools. The query systems allow users to filter and access data at multiple levels of detail. These systems were designed to meet the needs of individual end users who log in to the online system, manually complete forms for defining their query, and then view the results in tables/graphics or download the data. While these systems serve the individual user, they are not easily integrated into a distributed emission inventory framework where automated computer-to-computer, rather than human-to-computer access is needed. However, supplementing existing systems with distributed data capabilities is feasible.

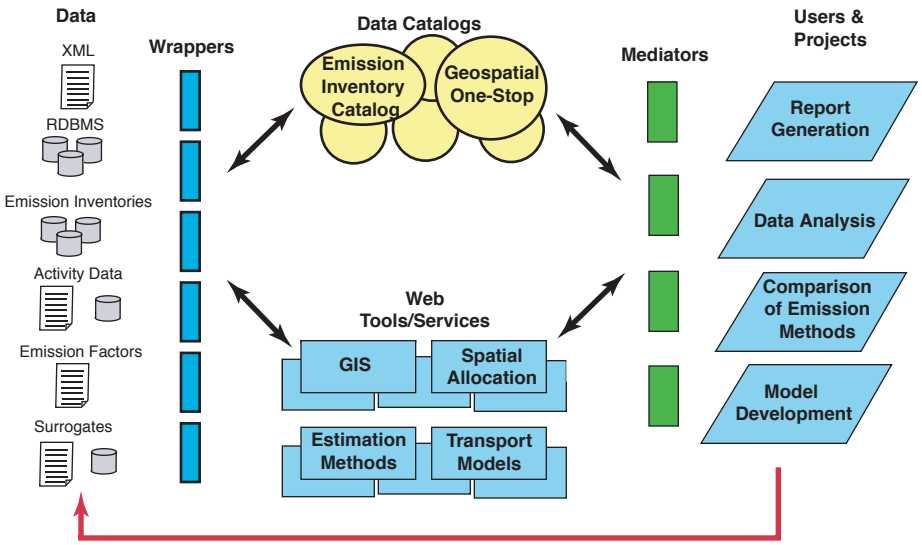

Figure 6.4. Conceptual Diagram of a Distributed Emission Inventory.

Approaches to developing distributed emission inventory databases can be grouped into two general categories: those that make data files available for external access and those that implement innovative information technologies and standards to make their data dynamically accessible.

For smaller inventories the solution can be straightforward – provide an Internet (ftp or http) address where Microsoft Access, Microsoft Excel, or ASCII text files are stored, giving a description of the data format and a consistent file-naming convention. For example, if emission inventory A has point emission data for each year since 2000 and each year is stored in a separate file, they might use a naming convention such as NAME_Type_Year so that the files stores would be InventoryA_Point_2000.dat, InventoryA_Point_2001.dat, and so forth. An external user can then automatically access these data using a 'get data' request based on that inventory's file naming convention. When new data become available in the inventory, the 'get data' request can automatically retrieve the new data.

For larger, more complex inventories, alternative methods are in order. Certainly, a larger inventory could provide subsets of its inventory in separate files through ftp or http addresses. A more attractive scenario is where the forms that allow users to query the inventory are "filled out" by the computer rather than by hand. This would allow dynamic access to the data and opens possibilities for "middleware" to provide value-added processes (filtering, aggregation, and integration) to the data. Middleware may make the data available in a specialized format, in different graphical views, or through tools that allow the data to be combined with other data. For example, a middleware application may provide a tool that could access multiple distributed inventories through a single query form thereby avoiding the need for a single user to access each inventory individually. The use of standardized naming conventions and adhering to national and international standards provided by the National Institute of Standards and Technology and the International Organization for Standardization greatly simplifies the task of providing data to the users. The U.S. EPA efforts to implement the Federal Registry System may facilitate the integration of disparate databases for industrial facilities.

An emission network using middleware would allow automated access to each emission node on the network after each data server implemented a web interface method of dynamically accessing its data. A new category of information technology, called web services, offers one method for creating nodes on the distributed network. Web services consist of self-contained software that uses XML-based standards for describing themselves and communicating with other web resources. These characteristics allow web services to be reused in a variety of independent applications.

In the web services network approach, mediators serve the role of brokers, providing users with the interfaces for finding available data, dynamically retrieving it, and integrating it with other distributed data sources. These network users can function on an independent level, each addressing local issues of importance. These individual components can then be integrated or modified to handle differing data types dynamically on demand.

Web service technology is still evolving and does not currently provide a complete off-the shelf software solution. However, many required components are considered standards in web programming applications and therefore make it possible to create an operational data web service network. These components allow computer-to-computer communication in a platform- and programming language independent manner. Additionally, web service technology provides existing software applications with service interfaces without changing the original applications, allowing them to fully operate in the user's existing environment.

Distributed data network principles are being studied and implemented by a variety of emission relevant projects and programs:

- The CEC commissioned a study examining available data and technology for a distributed North American emission inventory (http://capita.wustl.edu/NamEN).
- The U.S. EPA is initiating a program for Networked Emission Inventories for Global Emission Inventories (http://www.neisgei.org).

- A NASA- and NSF-funded project is pursuing web services for aerosol data and tools (http://www.datafed.net).
- The U.S. EPA is developing a network for exchanging data between states and the agency (http://exchangenetwork.net).
- A U.S. federal effort aims to provide single-point access to interoperable data sources (http://www.geo-one-stop.gov).

Other examples of Internet-based systems include CARB's GIS mapping tool, recently developed to display the amounts and spatial distributions of emissions in California. The prototype system is called CHAPIS, Community Health Air Pollution Information System, and provides a mapping tool to analyze the spatial distribution of emissions from point, area, and mobile sources of various criteria and toxic air pollutants. In addition, the Great Lakes Commission has begun development of an Internet-based system to provide emission data, including charting and mapping tools designed to meet client needs. The system is called CAROL, Centralized Air emission Repository OnLine, and is designed to provide easy access to the Great Lakes Toxic Air Pollutant Emission Inventory.

The distributed emission inventory concept, combined with electronic formatting for data entry, and electronic access to AP-42 data is expected to enhance the timeliness of developing a bottom-up emission inventory like the NEI. In time, analogous methods are likely to be deployed in Canada and Mexico to assist the three nations in more rapid, accurate development of the inventories.

6.4 SUMMARY AND CONCLUSIONS

The previous sections of this chapter lead to a number of important conclusions concerning tools for future emission inventory development and communication. First, the examples given here demonstrate that a number of observation and analysis techniques are currently in or beyond the development stage, and offer major opportunities for improving emission rate estimation. Most of the noted techniques provide data for determining emission rates directly, allowing their results to be adopted into the inventory structure without applying the emission factor/activity factor paradigm of Equation (2.1). While these methodologies represent various levels of maturity, all show considerable potential for future use, and many can be applied to address the weaknesses of today's inventories discussed in Chapters 5 and 7.

Second, many (but not all) of the techniques discussed here are more amenable to constructing top-down "reality checks" of bottom-up inventory estimates, rather than themselves providing bottom-up information. While this associates a somewhat secondary nature with these techniques, they are nonetheless highly relevant for three important reasons:

- Major improvements in cost-effective source characterization can be achieved with new ambient air measurements. These measurements provide direct estimates of emission rates which complement conventional stack or source testing. The array of ambient observation techniques offers important opportunities for emission observations, especially for sources such as transportation and fugitive categories, which are otherwise difficult to characterize.
- On occasion, top-down checks such as aircraft and satellite observations have indicated major errors in previously existing bottom-up inventories. Examples in this chapter and in Chapter 7 give evidence for this finding.
- Many circumstances involving multiple small and/or fugitive sources result in significant emissions, but are difficult if not impossible to characterize using conventional bottom-up techniques. Under such circumstances those techniques normally described as "top-down" become the only practical approach for emission estimates.

Third, optimum effectiveness of many of the methods described here often lies in a combination of two or more of these techniques. Aircraft observations combined with an inverse-modeling interpretation is an example of such a combination.

Fourth, potential advances in database management techniques, practices, and facilities can be expected to substantially enhance the future access, usability, and quality of emission inventory data. Although some highly visionary advancements have been suggested for the future many, somewhat less ambitious, improvements can be incorporated over the near term. Forming a distributed emission inventory data network is a key example of such an action.

Fifth, significant improvements are possible for conventional emission inventory analysis, including refining estimates of emission factors and activity factors. Utilizing data from enhanced ambient monitoring capability, newer measurement techniques for deriving factors, and relating such data to conventional reference test methods, are particularly challenging aspects of this effort.

Finally, and as noted in the introduction to this chapter, members of the emission inventory community should recognize that they themselves are primarily responsible for pursuing this advanced agenda. To do this, it is important to establish an active, two-way dialog between emission inventory developers and scientists involved in creating future measurement and interpretive methodologies. Active promotion of this interaction is a strong recommendation of this Assessment.

Table 6.4 summarizes these techniques and provides an indication of where the different methodologies are linked with current emission inventory deficiencies. Although the tabulation does not evaluate whether new methods are superior to older techniques, it clearly shows that a variety of opportunities exist for enhancing the available information for inventory development.

The following recommendations derive from this chapter:

- Where appropriate resources are available, special efforts should be made to take advantage of the contemporary measurement methods and source-characterization experiments noted in this chapter to minimize the use of AP-42–based emission estimates, which involve "default" characterizations of undetermined local applicability.
- Increased effort should be made to maximize use of ambient measurements for deducing emission rates and chemical-source profiles, as well as for cross-checking existing emission inventories. The use of receptor-modeling and and inverse-modeling techniques, in combination with regulatory air quality modeling analysis should be encouraged for this purpose.
- Increased efforts should be fostered to increase the accessibility, transparency and timeliness of emission inventory publication by taking advantage of contemporary information technologies.
- Establishment of a continuing dialog between emission inventory developers and scientists involved in creating future measurement and interpretive methodologies will facilitate future development and the widespread application of emerging technologies exemplified here.

Table 6.4. A Summary of Weaknesses in Emission Inventories Addressed by Innovative Technology Applications (3 pages).

Identified uncertainty	Satellite/aircraft remote sensing	Ground remote sensing	Alternative mobile measurements	Dilution tunnel	CEMS	Aircraft plume observations	Direct flux measurements	"Top down" modeling	Advanced data management.	Comments
All sources										
Quantify uncertainties	--	Opportunities for stationary mobile	Options to enhance real world data	Improve source data, account for semivolatiles and range of emissions	Large potential for stationary sources	Cross-check for emission factors and emission reports	Important for fugitives and natural emissions	Assist in quantifying uncertainty	Include uncertainty in data base	Special measurements limited by short-term samples/models
Small sample limitation	Helpful for location, and possibly large scale	Potentially important for stationary and mobile	Add substantial fleet data	--	Addresses small sample limit	--	--	Means for extrapolation to many sources	--	Remote sensing potential large but detection limit a problem
Spatial/ temporal disaggregation	Assist for large scale	Can clarify disaggregation	Mostly small scale observations	--	Addresses this issue at single source level	Assists in spatial resolution of plumes	Small scale fluxes point measured	Means for addressing multiscale	--	Rely heavily on modeling with measurement support - Satellite or spatial/ temporal measurements potentially useful
Multiscale resolution	Assist for large scale	Best for small scale resolution	Mainly small scale	--	--	Assists in spatial resolution	Small scale fluxes	Means for extrapolating to multiscale	Represent multiscale in data base	Modeling key to integrating point measures - remote sensing may assist
Timely update and report	Adopt satellite technology where possible to add to timely data access	--	--	--	Automated data shortens report time	--	--	--	Key to timely reporting	Organization of data mgmt. combined with continuous measurements with automation will resolve this weak
Rigorous QC/QA application	--	Offers a means of cross-checking estimates	Cross-check on model estimates	Cross-check on emissions	Easier to formalize process	Adds method for cross-checking		Cross-check on emission models	Important for QC/QA	Add measurement cross-checks and modeling as key tools

Table 6.4. A Summary of Weaknesses in Emission Inventories Addressed by Innovative Technology Applications (3 pages).

Identified uncertainty	Satellite/aircraft remote sensing	Ground remote sensing	Alternative mobile measurements	Dilution tunnel	CEMS	Aircraft plume observations	Direct flux measurements	"Top down" modeling	Advanced data management.	Comments
Documentation inadequate	--	--	--	--	Formalizes reporting	--	--	--	Important to documentation	Increased accessibility and transparency will depend on documents
Biogenic component not characterized	Potential application of land use and biogenic inference	Potential for small scale flux measurements	--	--	--	Potential for flux measure	Important for biogenics	Cross-check on emission models	Must include reporting of biogenics	Increasing importance for criteria pollutants and large scale phenomena
Large uncertainty in toxic air pollutants	--	Sensors limited but potential	Opportunities for special pollutants, ultrafines, and HAPs	Capable of toxic air pollutant testing	Limited sensors for toxic air pollutants	--	--	Crosscheck on emission esimates	Attention to data base important for improving emission inventories	Special concerns for measurements or sample-detection limits
Stationary sources										
Uncertainty w/o CEMS	Qualitative locator for plumes	Complement CEMS for testing	--	Complement sampling for exotic species	--	Adds means of cross-check of default emission and activity factors	--	Crosscheck on emission estimates	Need for integrating CEMS with conventional data	Develop low cost CEMS for deployment to new categories of sources
Multiple source averages and short sample	--	Study a subset for limits of averages and sampling	Nonroad cases may be important for sampling	--	Facilitates multiple source averaging	--	--	Cross-check on emission estimates	Add document for limitations and uncertainty	Long term study use CEMS
Area/mobile sources										
Limitations for fugitive and mobile emissions	Locator for multiscale dust storms, fires, land use	Potential for some fugitive/ mobile source testing	Cross-check on model estimates	Important for SVOC from combustion	--	Potential for improving flux measures	Opportunity to reduce area source uncertainty	Cross-check on estimates for multiscales	Document limitations and uncertainty-links with models	Recognize increasing importance of fugitive emissions and other source types

Table 6.4. A Summary of Weaknesses in Emission Inventories Addressed by Innovative Technology Applications (3 pages).

Identified uncertainty	Satellite/aircraft remote sensing	Ground remote sensing	Alternative mobile measurements	Dilution tunnel	CEMS	Aircraft plume observations	Direct flux measurements	"Top down" modeling	Advanced data management.	Comments
Limitations from updating	--	Can add tools for update data	Can add observations for updating with real-world fleet	Provide insight on SVOC and ultrafines	--	--	Provides a means for update fugitives		Document changes, upgrades and flag new data	Important function for data management
Mobile/ fugitive not rated for quality	Cross-check on location of impact from multi scale events	Can add data for quality check	Support for quality rating	Revise report for emissions	--	Adds a means of cross-check	Improves quality estimate	Crosscheck on multiscale estimates	Add documentation in system	Important to account for fugitive emissions and mobile fleet categories
Large uncertainties for all vehicle classes undocumented	--	Cross road measurements proven for data	can add observations for improving documented emissions	Add data for testing in laboratories	--	--	--	Cross-check on vehicle fleets	Add to data management system with new data and uncertainty estimates	Priority steps to reduce uncertainty in fleet descriptions important
Models do not account for real world variability	--	Should enhance inventory using receptor and inverse model	Improve knowledge of real word fleet emissions	--	--	--	Improve fugitive and biogenic models with actual observations	Models needed to compare real world data with emission models	Facilitate linkage between data and models	Importance of mobile sources and natural emissions for OC increasing
Nonroad emissions based on default estimates/ uncertainty undocumented	--	Observations should improve estimating emissions	--	Use for estimation of uncertainties comparable with mobile	--	--	--	Add for cross-check	Add emiss. modeling link with data management	Need to add data to account for changing fuels
Nonroad emissions not tied to real world measurements	--	Obs. Should improve with use of remote sensing	--	Use for estimation of OC and BC, toxic air pollutants	Potential for inexpensive CEMS-like sensors	--	--	Improve estimates using adv. NONROAD and cross-check measures	Add to data management platform with link to models	Need to add data for alternate fuels

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CHAPTER 7

TOP-DOWN ASSESSMENTS OF EMISSION INVENTORIES

Chapter 7 Objectives:

- ***To introduce top-down techniques for evaluating the strengths and weaknesses of current inventories***
- ***To provide evaluations of important sectors of current inventories.***

This chapter uses some of the tools of Chapter 6 to estimate quantitative confidence limits on the emission estimates for a few of the more important source categories. This chapter illustrates through several examples the likely magnitude of uncertainty in aggregated national emissions and some specific urban or point sources. Only the U.S. NEI is directly considered here for three reasons. First, Canada and Mexico often follow U.S. inventory development techniques, so the uncertainty assessment techniques for the U.S. NEI will likely be applicable to those inventories as well. Second, the NEI is the U.S. inventory of greatest interest and applicability, and it is readily available for investigation through publicly accessible documents. Third, the states have reviewed and provided input for the U.S. NEI inventories for their areas as used for SIPs.

This chapter has two major objectives: first, to introduce various top-down techniques for evaluating the strengths and weaknesses of current inventories, and second, to provide evaluations, as far as possible, of important sectors of current inventories. Top-down tests of emission inventories are tests conducted outside the structure of the emission inventory. They do not explicitly consider the individual components (e.g., emission factors or activity factors) that go into the development of inventories from the bottom up. Rather they consider independent information such as ambient measurements of the emitted species. Thus, a top-down approach can be thought of as an attempt to partially confirm an inventory. Ideally, such a test is designed to address a critical aspect of an inventory in a simple and unambiguous manner.

Although top-down tests provide an indication of the accuracy of existing inventories, they do not provide clear guidance regarding the specific cause of any identified inaccuracies. Chapter 8 deals with systematic approaches for quantifying inventory uncertainty from the bottom up; i.e., working within the structure of the inventory to derive a quantitative measure of the inventory uncertainty through uncertainty analysis and sensitivity analysis. These approaches are complementary to the top-down tests, because they can apportion the uncertainty to the various components that go into the inventory. Such apportionment is critical for identifying the most effective approach for improving inventories.

In the following, it is assumed that the ambient measurements or other independent information used in the evaluations are accurate, and that they are correctly interpreted for both national and local conditions. Any discrepancies identified are assumed to be due to weaknesses in the inventories, and, where possible, suggestions for the modification of the inventories are made so as to resolve the discrepancies. However, the accuracy and interpretation of the measurements may have weaknesses themselves. As reflected in Figure 2.1 and the discussion in Box 7.1, the discussion presented here must be considered as only the first step in a repetitive process of improving

Box 7.1 Verification, Validation and Confirmation

Oreskes et al. (1994) provide a useful context for assessing any emission inventory. They note that:

- In a rigorously defined sense it is impossible to verify or validate any numerical model. Such terms imply that the model is an exact representation of a real system, while any model is necessarily an incomplete description of reality.
- At best a model can be partially confirmed by demonstration of agreement between the results of the model and observational data. This confirmation increases confidence in the utility of the model for its designed purposes. However, the confirmation must remain incomplete because, regardless of how many confirmatory tests are satisfactorily completed, additional tests may reveal inconsistencies between the model and present or future observations.

both the inventories and their evaluation through these top-down tests. The ultimate goal is to bring the inventories and their evaluations into agreement.

7.1 EVALUATION OF ONROAD VEHICLE EMISSIONS IN THE UNITED STATES

Onroad vehicle emissions are perhaps the most important sector of the inventory relating to criteria or criteria-related pollutants because (1) they account for a major share of VOC, NO_x and CO emissions; (2) these VOC emissions provide the majority of the most photochemically reactive VOCs; and (3) these emissions are localized in urban areas, which account for the majority of the NAAQS ozone violations. Accurate emission estimation for this source is difficult since it must entail the integration of the emission factors (e.g., grams / mile driven) for a diverse, constantly evolving vehicle fleet multiplied by highly variable activity factors (e.g., average miles driven per unit time for each vehicle type under varying vehicle operating conditions such as ratios of cold starts or high-load accelerations). This section examines the reported onroad vehicle emissions of VOC, NO_x and CO for internal consistency over the past two decades and identifies inconsistencies with ambient measurements, which may indicate weaknesses of the inventories. NRC (2000) notes that quantitative estimates of overall accuracy and uncertainty have not been provided for inventoried onroad emissions, due to the lack of available data. At least an initial assessment of the accuracy of these emission estimates is provided here.

Two features of this section should be noted. First, wherever possible, national emissions are tested, even though local, county-level emission inventories exist. This approach requires nationally representative data, rather than purely local measurements to reach as general conclusions as possible. However, studies of local or regional inventories can yield important tests of inventories; for example the investigation of the weekday-weekend effect in California have shed light on disparities in the MOBILE6 model (see e.g., Fujita et al., 2003a,b and other papers in that journal issue). Second, no evaluation of PM emissions from onroad vehicles has been included in this chapter; however developing better PM inventories is of high priority. Source apportionment studies have given an idea of how PM sources are divided between direct emissions and secondary formation in the atmosphere, and how the direct emissions compare with the emission inventories. Presently the MOBILE6.2 model does not cover high-emitting PM vehicles for either gasoline or diesel fuel classes; current work is underway to incorporate these high-emitters into the model.

7.1.1 History of Temporal Trends of Onroad Vehicle Emissions

The U.S. EPA regularly reports estimated emissions and their trends over the previous decades, generally in annual National Air Quality and Emissions Trends Reports. Recently these reports have been supplemented with emission tables posted on the website of the Technology Transfer Network:

Clearinghouse for Inventories & Emission Factors (http://www.epa.gov/ttn/chief/trends/index.html). This section compares a recent historical sample of these Trends Reports (U.S. EPA, 1990; 1995; 2000; 2003) with an earlier inventory developed for NAPAP (Saeger et. al., 1989) and the most recent emission tables (1970 – 2002; average annual emissions, all criteria pollutants - posted November 22, 2004 on the above website.) This comparison aims to determine if the estimated trends are converging to more precisely defined values, or if there is a significant element of scatter in the estimates that may indicate fundamental uncertainties in the estimation methods.

Figure 7.1 presents estimated onroad emissions from the six references listed above for VOC, NO_x and CO. It is important to note that the 2004 Trends Tables utilize the latest MOBILE6 model, and that those tables are consistent with Version 3 of the 1999 U.S. NEI. All of the other reports use earlier versions of the model to estimate onroad vehicle emissions. In the following tests, greater emphasis will be placed on the two more recent reports for present and past years. The Trends Reports are revised from year to year; both the current year and prior year inventories are updated using the latest models and other information.

From the figure it is clear that the different inventory development techniques that have been used over the years have yielded results that differ in some important respects. For 1998 (the last year reported in the 2000 Trends Report) only minor increases of 10 and 14 percent are noted in the VOC and NO_x emissions, respectively, between 2000 and the later estimates. However, the estimate for CO increased by 45 percent. These comparisons show that the most recent nationally aggregated emission estimates are different by at least ~10-15 percent for VOC and NO_x and ~50 percent for CO. These comparisons suggest that there is significant uncertainty in the emission estimates.

Also of concern is the larger variability apparent in the estimates for earlier years. For example, for 1985 (the one year with estimates from all six inventories) the 2004 estimate is higher than all previous estimates by factors of up to 1.6, 1.4 and 2.5 for VOC, NO_x, and CO, respectively. These relatively large factors indicate that the onroad emission estimates for the

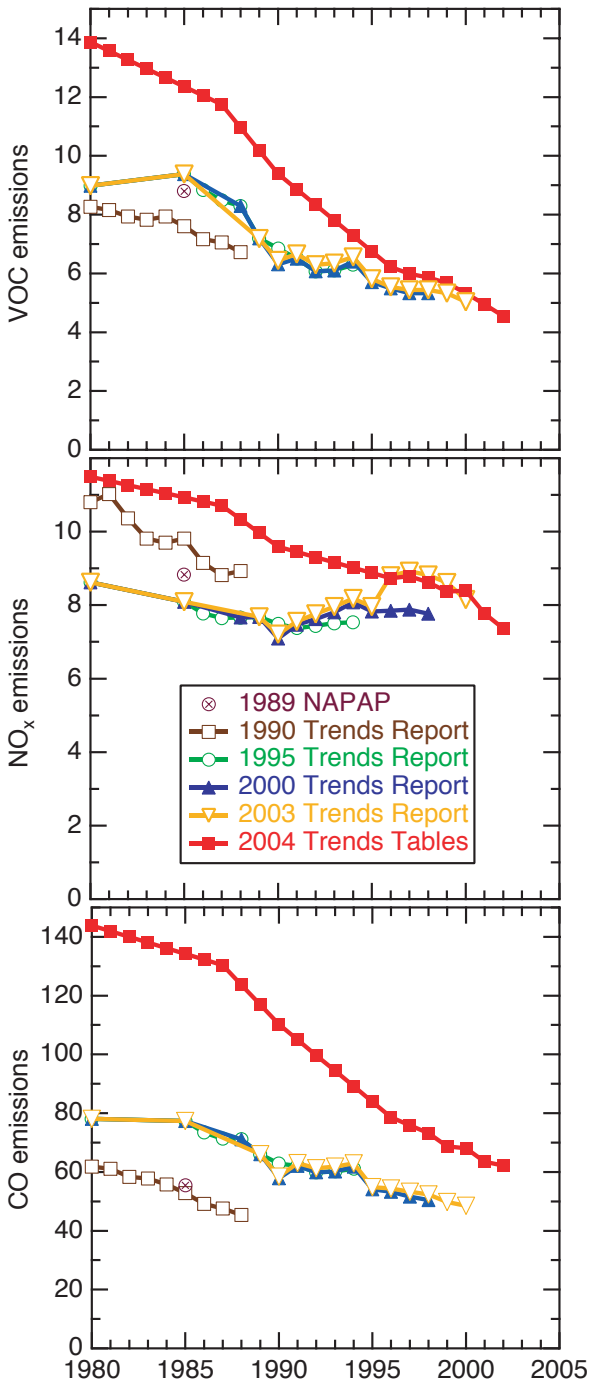

Figure 7.1. National onroad vehicle emission estimates from six U.S. inventories in units of 10^6 tons/yr. All estimates are for onroad vehicle emissions only, except for NAPAP and the 1990 Trends Report which include total transport sources. For CO, NAPAP includes total area sources; these are the most detailed breakdowns available in the published reports. The dates indicate the year of publication of the inventory report.

past two decades are significantly less certain than the estimates for more recent years.

7.1.2 Temporal Trends of Onroad Vehicle CO Emissions Compared to Ambient Observations

Analysis of ambient measurements of emitted species can, in many instances, provide valuable insights into the magnitudes and temporal trends of the emissions that produce those ambient concentrations. The goal here is to use the temporal trend of ambient CO concentrations in U.S. urban areas to test the temporal trends of reported CO emissions from onroad vehicles. CO is selected for this analysis because reliable ambient measurements have been made over the last three decades at hundreds of urban stations throughout the U.S.

It is possible to select aggregated ambient CO data that closely reflect onroad vehicle emissions. The maximum CO levels observed in urban areas are utilized here. In 2002 (the latest year covered by the 2004 Trends Tables) 56 percent of total CO emissions are attributed to onroad vehicles, which are highly localized in urban areas. The maximum CO levels occur in winter, when urban emissions from the two other major CO sources are minimized. These sources are 22 percent from offroad vehicles, primarily lawn and garden and recreational vehicles, which maximize in the summer, and 15 percent from forest and agricultural burning, which also maximize in the summer and generally occur outside urban areas. A minor confounding factor is the background levels of CO likely transported into urban areas. However, these levels are a few tenths of a ppmv, so their influence can be neglected. Hence temporal trends in maximum urban CO levels can be confidently attributed to trends in CO emissions from onroad vehicles.

Figure 7.2 compares measured mean CO ambient levels with the emissions from Figure 7.1 for the two most recent emission reports. The ambient mixing ratios correspond to the mean maximum levels observed at more than 300 U.S. urban sites, which are tabulated in the U.S. EPA Trends Reports. (The statistic reported is the second highest annual maximum 8-hour average).

The trend of the mean ambient concentration follows the trend in the 2004 Trends Tables much more closely than that in the 2003 Trends Report. This suggests that the MOBILE6 model is correctly predicting the relative changes in CO emission rates with time. This conclusion is supported by the average 1985-2000 yearly decreases: 4.9 percent/year for the ambient concentrations compared to 4.9 and 2.8 percent/year for the 2004 Trends Tables and 2003 Trends Reports, respectively. However, while these comparisons indicate that the temporal trend in the 2004 Tables is more realistic than that in the 2003 Report, the comparisons provide no information regarding the accuracy of the emission magnitudes in any particular year or report.

7.1.3 Onroad Vehicle CO/NO_x Emission Ratios Compared to Ambient Measurements

In favorable situations, ratios of ambient concentrations can be directly compared with ratios of emitted species. For example, Fujita et al. (1992) showed that the ratios of ambient CO to NO_x concentrations measured during the morning traffic peak provided an accurate indication of the emission ratios of these species from onroad vehicles in the California South Coast air basin. The goal here is to use measured ambient CO/NO_x ratios obtained throughout the United States to test reported CO and NO_x emissions from onroad vehicles.

Parrish et al. (2002) showed that ambient measurements at carefully selected urban sites accurately reflect the absolute values and temporal trends of the CO to NO_x ratio in onroad vehicle emissions. For CO/NO_x ratios the separation of the influence of onroad vehicle emissions from the influence of other source emissions is of greater concern than for the ambient CO levels discussed in the preceding section. Compared to CO, NO_x from onroad vehicles account for a smaller fraction (35 percent) of the total NO_x emissions, while the two other major sources (offroad vehicles and industrial plus electrical power generation) account for larger fractions (19 percent and 44 percent, respectively). It is important to minimize the confounding influence of these two sources. A four-pronged approach is adopted:

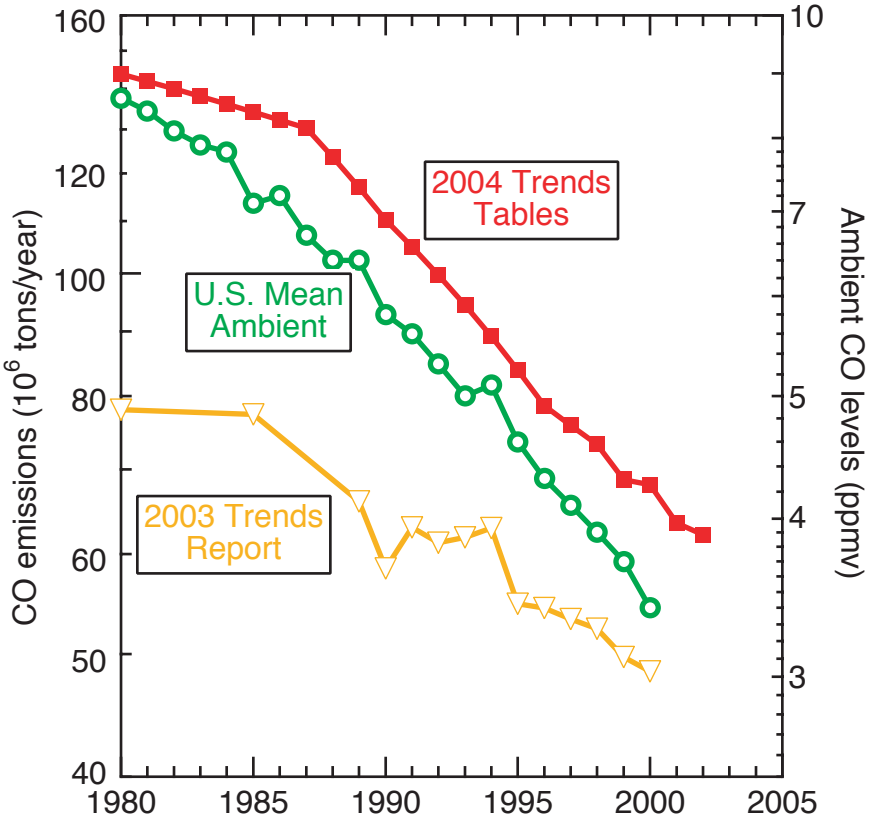

Figure 7.2. Semi-log plot of national onroad vehicle temporal emission trends. Two U.S. inventories are compared to observed second-highest annual maximum 8-hr average concentration.

1. Data are considered only from urban areas, where the onroad emissions are localized. In general, the other major NO_x and CO sources are less localized in these areas.

2. Data that avoid very local sources and reflect well-mixed urban emissions are utilized when possible. The goal is to obtain measurements representative of the urban onroad vehicle fleet rather than any particular traffic flow.

3. Data are considered only from the morning onroad vehicle traffic peak, which minimizes several potential problems. First, this is the time of maximum onroad vehicle traffic volume and especially maximum ambient concentrations from those emissions, since they are confined to a shallow mixed layer. Second, this is also likely to be a period of minimum offroad vehicle activity. Third, the influence of industrial and electrical power generation emissions are minimized, because they are predominantly above the morning mixed layer. Finally, this morning period is characterized by low photochemical activity, so the loss of emitted NO_x due to photochemical conversion and deposition processes will minimally perturb the ambient CO/NO_x ratios from those emitted.

4. The CO/NO_x emission ratios are determined from the slope of the correlation between measured CO and NO_x mixing ratios as discussed more fully by Fujita et al. (1992) and Parrish et al. (2002). This analysis has three important attributes. First, transport of regional levels of CO into the urban area does not affect the analysis, because the intercept but not the slope of the correlation is affected by that transport. Second, industry and electrical power generation sources emit little CO, so NO_x from these sources is poorly correlated with CO, and has little influence on the slope. Third, the offroad vehicle

contributions to CO and NO_x emissions are also poorly correlated, since lawn and garden gasoline engines dominate CO emissions and nonroad diesel engines dominate NO_x emissions; thus, these emissions also have little influence on the slope.

Figure 7.3 shows the CO to NO_x emission ratios from onroad vehicles from the two most recent emission reports discussed in the preceding sections, and compares these inventory ratios to CO/NO_x ratios derived from the five ambient data sets summarized in Table 7.1. All of the ambient data are from the summer, except for the wintertime Boulder study. The Nashville and Boulder results (for clarity this latter site is not included in Figure 7.3) are from single sites selected to sample well-mixed urban onroad vehicle emissions. CO and NO_x at these sites are highly correlated ($r^2 \geq 0.9$), indicating the site selection was successful. The site in Atlanta, GA has only a short data record (the point in Figure 7.3 represents the average for 1991-2001 August data) with weaker correlations ($r^2 = 0.5$ to 0.8), which reflect the site's closer proximity to local traffic. The Los Angeles data set combines all August data from eight sites distributed throughout that region. The 1987 result is from Fujita et al. (1992); the later results are from the same sites, except the Pomona, CA site has been substituted for the discontinued Claremont, CA site used by Fujita et al. (1992). Perhaps surprisingly, these CO and NO_x data are highly correlated ($r^2 =$ 0.8 to 0.9), which indicates a highly homogenous onroad vehicle emission mix throughout the Los Angeles region. Finally, the AIRS data set includes all co-located CO and NO_x measurements in the U.S. EPA's AIRS database. Each year includes over 100 primarily urban sites covering the entire country. Each point is equal to the slope of the correlation

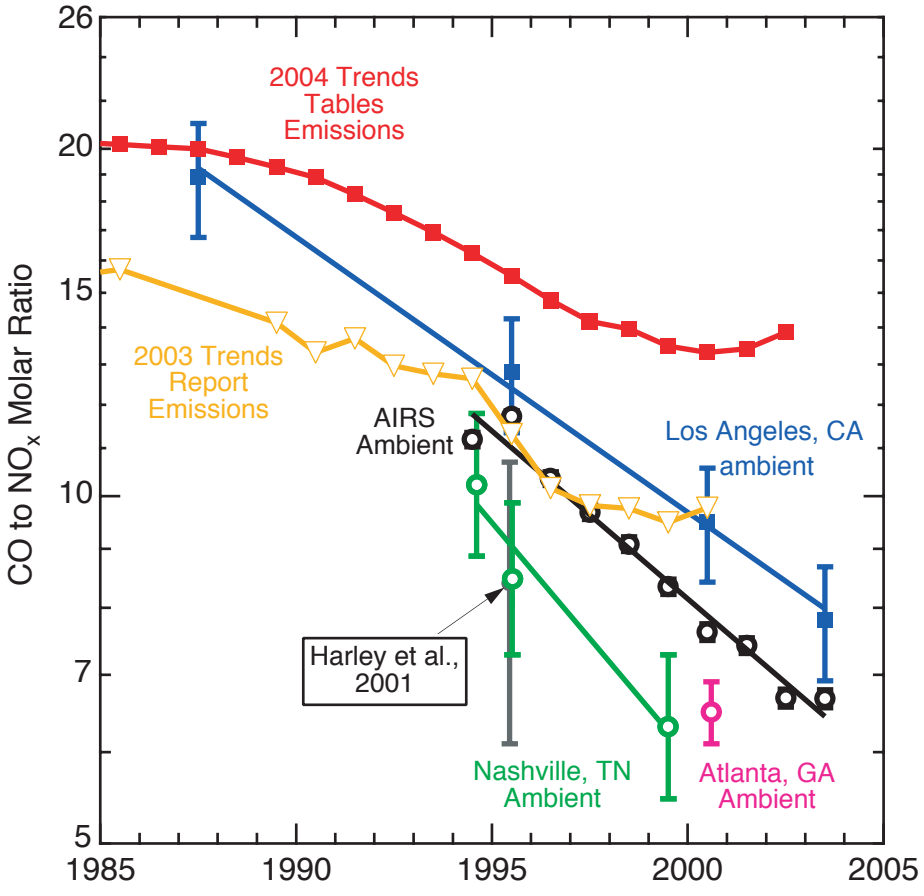

Figure 7.3. Semi-log plot of temporal trends of CO to NO_x ratio in onroad vehicle emissions. National emissions from two U.S. inventories are compared to ambient ratios measured in Los Angeles, Nashville, Atlanta and the AIRS network.. Figure based on that in Parrish et al., 2002.

Table 7.1. Derived CO/NO_x Emission Ratios During Morning Traffic Peaks (molar ratios).

Location	Measurement period	Ratio in 2000[a]	Temporal trend[a] (%/yr)	r^2	Data Source
Los Angeles, CA	1987-2003	9.4 ± 0.7	-5.5 ± 0.4	0.95	Fujita et al. (1992), CARB[b]
Boulder, CO	1989-1999	9.0 ± 1.2	-6.7 ± 0.5	0.94	Parrish et al. [2002]
Nashville, TN	1994-1999	5.7 ± 0.4	-8.8 ± 1.0	0.96	Parrish et al. [2002]
Atlanta, GA	1999-2001	6.5 ± 0.4	----	----	SEARCH[c]
U.S. Urban	1994-2003	7.9 ± 0.1	-6.6 ± 0.3	0.97	AIRS[d]

[a] Values derived from exponential fits as shown in Figure 7.3.
[b] 1995 and later data from CARB website (http://www.arb.ca.gov/adam/cgi-bin/db2www/adamhourly.d2w/start).
[c] SEARCH (Southeastern Aerosol Research and Characterization Study) 2005. Data downloaded from http://www.atmospheric-research.com/public/index.html.
[d] Data provided by from the U.S. EPA AIRS data base.

between CO and NO_x measurements at all of those sites from July and August for 6:00-9:00 am local time. Not surprisingly, these data have weaker correlations (r^2 = 0.4 to 0.6), reflecting not only the proximity of some sites to local traffic sources, but also regional differences in the average onroad vehicle CO to NO_x emission ratio.

Figure 7.3 and Table 7.1 indicate that there are small regional differences both in the temporal trend, and in the magnitude of the CO to NO_x emission ratio. Noticeably apparent are higher ratios with slower temporal decrease in the Los Angeles area and lower ratios with more rapid decrease in the southeastern U.S. These patterns could each be compared to the available emission inventory for the respective area. However, these differences are not great, and comparison to the national emission inventory is used instead. In Section 7.1.5, the AIRS trend, which represents stations from the entire country and falls in the middle of the observed variations, will be taken as representative of national onroad emissions.

Comparison of the inventory trends with the ambient data trends in Figure 7.3 leads to two conclusions. First, the 2004 Trends Tables emission ratios are significantly higher than found in the ambient data, particularly in more recent years. The 2003 Trends Report also rises above the ambient trend after 1997. This indicates that the CO emission estimates are higher and/or the NO_x emission estimates are lower than can be consistent with the ambient measurements. These are not small differences; by 2002 they are greater than a factor of 2 for the 2004 Trends Tables. Second, the temporal trends of the inventory ratios are not as steep as the trend of ambient ratios. However, the preceding section found good agreement between the temporal trends of the ambient CO levels and the CO emissions in the 2004 Trends Tables. These two findings indicate that NO_x emission estimates are decreasing too rapidly (or increasing too slowly) to be consistent with the ambient determinations.

Some caveats should be discussed with regard to these conclusions. First, the error bars shown in Figure 7.3 represent the uncertainty in deriving the slope of the CO/NO_x correlation, but do not include any added uncertainty due to the possibly confounding effects discussed above. It is not possible at this point to assign reliable confidence limits to the ambient determinations of the onroad vehicle emission ratio, since the magnitude of the confounding effects have not been quantified. However, the conclusions reached here can be compared with other work. CRC (2004) recently reviewed results from tunnel studies and remote sensing measurements of onroad vehicle emissions that suggested an overestimate of about a factor of 2 in the MOBILE6 predictions for the CO emissions from onroad vehicles. However, they also reported measurements of ambient CO/NO_x ratios that implied contradictory conclusions; these ambient

ratios suggested an even larger underestimate in the CO emissions. Consequently, CRC (2004) could reach no firm conclusions regarding the accuracy of the MOBILE6 predictions. Unfortunately the ambient analysis was handicapped by using CO and NO_x data from sensors sited at locations within urban areas that were 3 to 20 km apart, which precluded use of the correlation analysis employed here. The conclusions reached above provide a resolution of the contradiction in CRC (2004), since they are also consistent with an overestimate of about a factor of 2 in the MOBILE6 CO emissions.

7.1.4 Comparison of Fuel-Based and Mileage-Based Estimates of Onroad Vehicle Emissions

A fuel-based approach to emission inventory development provides an effective comparison for the mileage-based method used by the U.S. EPA and others. In one example, Harley et al. (2001) developed an inventory for Nashville, TN in 1995 by taking gasoline and diesel fuel sales as the activity factor and determining emission factors expressed as per unit of fuel burned. CO emission factors were determined from infrared remote sensing of over 34,000 vehicles at 13 sites in the urban area. VOC emission factors were estimated from these derived CO emission factors and measured VOC/CO ambient concentration ratios in central Nashville. NO_x emission factors were developed from roadway tunnel measurements made in other U.S. locations. The goal here is to use this comparison to test the accuracy of the estimated magnitude of emissions from onroad vehicles.

In Figure 7.3 the CO/NO_x emission ratio from the fuel-based inventory (Harley et al., 2001) is compared to the ambient ratio discussed in the previous section. The excellent agreement gives us confidence both in the results of the fuel-based emission calculation, and in the validity of directly comparing those ambient concentration ratios with the ratio of the emissions from inventories.

Figure 7.4 compares the results of the fuel-based and U.S. EPA inventories. The U.S. EPA inventory was based on the MOBILE5B emission factor model, which is the modeling basis for the 2000 and 2003 Trends Reports. Thus, the comparison in Figure 7.4 is a test of these Trends Report emissions, but not the 2004 Trends Tables, which are based on MOBILE6. This comparison suggests three conclusions:

1. There is excellent agreement in the total VOC and NO_x emissions. This comparison increases the confidence in the Trends Reports' estimates of these emissions for 1995.

2. The U.S. EPA CO emission estimate is about 40 percent higher than the fuel-based estimate. This suggests that the inventory overestimate of the CO to NO_x emission ratio discussed in Section 7.1.3 is at least partially due to an overestimate of the CO emissions as opposed to an underestimate in the NO_x emissions.

3. Even though the total NO_x emissions agree well, the fraction the U.S. EPA attributed to diesel-powered vehicles is much smaller in the U.S. EPA inventory (25 percent), than is the fuel-based inventory (47 percent). The latest U.S. EPA emission estimates are in closer agreement with the fuel-based inventory. For example, the 1995 nation-wide diesel contribution to NO_x emissions from onroad vehicles is estimated as 43 percent in the 2004 Trends Tables compared to 32 percent in the 2000 Trends Report.

Both the fuel-based and mileage-based approaches are subject to significant uncertainties. Two particular issues that the fuel-based approach must grapple with are (1) the uncertainty associated with fuel sales data and apportioning such data to the study area, and (2) limitations and errors associated with deriving emission factors from measured onroad vehicle emissions at a relatively small number of sites that may not be representative of the complete driving cycle, and likely may miss higher CO emissions associated with "cold-starts" of gasoline engines. Consequently, examination, testing and modification of both emission inventory approaches must continue until they agree.

The experience in comparing fuel-based and VMT-based emissions in California provides an example for the national inventory to emulate. In this work, Singer and Harley (2000) developed a fuel-based inventory for the Los Angeles area for the summer of 1997. Their emissions were higher than the then

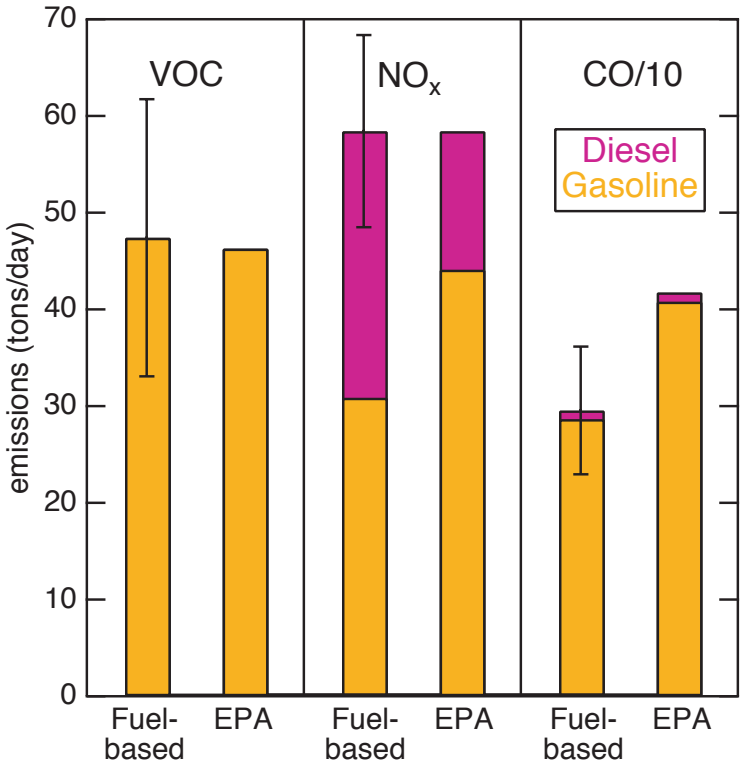

Figure 7.4. Comparison of fuel-based emission inventory for Nashville in 1995 with the U.S. EPA emission inventory for that county (Harley et al., 2001). CO emissions are divided by 10 to include on the same ordinate. The error bars indicate the estimated uncertainty of the total fuel-based emissions.

current California mobile emission model (EVEI 7G) estimates by factors of about 2.4 for CO and 3.5 for VOC. However, an improved California model (MVEI 2002) now has come into agreement with the Singer and Harley (2000) estimates (CARB, 2002). It is recommended that high priority be extended to these reconciliation efforts for the NEI and for other regions of the country.

7.1.5 Reconciliation of Estimated Onroad Vehicle Emissions with Ambient Measurements

The three preceding sections have compared estimated emissions to ambient measurements and compared two inventories developed from different approaches. These comparisons have identified inconsistencies that indicate significant errors, either in the inventories or in the ambient measurements and/or their interpretation. Here, a process of identifying the errors that underlie the identified inconsistencies is presented, with the goal of guiding improvements in emission inventories as well as their evaluation through ambient measurements. The goal of this section is to suggest changes in the onroad vehicle emission estimates that are necessary to reconcile them with the ambient measurements and the fuel-based inventory.

Figure 7.5 shows inferred onroad vehicle emissions for NO_x and CO (black symbols) for the 1990-2000 period. These inferred emissions are consistent with all of the ambient data discussed above, and are derived from four assumptions:

1. Consistent with the fuel-based inventory discussion in Section 7.1.4, the 1995 NO_x emissions from the 2003 Trends Report are assumed to be accurate. The inferred NO_x emissions in 1995 are set equal to the value for that year from Table A4 of that report (solid black circle in upper panel of Figure 7.5).

2. Also consistent with the fuel-based inventory discussion in Section 7.1.4, the 1995 CO emissions from the 2003 Trends Report are assumed to be overestimated by 40 percent, not only in Nashville, but nationwide. The inferred CO emissions in 1995 are set equal to the value for that year from Table A2 of that report divided by 1.4 (solid black circle in lower panel of Figure 7.5).

3. Consistent with the discussion in Section 7.1.2, CO emissions are assumed to have decreased by 4.9 percent/year, the rate of decrease of the ambient CO levels for 1985-2000. Extrapolating this rate of decrease backward and forward in time for five years from 1995 gives the inferred CO emissions for all years (open black circles in lower panel of Figure 7.5).

4. Consistent with the discussion in Section 7.1.3, the CO to NO_x emission ratio is assumed to have decreased by 6.6 percent/year, the rate derived from the nationwide AIRS data set. This implies an increase in NO_x emissions of 1.9 percent/year.

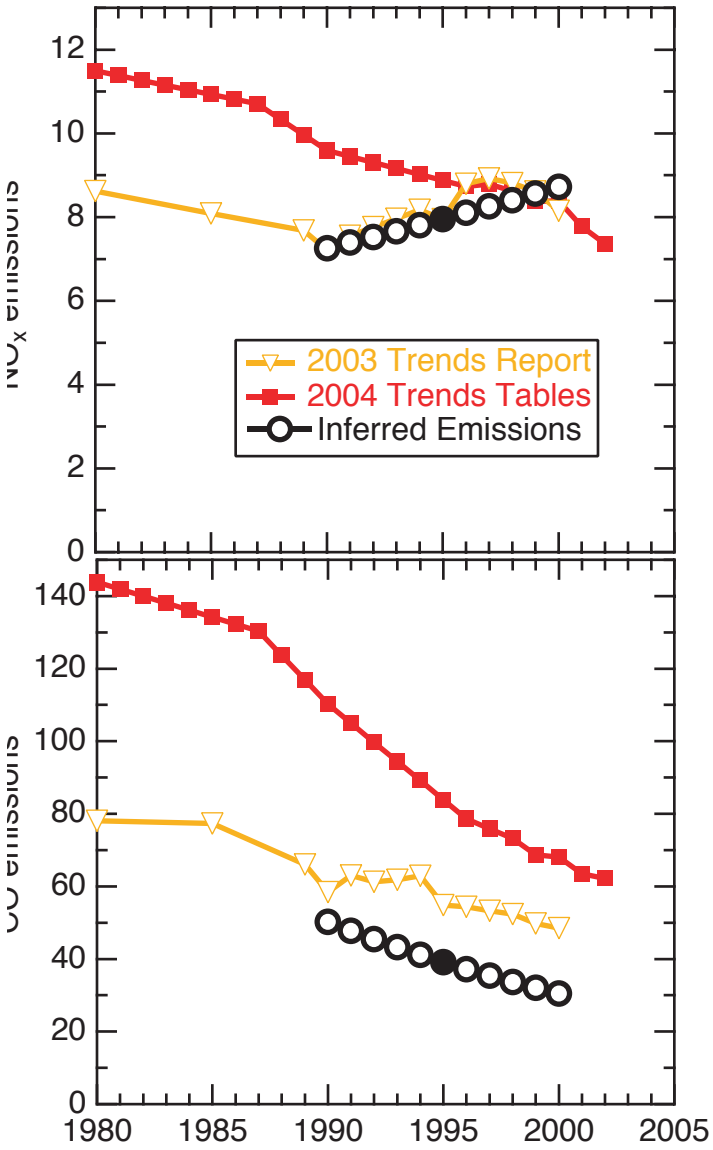

Figure 7.5. National onroad vehicle emissions from the two most recent U.S. inventories in Figure 7.1 compared to the emissions inferred from ambient measurements. Units are 10^6 tons/year.

Extrapolating this rate of increase backward and forward in time from 1995 gives the inferred NO_x emissions for all years (open black circles in upper panel of Figure 7.5).

If these inferred emissions are accurate, then these results imply that errors exist in the onroad vehicle emission estimates from the Trends data. Two apparent errors are particularly notable. First, CO emissions in the 2004 Trends Tables may be overestimated by about a factor of 2 for 1990-2000, while the 2003 Trends Report may overestimate the emissions by a smaller factor averaging about 40 percent. Second, the temporal trend of NO_x emissions is poorly defined by the emission inventories. The 2003 Trends Report shows an increase averaging 2.8 percent/year from 1990-1997 followed by a decrease, while the 2004 Trends Tables show a continuing decrease averaging 1.4 percent/year for 1990-2000. Figure 7.1 shows that the temporal trend of the NO_x emissions has been revised between each successive emission report, always with higher estimates for the 1990-2000 period. However, despite these divergent temporal trends, the 2003 Trends Report values are within 9 percent of the inferred NO_x emissions for all years, and the 2004 Trends Table values are within 20 percent of the inferred NO_x emissions for all years after 1992.

No substantial inconsistencies have been identified in the VOC onroad vehicle emissions. The fuel-based and the U.S. EPA inventory, consistent with the 2003 Trends Report agreed very well for 1995 in Nashville (Figure 7.4). The 2004 Trends Tables estimates for years after 1993 are no more than 18 percent higher than the 2003 Trends Report (Figure 7.1). The temporal trend of the VOC road emissions for 1985-2000 in the 2004 Trends Tables corresponds to an average decrease of 5.9 percent/year, which is in reasonable agreement with the decrease in CO emissions of 4.9 percent/year assumed above. This agreement between the temporal trends of CO and VOC onroad vehicle emissions is expected from onroad vehicle emission studies (Parrish et al., 2002). CRC (2004) found good agreement of ambient VOC/NO_x ratios with inventories in the 1998-2000 time period, which is in accord with the separate analyses presented here for VOC and NO_x.

Future steps in the process to reconcile the top-down tests with emission inventories ideally will include feedback from inventory developers regarding the validity of the suggested inventory changes and evaluation of errors in the ambient measurements and/or their interpretation. With regard to this last point, the rate of increase in the inferred onroad vehicle NO_x emissions is derived from the difference between the rates of decrease of two temporal trends (ambient CO levels and ambient CO to NO_x ratio) determined from measurements. This difference between two measurement-derived quantities may be a significant source of uncertainty in the inferred emissions discussed here.

In Figure 7.5, the inferred increase in NO_x onroad vehicle emissions is in reasonable accord with the trend in the 2003 Trends Report. This increasing trend is not present in the 2004 Trends Tables. It may be fruitful to investigate if the 2003 Trends Report is more accurate than the later report and the cause of the disappearance of the increasing NO_x emission trend between the reports. This investigation may focus on the inconsistency in the apportionment of NO_x emissions between gasoline- and diesel-fueled vehicles identified in the inventory comparison in Figure 7.4. Through the 1990s, emission factors for diesel vehicles remained approximately stable, while diesel fuel consumption increased. As noted by NRC (2000), NO_x emissions from heavy-duty diesel vehicles were underestimated in the then-current MOBILE model, and NO_x (as well as PM) emission rates were highly uncertain.

One implication of the decreasing trend in CO emissions from onroad vehicles deserves attention. If the trend in Figure 7.5 has continued to 2002 and if the other CO emissions for that year in the 2004 Trends Tables are accurate, then the onroad vehicle contribution to the total U.S. CO emissions has declined to about 40 percent in 2002. This implies that other emission sources (which may be even more uncertain) are accounting for a majority of the total inventoried CO emissions. For example, emissions from nonroad vehicles and engines would nearly equal those of onroad vehicles. Thus, emissions from sources other than onroad vehicles should be an increasing focus for future inventory improvement and uncertainty analyses.

7.1.6 Evaluation of VOC Speciation in Onroad Emission Inventories

Evaluation of ambient VOC measurements under appropriate conditions can provide critical tests of VOC speciation. Benzene and acetylene are particularly appropriate for testing onroad vehicle emission for three reasons. First, they are primarily emitted from onroad vehicles, so ambient urban levels do provide information regarding this source. Second, they react slowly in the atmosphere with lifetimes on the order of ten days, so their interrelationship is not affected by removal in the atmosphere. Third, both of these hydrocarbons are in the top ten in terms of ambient urban levels, so quantification of their concentrations is not limited by instrumental sensitivity. The goal of this section is to use the measured ratio of ambient concentrations of these species to test the ratio of these species in onroad vehicle emission inventories.

Fortin et al. (2005a) show that the benzene to acetylene ratio is remarkably invariant over large regions of the country in any given year, and that this ratio exhibits long-term trends in response to VOC emission control measures (Figure 7.6). Before 1994, the ratio increased slowly due to the preferential removal of acetylene by automotive catalytic converters, which penetrated the vehicle fleet during this period. Specific benzene control measures were begun in 1994 in response to the 1990 Clean Air Act Amendments, which have substantially reduced the ratio in recent years. These ratios and their trend can be compared to the VOC speciation in emission inventories.

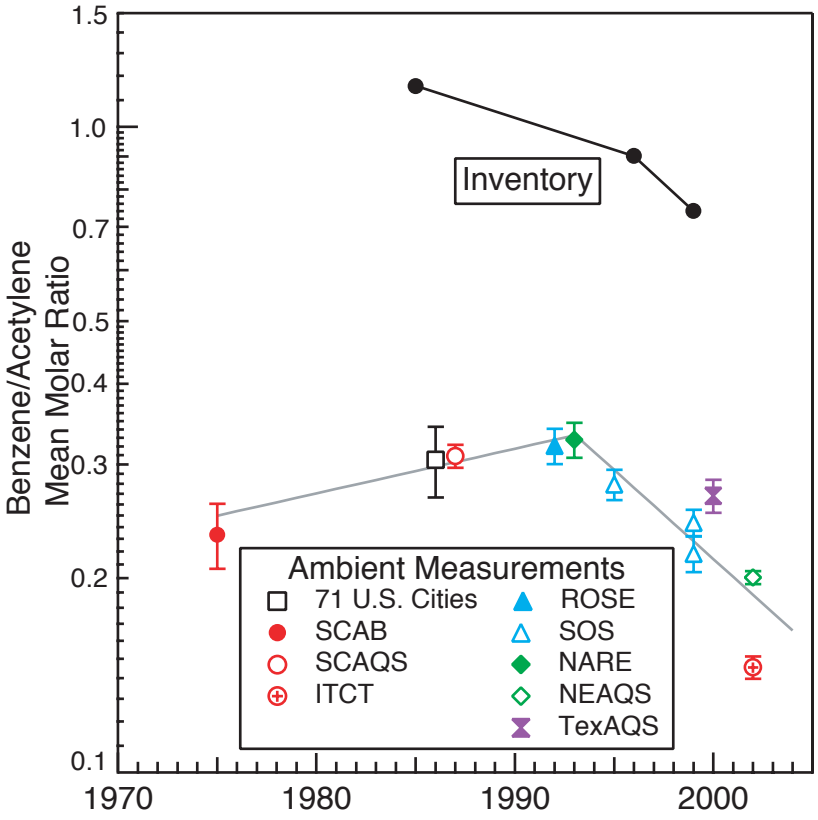

Figure 7.6. Observed trends in the mean ambient benzene to acetylene ratio from field study data as a function of year on a semi-log plot. The colors of the symbols indicate geographic location: Average of 71 U.S. urban areas (black), California (red), southeast (blue), northeast (green), and Texas (purple). The error bars indicate the 95 percent confidence limit of the mean. The gray lines indicate estimated ambient trends before and after 1993. The inventory ratios are from Table 7.1. (Figure closely follows that of Fortin et al. [2005a].)

Total national benzene and acetylene emissions from three recent emission inventories are given in Table 7.2. The corresponding ratios are plotted in Figure 7.6. The NEI 1996 and 1999 numbers were obtained by applying the SPECIATE software to the respective NEI. The 1996 number agrees to within 10 percent with the 1996 National Toxic Air Pollutant inventory for benzene (http://www.epa.gov/ttn/atw/nata/). Interestingly, the National Air Quality and Emissions Trends Report, 1999 states that the average annual ambient levels of benzene decreased by 40 percent from 1994-1999, but this decrease is not reflected in the benzene emission numbers.

The comparison between the ambient and inventory ratios is quite poor. The inventory values are a factor of 3 to 4 higher than the ambient measurements, and the temporal trends are not clearly in agreement. The ambient measurements must be considered to accurately reflect average emissions. The measurements are from at least seven different research groups and span most of the country. Benzene and acetylene react similarly and so slowly that average emission ratios are not significantly altered before measurement. Disagreements must reflect biases in the inventory ratios. Although the recent trend in the inventory appears to parallel the ambient trend, it is for the wrong reasons. The ambient ratio is believed to have decreased due to decreasing benzene emissions, but Table 7.2 shows that in the inventories benzene emissions have remained nearly constant while the acetylene emissions have increased, resulting in a decreasing ratio.

In conclusion, the VOC speciation in the NEI compared to ambient measurements as tested by these example species shows a difference of factors of 3 to 4, the temporal trend in the inventory emissions is not consistent with the observations, and the NEI does not reflect trends in ambient concentrations that are discussed in the Trends Report. There is a critical need for a re-evaluation of the VOC speciation in the NEI. Correctly interpreted, reliable ambient concentration measurements must be one of the important guides for this re-evaluation. This conclusion is in accord with the finding by NRC (2000) that the database, upon which the SPECIATE system is based, is now out of date, especially for mobile-source emissions.

7.2 EVALUATION OF POWER PLANT EMISSIONS IN THE UNITED STATES

Power plant emissions account for a major share of NO_x, SO_2 and CO_2 emissions, and are responsible for some of the highest concentrations of these species encountered in the ambient atmosphere. In contrast to onroad vehicle emissions, there are a great many detailed, hourly emission data available, because generally these emissions are measured by CEMS (see Sections 4.7.4 and 6.1.3). These CEMS are required by the U.S. EPA Acid Rain Program, and are maintained to high standards, with daily zero and span calibration checks, routine multipoint calibrations, and regular independent accuracy audits. Accurate emission inventories should be available

Table 7.2. Benzene and Acetylene Emissions (10^5 moles/hour).[a]

Species	NAPAP 1985	NEI 1996	NEI 1999
Benzene	10.69	4.08	3.98
Acetylene	9.24	4.53	5.38
Ratio	1.157	0.901	0.740

[a]The emissions are given in units of moles/hour to ease direct comparison of inventories and the derivation of ratios. For comparison 1 mole/hour corresponds to 0.251 tons/year of acetylene and 0.753 tons/year of benzene. There are subtle differences in the units: 1985 are annual average hourly emissions; 1996 are hourly average for ozone season workday; and 1999 are hourly average for all summer days. These differences are likely small. The emissions exclude all fire emissions, because the ambient measurements were not significantly affected by fire emissions. The 1985 benzene emissions include halobenzenes.

simply from the integration of these CEMS data over the time period of interest. In this section, the reported power plant emissions are examined for internal consistency over the past two decades, and the consistency of CEMS data with aircraft measurements is investigated.

7.2.1 History of Temporal Trends of Power Plant Emissions.

This section examines the history of emission trend estimates for power plants in a manner similar to that presented in Section 7.1.1 for onroad vehicle emissions. The aim is also the same: to determine if the estimated trends are converging to more precisely defined values, or if there is a significant element of scatter in the estimates that may indicate fundamental uncertainties in the estimation methods.

Figure 7.7 presents inventoried emissions of NO_x and SO_2 from fuel combustion in electrical utilities. The numbers come from five of the six references investigated in Section 7.1.1. (The 1990 Trends Report does not give emissions from power plants separately from other point sources). It is clear here that there has been little variation in the emission estimates for any given year, with only the NO_x emissions in the 1995 Trends Report significantly different (as much as 19 percent higher) than the other estimates. This test gives no indication of any important uncertainties in the estimated trends of power plant emissions.

7.2.2 Tests of CEMS Data for Power Plant Emissions

Transects of power plant plumes by aircraft capable of making rapid measurements of the emitted species provide a means of deriving emission fluxes from ambient measurements. These measurements can be directly compared with the CEMS data collected at the time of emission of the sampled plume. The primary goals in this section are (1) to test the consistency of the available CEMS data with aircraft flux measurements, and (2) to test the integration of CEMS data into annual inventories.

In principle, the absolute flux of a species emitted from a source can be directly determined from aircraft measurements of its concentration in the downwind plume. The flux is equal to the wind speed at the time of emission multiplied by the integral of the species concentration over the cross section of the

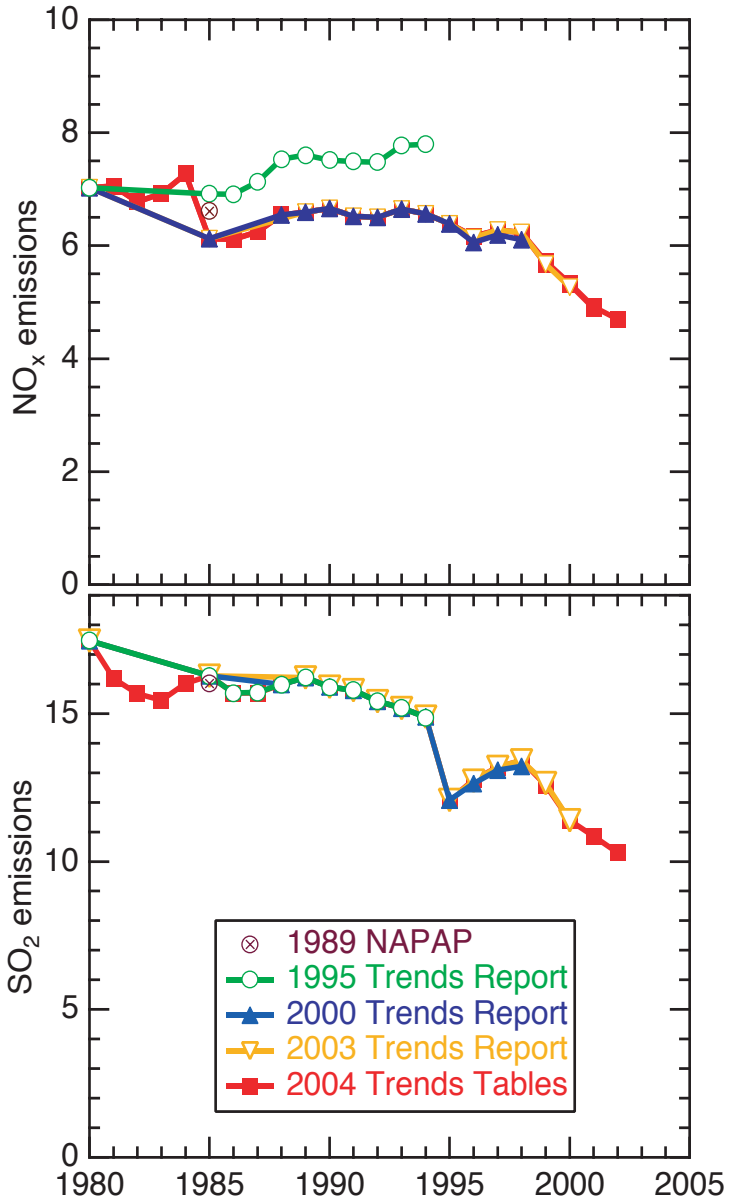

Figure 7.7. National power-plant emissions from five U.S. inventories in units of 10^6 tons/year. The dates indicate the year of publication of the inventory report.

plume perpendicular to that wind direction. These concentration data can be collected during aircraft transects of the plume. In practice, collection of data of adequate spatial resolution and coverage to allow accurate integration over the plume cross section is daunting. Generally the plume flux determinations are carried out under favorable conditions that allow significant simplifications (see Ryerson et al., 1998, and references therein).

The favorable conditions for aircraft plume flux determinations are those where three approximations can be made: (1) the plume is confined to the PBL, (2) the plume is well-mixed over the depth of the PBL, and (3) the wind speed and direction in the PBL are constant from time of emission to measurement. Under these conditions the flux of species m can be calculated from wind and concentration measurements collected in a single plume transect:

$$\text{flux}_m = v \bullet \cos\alpha \int_0^{z_0} n(z)dz \int_{-y}^{+y} X_m(y)dy \quad (7.1)$$

Here v is the wind speed and α is the deviation of the aircraft transect from perpendicular to the wind direction, $n(z)$ is the number density of air as a function of z, the height above ground, z_o is the PBL height, and $X_m(y)$ is the mixing ratio enhancement above background of species m as a function of y, the cross plume distance. Under optimal conditions the uncertainty in this calculation can be as low as plus or minus 20 percent. Figure 7.8 shows data collected under such favorable conditions. The fluxes derived from Equation (7.1) for NO_x, SO_2 and CO_2 agree very well with tabulated CEMS data. (The NO_y measurements plotted represent the sum of all oxidized nitrogen species, which includes not only the emitted NO_x that remains in the plume, but also any species, such as HNO_3 and PAN, that are produced by photochemical oxidation of NO_x between emission and measurement.)

Under conditions where one or more of the above approximations fail, it is still possible to determine

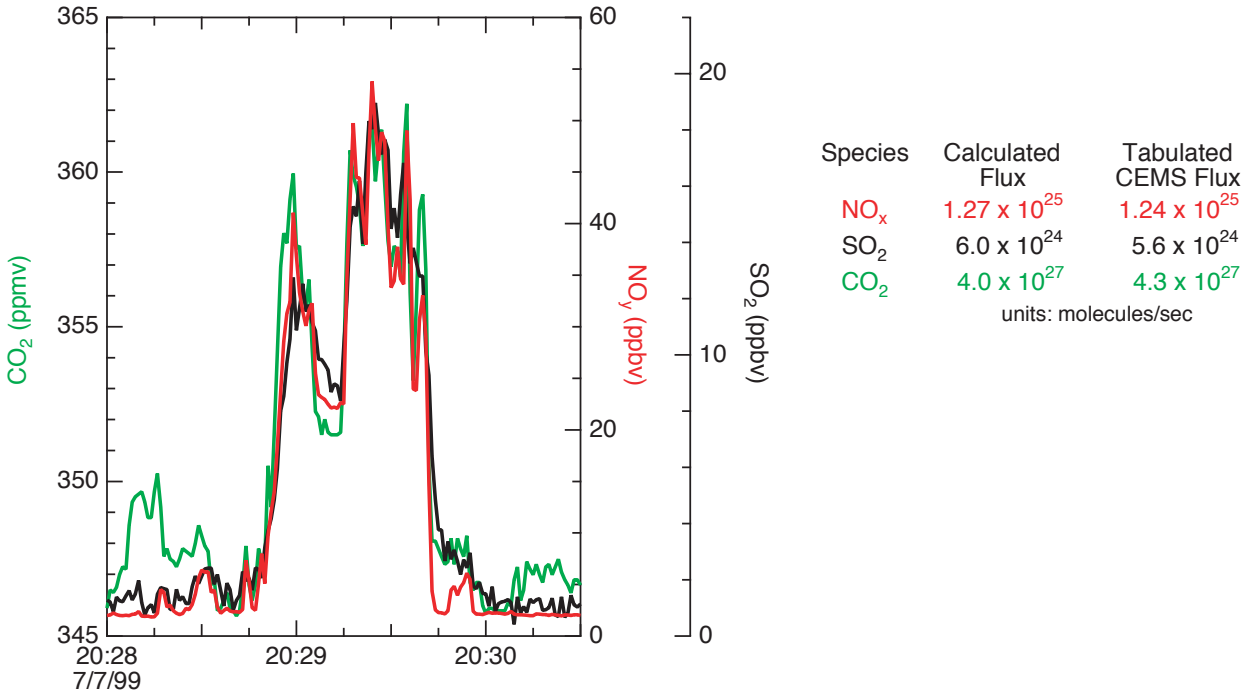

Figure 7.8. One-second average data collected during a 2.5 minute transect of the Thomas Hill coal-fired power plant in Randolph County, MO during the 1999 Southern Oxidant Study. This transect was conducted 20 km downwind of the plant, approximately 1.5 hours after emission. The fluxes of the three emitted species calculated from Equation (7.1) are compared to those reported from CEMS measurements.

at least the ratio of the fluxes of two emitted species, even from only a partial transect of the emission plume. The slope of the correlation between the concentrations of two species is equal to the ratio of their fluxes. For example, for the data of Figure 7.8 the slope of NO_y versus CO_2 is 3.3 x 10^{-3} with an r^2 of 0.93; the corresponding slope for SO_2 versus CO_2 is 1.14 x 10^{-3} with an r^2 of 0.89. These slopes agree well with the ratios of the CEMS emissions: 3.3 x 10^{-3} and 1.30 x 10^{-3}, for NO_x/CO_2 and SO_2/CO_2, respectively. These derived slopes are not affected by failure of any of the three approximations listed above.

Finally, conservation of the emitted species in the plume from emission to measurement is required to determine an absolute emission flux. This conservation implies negligible loss by any mechanism, such as in-situ chemical removal, surface deposition or venting of the plume out of the PBL. The determination of flux ratios is not sensitive to boundary layer venting, but is affected by different rates of removal of the two species by either chemical removal or surface deposition.

Nearly 50 such plume studies on over 30 CEMS-equipped power plants during field studies in 1995, 1997, 1999, 2000, and 2002 have been conducted (Ryerson et al., 1998; Neuman et al., 2004 and references therein.) Fortin et al. (2005b) have summarized all of these studies and their results are shown in Figure 7.9. Figure 7.9(a) compares the flux ratios of NO_x to CO_2 and SO_2 to CO_2 derived from CEMS to those derived from aircraft transects. On average these flux ratios agree within the estimated uncertainty of the ambient determination (plus or minus 20 percent), although there are occasional significant discrepancies. Figure 7.9(b) compares the fluxes measured for NO_x, SO_2 and CO_2, with those derived from the CEMS data. Agreement on average is again within plus or minus 20 percent, again with occasional significant discrepancies. These comparisons indicate that emission fluxes of NO_x, SO_2 and CO_2 from power plants derived from CEMS measurements are highly accurate.

The significant discrepancies between the CEMS and aircraft determinations are generally due to the inherent uncertainty of comparing an in-situ stack measurement with the aircraft-based measurement. However, occasional inaccuracies in the CEMS data are indicated. At those times the aircraft sequentially sampled plumes from two or three closely spaced plants on a single transect, and then repeated that transect two or three times. Consistent, good agreement between the aircraft measurements and the CEMS data was found for some or all of the emitted species from one or two of the plants and consistent, poor agreement for one or more species from a different plant. These observations indicate inaccuracies in the CEMS data in those specific instances.

Both the flux ratios and the absolute emission fluxes from CEMS agree equally well, on average, with those derived from ambient aircraft measurements. It is notable that the absolute flux determinations (which depend on the measured total stack flow in the CEMS determinations) are as accurate as the determination of the ratio of fluxes (which are independent of the total stack flow). However, the absolute determinations shown in Figure 7.9(b) do show larger scatter, but this is partly or wholly due to the reduced precision of the absolute flux determination by aircraft.

The preceding discussion concludes that aircraft flux measurements of power plant emissions are consistent with hourly CEMS data, adding confidence to both methods. The question remains if these short-term measurements are accurately integrated into annual emission inventories. As a check, the 1999 CEMS data for NO_x and SO_2 for seven power plants in five states were integrated. On average these integrals agreed with the values in Version 3 of the 1999 NEI to within 1 percent, and the largest discrepancy was 4 percent. These small differences simply may be due to differences in the method of handling missing data. Finally, the sum of all of the power plant emissions in Version 3 of the 1999 NEI was verified to be consistent with the values listed in the 2004 Trends Tables for fuel combustion in electric utilities.

In contrast to the accurate CEMS-derived emissions, CO emissions from power plants are generally estimated from emission factors appropriate to the burner technology and type and amount of fuel consumed. Nicks et al. (2003) have observed that power plants, particularly those fueled by lignite

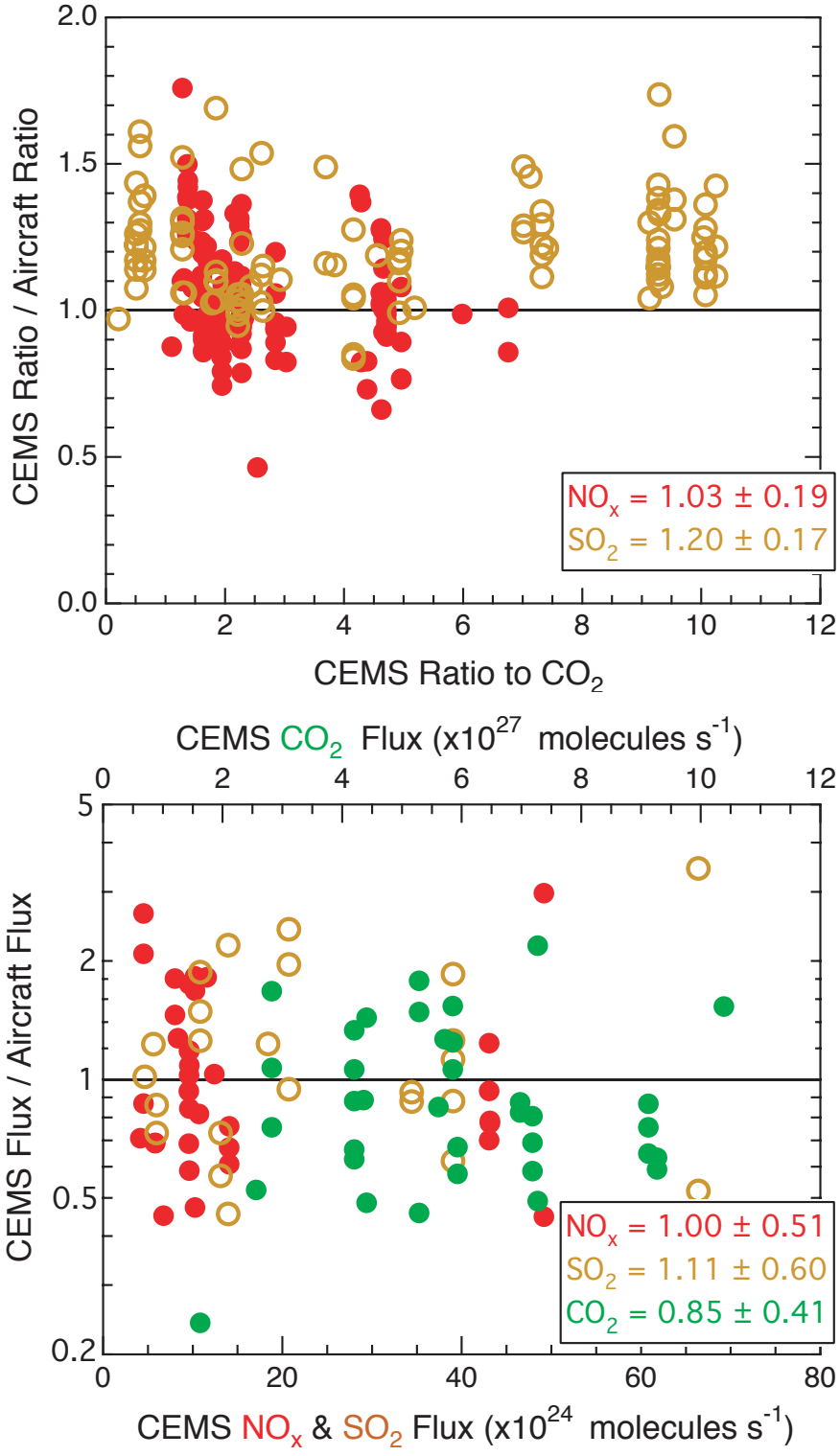

Figure 7.9. Power-plant emission fluxes from CEMS data compared to those determined from aircraft plume transect measurements. **(a)** Emissions of NO_x and SO_2 ratioed to those of CO_2. **(b)** Absolute fluxes of all three species. The annotations give the geometric average and standard deviations for the color-coded ratios.

coal, but including one gas- and sub-bituminous coal plant, can emit CO at rates more than a factor 10 higher than inventoried. Nevertheless, power plants still constitute only a minor fraction of total anthropogenic CO emissions.

In summary, power plant emissions based upon CEMS data are highly accurate from hourly to annual average time scales. However, the interpretation of annual average emissions must proceed with caution since the CEMS data indicate that emissions from most power plants vary on all time scales from hours to months to years. Consequently detailed photochemical models should include the hourly CEMS emission data in order to accurately simulate these point source emissions effects on ozone and aerosol formation downwind.

7.3 EVALUATION OF EMISSIONS FROM TEXAS PETROCHEMICAL FACILITIES

The greater Houston, Texas, metropolitan area is distinguished by the largest concentration of petrochemical industrial facilities in the United States. Further, Houston is noted for some of the highest present-day ambient ozone concentrations routinely encountered in the continental United States. Hourly averaged ozone concentrations measured at surface sites in the area can exceed 200 ppbv during severe episodes. However, photochemical models based on existing emission inventories are not able to accurately reproduce these high ozone levels. The Texas Air Quality Study (TexAQS 2000) was conducted to develop a comprehensive understanding of these extreme ozone episodes.

During the TexAQS study, aircraft measurements of plumes (see Section 7.2.2) emitted from the petrochemical industrial facilities established that these emissions were responsible for the extreme ozone episodes (Ryerson et al., 2003; Wert et al., 2003). Strongly elevated concentrations of NO_x and reactive VOCs simultaneously present are required for rapid formation of high levels of ozone. NO_x emissions from a large petrochemical facility can approach those from a large electric power plant. These NO_x emissions are co-located with large emissions of reactive VOCs, primarily ethene and propene, released from the petrochemical processes. Thus, conditions for high ozone formation rates are routinely found in the NO_x- and VOC-rich plumes from the petrochemical industrial facilities.

The failure of previous modeling efforts to reproduce the observed extreme levels of ozone was traced to a very large underestimate of alkene emissions from the petrochemical facilities. Measurements established that the alkene emissions were generally as large or larger than the NO_x emissions from the petrochemical complexes. However, alkene emissions derived from the previous inventory were smaller by factors of 10 to 100. Photochemical modeling using VOC emissions scaled up to resolve this discrepancy accurately reproduced the observed concentrations of ozone. These models also accurately predicted the concentrations of other photochemical products, in particular formaldehyde, which is directly produced from the alkenes (Wert et al., 2003). Thus the very high ozone levels observed in Houston downwind of petrochemical plants can be explained by underestimated alkene emissions.

The cause of the underestimate of the alkene emission inventory is poorly understood. One of the major goals of the planned TexAQS 2006 study is to determine the source of the very large reactive VOC emissions from within the petrochemical facilities. However, one aspect of these emissions is clear; the observed discrepancy was generally consistent over all of the facilities sampled during the four-week, August-September, 2000 period of the study. Investigation indicated that the observed discrepancies could not be attributed to reported upset or other transient conditions. Since emissions during startups, shutdowns, and malfunctions are not normally reported in emission inventories, and since emissions from these operations can be significant, these situations need to be addressed in emission inventories.

Allen et al. (2004) have evaluated the variability of alkene emissions, and point out that frequently a single source within a complex can dominate that complex's emissions, and can even approach the annual average of the inventoried emissions for the entire Houston area. This variability is an important feature of these emissions that must receive due

consideration in photochemical modeling. However, Allen et al. (2004) discuss this variability in relation to the tabulated emission inventories. If the variability were compared to the emissions scaled up to match the observations discussed above, its significance would be much reduced.

The findings discussed above promise substantial economic benefits for the Houston area. Prior to the TexAQS 2000 study the state had devised a strategy to result in compliance with the ozone standard and avoid federal sanctions. Based on existing emission inventories, reduction of point source NO_x emissions by 90 percent were required among other control measures. Following the discovery of the large alkene emissions less stringent NO_x reductions, combined with reductions in these alkene emissions, were selected as an effective strategy to meet the air quality standards. This strategy could have reduced economic impacts. A study sponsored by local interest groups (Tolley and Smith, 2001) concluded that ten years after implementation, a 90 percent reduction in NO_x emissions would result in 65,000 fewer jobs and a $9 billion smaller regional economy compared to a 79 percent NO_x reduction strategy that allowed emissions trading. Even when the costs of VOC controls are included, the revised control strategy (which was enabled and supported by the revised emission inventory) resulted in considerable annual savings compared to the original NO_x-only alternative.

MARAMA (2003) have provided evidence that the Houston findings are relevant to other regions of the country. They report that high levels of alkenes are observed in plumes downwind of petrochemical facilities along the U.S. mid-Atlantic Coast. These plumes also contained substantially elevated ozone levels.

7.4 SOURCE APPORTIONMENT FROM CHEMICAL MASS BALANCE

Receptor methods for source attribution are based on the interpretation of measured ambient concentrations of species to infer sources and to quantify the contributions of these sources to the ambient concentrations. These methods have been extensively reviewed by Watson et al. (2001) for VOC emissions and in Chapter 7 of NARSTO's PM Assessment (NARSTO, 2004). The CMB approach relies upon fitting measured concentrations of ambient species to a linear combination of source profiles. Each source profile defines the relative abundance of the measured species in the emissions from that source. Source profiles may be derived from direct measurements of the composition of the source emissions, or from statistical analyses of the ambient measurements themselves (see e.g. Henry et al., 1994). The CMB approach to source apportionment has provided important evaluations of inventories.

Watson et al. (2001) conclude from their review of CMB analyses that gasoline-related sources (vehicle exhaust and evaporation) generally contribute up to 50 percent or more of the ambient VOC, similar to or larger than their proportions in emission inventories. In contrast, coatings and solvent contributions were found to be much lower than attributed in emission inventories.

One illustrative example presented in the NARSTO PM assessment discusses the relative contribution of $PM_{2.5}$ sources in Denver, CO derived from a chemical mass balance analysis of ambient measurements. (Section 6.2.1 discusses CMB and other receptor modeling techniques in more detail.) The CMB technique derives the contribution from secondary PM formation as well as emissions from primary sources. The relative contributions of the primary sources are compared with those included in the corresponding emission inventory. The comparison found substantial discrepancies. Compared to the CMB approach, the inventory:

- Showed nearly twice the fractional contribution from fugitive dust emissions
- Underrepresented cold start gasoline vehicle exhaust, which makes a substantial contribution in the CMB analysis
- Underrepresented high emitter (i.e., poorly maintained) gasoline vehicles.

The inventory indicated that diesel emissions should have been over three times those of gasoline vehicles, while the CMB analysis showed the ratio of gasoline

vehicle to diesel emissions to be just the opposite. This study again underscores the importance of assessing emission inventories through comparison with ambient measurements.

7.5 INVERSE MODELING APPLICATIONS

Section 6.2.2 discusses inverse modeling as one of the evolving tools that will help to improve emission inventories. A study that evaluated the U.S. emission inventory for NH_3 provides an illustrative example of the application of this tool. It is an excellent example of the feedback that must occur between emission inventory developers and top-down tests of the inventories; in this case large initial discrepancies have been resolved.

Gilliland et al. (2003) used measurements of both precipitation-weighted NH_4^+ wet concentration and ambient NH_x (NH_3 + NH_4^+) as bases for inverse modeling to test the accuracy of the U.S. 1990 NEI estimates of NH_3 emissions in the eastern United States. Both bases gave a consistent conclusion; i.e., the annual average emissions in the NEI should be 25 to 30 percent lower and should have a strong seasonal cycle. The NEI itself does not specify any seasonality, which has to be introduced via an emission processing model.

A notable feature of this study is that predictions for aerosol NO_3^- (a quantity not included in the inverse modeling optimization) were much improved when the model incorporated the reduced NH_3 emissions. This improvement greatly increases the confidence that can be placed in the conclusions of the inverse modeling procedure.

A cautionary note for inverse modeling procedures is that they implicitly assume that the models correctly predict all observed parameters, and any disagreements between measurements and model results are assigned to problems in emission inventories. In this example study, Gilliland et al. (2003) investigated where problems in the model could possibly be contributing to the disagreements; they concluded that there were two critical areas of model uncertainty: total model precipitation and the NH_3 dry deposition.

Subsequent work involving both further bottom-up, process-based emission inventory development (Pinder et al., 2004) and inverse modeling has led to a convergence of the two approaches (Gilliland et al., 2005a,b; Pinder et al., 2005). The consensus picture that emerged is ammonia emissions with an approximately 25 percent larger seasonal amplitude than originally proposed by Gilliland et al. (2003), primarily because of even larger decreases in winter emissions. The bias in the 1990 annual NEI inventory has been corrected in the new 2001 NEI inventory, with only an 8 percent increase in the annual 2001 emissions suggested by the inverse modeling results. These studies represent a successful example of feedback from top-down emission studies providing guidance for the refinement of bottom-up inventories.

7.6 SUMMARY AND CONCLUSIONS

This chapter has illustrated a number of techniques that utilize ambient measurements to test emission inventories. These top-down tests have reached some conclusions regarding important current emission inventories:

1. Short-term, i.e. hourly, and longer-term average power-plant emission inventories based upon CEMS measurements are generally accurate to better than plus or minus 20 percent. In a few cases significant disagreements between the aircraft measurements and the CEMS data have been observed. These are attributed to the inherent uncertainty of comparing an in-situ stack measurement with an aircraft based measurement and to occasional inaccuracies in the CEMS data.

2. The U.S. onroad vehicle emission inventories have improved substantially in the last decade; however, they may have serious shortcomings. The most recent tabulations (the 2004 Trends Tables based upon the MOBILE6 model):

    - Accurately estimate NO_x emissions for recent years, but indicate a decreasing temporal trend through the 1990s, while top-down evaluations (and previous Trends

Reports) indicate an increasing temporal trend over that period.

- More accurately reproduce the apportionment of NO_x emissions between gasoline and diesel-powered vehicles than did previous Trends Reports.
- Accurately capture magnitude and temporal trend of VOC emissions. However, speciated VOCs from MOBILE6 may be inaccurate by factors of 3 or more, depending on the constituents.
- Accurately capture the temporal trend of CO emissions, but may overestimate the magnitude of these emissions by about a factor of 2.

These results provide approximate confidence levels that can be placed on these emissions estimates.

3. Past inventories for the Houston area underestimated emissions of alkenes (ethene and propene) from petrochemical facilities by factors between 10 and 100. This experience shows that field experiments combined with modeling can be effective in identification and reconciliation of serious discrepancies in emission inventories.

4. Inverse modeling indicated that the 1990 NEI overestimated NH_3 emissions by 25 to 30 percent, and a strong seasonal cycle should be specified for those emissions. Inventory development and improved inverse modeling have reconciled these discrepancies in the 2001 NEI.

The methods illustrated here are important as consistency checks on emission estimates, and provide approximate confidence levels for these estimates. However, it is important to note that these top-down tests cannot be taken necessarily as definitive. With a combination of top-down tests and bottom-up estimates of emissions, disparities between the two require the data analyst and inventory developer to work together. Through cooperative efforts, the differences can be reconciled. The resulting analysis may reveal that bottom-up inventory needs improvement, or that the top-down process has problems, which require resolution. The ultimate goal is to achieve sufficient accuracy to allow the intended use of the inventory.

The emerging lesson from these evaluations is that without the support of direct measurements, current bottom-up inventories are not yet accurate enough for some technical uses. Yet, bottom-up inventories are indispensable components of photochemical models, and the foundation upon which knowledge of pollutants in the atmosphere is based. The Emission Inventory Flow Diagram (Figure 2.1) shows a proposed solution to this conundrum. It illustrates a continuing process of inventory development, testing through top-down evaluations and reviews, and evaluation in turn of the top-down tests. This process is then repeated until the top-down tests of the inventories indicate sufficient accuracy for the intended use of the inventory. Such an iterative process is required to improve existing inventories, and to develop new ones. The evolving tools discussed in Chapter 6 and the comparison between ambient measurements and emissions estimates exemplified in this chapter are essential for implementing this process.

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CHAPTER 8

METHODS FOR ASSESSMENT OF UNCERTAINTY AND SENSITIVITY IN INVENTORIES

The previous chapters note that current inventories contain little information regarding uncertainties of reported emission data; however, such information is highly important to decision makers in their attempts to plan and optimize pollution-management strategies. Up to this point, this Assessment has provided little insight on how quantitative uncertainty estimates are obtained, or on how this information can be applied once it is available. The present chapter addresses these questions by providing an overview discussion of:

- Motivations for uncertainty analysis and associated applications to emission inventory information
- Basic terminology and conceptual aspects of uncertainty analysis
- Methods for performing quantitative uncertainty and sensitivity analyses of emission inventory information.

Uncertainty analysis is a complex subject and is strongly rooted in basic statistical theory. Because of this, this chapter is presented at an overview level, which is supported by a more detailed mathematical discussion in Appendix C. Even more mathematical detail is available in several references, notably the books by Morgan and Henrion (1990) and by Cullen and Frey (1999). Given this graduated level of complexity, the reader can examine this subject at progressive levels, as dictated by his or her specific needs.

Chapter 8 Objective: ***To describe the methods by which the uncertainy in emission inventories is assessed depicted, prioritized, and reduced, and to provide a conceptual framework for emission inventory uncertainty analysis.***

8.1 MOTIVATIONS FOR UNCERTAINTY ANALYSIS

Numerous previous reports, particularly by the U.S. NRC (NRC, 1991; 2000; 2001; 2004a; 2004b), emphasize the importance of reporting uncertainties associated with emission inventory data. The 1991 report notes that the quality of current emission inventories is hampered by significant, yet poorly characterized uncertainties. The U.S. NRC (2004a) observes that inventory uncertainty analysis is usually impeded because of a perception of insufficient emission data. Ironically, this is usually the situation that exists when uncertainties are high, and uncertainty information is most critically needed.

Uncertainty quantification is useful in identifying problems and setting priorities for inventory improvement, as well as for helping decision makers to make robust decisions in the face of limited information. There remains an ongoing role for qualitative uncertainty assessments and qualitative acknowledgments of inventory limitations; however, quantitative uncertainty information is more

informative for decision-making purposes. While not all uncertainties can be quantified in a convenient fashion, the 2000 NRC report advises "that a perfect assessment of uncertainty cannot be done, however, should not stop researchers from estimating the uncertainties that can be addressed quantitatively."

Several key questions that motivate the need for quantitative uncertainty analysis can be derived from the 2000 NRC report as well as from additional sources (Bloom et al., 1993; Thompson and Graham, 1996). Itemized in Box 8.1, these questions are discussed sequentially in the following paragraphs.

Box 8.1. Key Questions Decision Makers Ask That Motivate Uncertainty Analysis

- How precise do emission estimates need to be?
- What is the pedigree of the numbers used as input to inventories?
- How precise are the estimates for emission and activity factors?
- What is the uncertainty in the overall inventory?
- What are the key sources of uncertainty in the inventory?
- How should efforts be targeted to improve the precision of emission estimates?
- How significant are differences between two alternatives?
- How significant are apparent trends over time?
- How effective are proposed control or management strategies?
- Is there a systematic error (bias) in the estimates?
- Is there ongoing research that might fill critical data gaps within the near term?
- Are the estimates based upon measurements, modeling, or expert judgment?

How precise do emission estimates need to be?

The required degree of precision of an inventory will vary depending upon its intended use. For example, if the purpose of the inventory is to serve as an input to an air quality model, then the desired precision of the inventory will be dictated by the model's ability to discriminate between different emission levels in making predictions of ambient air quality. If the model is relatively insensitive to a particular pollutant's emissions, then a relatively high degree of uncertainty might be tolerated. In contrast, if the assessment objective is to detect small changes in emissions from year to year as part of a trend analysis, then a small amount of uncertainty in annual-average emissions is desired. Precision is a concept that is applicable to all model estimates and observations.

What is the pedigree of the numbers used as input to inventories?

This question deals with issues of who developed the numbers, how they were developed, and who has reviewed them. For example, have they been subject to scientific peer review? Are the numbers based upon measurements or are these preliminary estimates based upon the judgment of an analyst? The decision maker is interested in the degree of confidence assigned to a number. In the context of emission inventories, this relates to concerns over whether the data were obtained using approved or acceptable measurement techniques and whether they pertain to a random representative sample of emission sources. Alternatively, data may have been obtained using a variety of measurement methods that may not be directly comparable, and might be for non-representative conditions (e.g., best practices rather than typical operating conditions). Thus, the data may be "bad" in some way or incomplete.

How precise are the estimates for emission and activity factors?

Typically, this question could be answered in terms of absolute or relative ranges (e.g., a 95 percent probability range of plus or minus 25 percent of the mean). Examples from the literature suggest that emission inventory precision varies depending upon the pollutant, spatial scale, and temporal scale. Examples of reported uncertainties for inventories, as described later in this chapter, range from

approximately plus or minus 20 percent to a factor of two or more. However, for some source categories within an inventory, the ranges of uncertainty can be much larger than this. This question can be answered at several levels of an analysis, including those for individual emission and activity factors that are inputs to an inventory.

What is the uncertainty in the overall inventory?

This question focuses on the simultaneous, combined effect of uncertainties in individual source activity and emission factors with respect to overall uncertainty of the entire inventory. This question can be answered by propagating uncertainty estimates for inventory inputs through the total inventory, an activity which can be thought of as a type of modeling analysis. Most inventories involve multiplication of activity and emission factors for individual source categories to estimate total emissions for each category, followed by summation of total emissions for each source category to arrive at a total inventory estimate. A variety of analytical or numerical methods can be applied to estimate the overall uncertainty in the inventory using a bottom-up approach. Such approaches are addressed in this chapter. Insight to this question also can be obtained from top-down approaches described in Chapter 7.

What are the key sources of uncertainty in the inventory?

This question also can be posed as: What source categories (or activity or emission factors) contribute the most to the overall uncertainty in the inventory? Identification of specific emission components helps to identify the source categories or inputs that are the largest uncertainty contributors. This insight can be used, in turn, to target resources to reduce those uncertainties that are largest and matter the most. There are various ways to answer this question, including various forms of sensitivity analysis. For example, in the context of a probabilistic uncertainty simulation for an overall inventory, various statistical methods can be used to determine which input distributions are responsible for contributing the most to the variance of the output.

How should efforts be targeted to improve the precision of emission estimates?

Knowledge of uncertainty in emission estimates helps guide additional data collection to reduce uncertainty in order to improve the precision of emission estimates. For example, the identification of key uncertainty sources can prioritize information-gathering efforts for the most important inputs. Because uncertainty results from lack of knowledge, an effective approach to its reduction is to obtain more knowledge, such as through additional measurements or the development of more precise and accurate measurement methods.

How significant are differences between two alternatives?

This question pertains to determining whether it is possible to discriminate between two alternative estimates even though they are both uncertain. For example, when comparing control strategies, does one offer a high confidence of a real emission reduction compared to a baseline even though both the estimates of baseline and controlled emissions are subject to uncertainty? This question can be answered by estimating the probability distributions for differences in emissions.

How significant are apparent trends over time?

This question pertains to evaluating the statistical significance of measured or estimated temporal changes in emissions, including long-term trends and cycles. Although formal time-series analyses are often applied for this purpose, simpler comparisons of distributions for specific time periods can also provide useful insights. For example, a probability distribution of the change in emissions from one time period to another can be used to assess the probability that emissions have increased or decreased, and the likelihood of various magnitudes of the change.

How effective are proposed control or management strategies?

This question addresses the confidence with which a standard will be met. For example, Hanna et al. (2001)

assess the uncertainty associated with estimates of predicted ambient ozone levels subject to a particular emission scenario, and Abdel-Aziz and Frey (2004) evaluate the probability of noncompliance with NAAQS for ozone based upon emission-inventory uncertainties propagated through an air quality model. A similar question might be: how likely is an exceedence of an emission budget? For this purpose, a probability distribution of estimated emissions can be compared with a point estimate of the emission budget in order to determine the probability that the emission budget will be exceeded and, if so, by how much.

Is there a systematic error (bias) in the estimates?

Systematic error, or bias, typically occurs when inferences are made on the basis of data that are not representative of the real-world situation for which an estimate is desired. For example, to estimate power plant emissions for a specific time period in a particular "target" geographic area, one should have data representative of the area's particular mix of power-plant designs, fuels, operating practices, loads, and ambient conditions. However, if data are available only for full-load operation of plants that differ somewhat in design, fuel, operation, and ambient conditions, then the average emission factors derived from the available data may differ from the "true" values for the target area. This question is difficult to answer in the absence of inventory comparisons using some type of a "ground-truth" or "reality check," which is the focus of the top-down approaches of Chapter 7. As described later in this chapter, it is possible to incorporate expert judgments regarding sources of bias. Furthermore, comparisons of probabilistic estimates with point estimates usually provide insights regarding the consistency of estimated statistical measures.

Is there ongoing research that might fill critical data gaps within the near term?

This question, and many of the others, is fundamentally motivated by the desire not to be unpleasantly surprised or overtaken by events. For example, if new research might resolve some of the key uncertainties in the assessment, is it worth waiting until that information is available before making a decision?

Are the estimates based upon measurements, modeling, or expert judgment?

This question again pertains to the pedigree of information used to support the emission estimates. While there is typically a preference for estimates based upon directly relevant measurements, the use of models and judgments may be justified when relevant data are not available. For example, available data may not be representative and thus inferences based upon them may lead to biases. Moreover, there may be gaps in available data such that it is not possible to make empirically based estimates for some inventory inputs. In such cases, inferences could be made based upon indirect evidence such as by interpolation, extrapolation, or model analysis. Alternatively they may be derived through elicitation of subjective judgment.

8.2 BASIC TERMINOLOGY AND CONCEPTS FOR UNCERTAINTY AND SENSITIVITY ANALYSIS

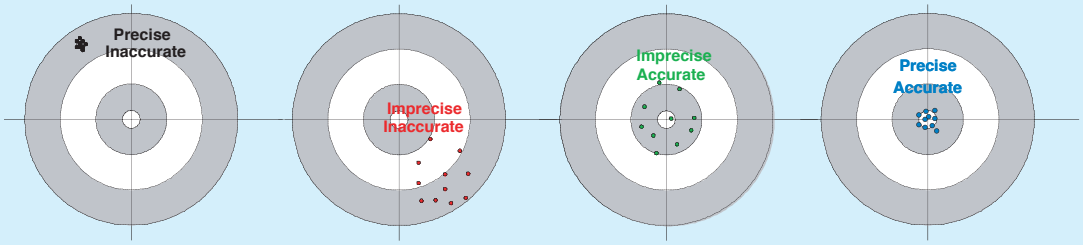
In order to further explore issues of uncertainty and sensitivity, a set of concepts and terminology is needed, as discussed here. More detail on concepts, terminology, and methodology is given in Appendix C.

Box 8.2 summarizes some basic terms that are used frequently in uncertainty analysis studies and applications. While most of these terms are straightforward, the concepts of uncertainty and sensitivity are rather involved and deserve some further elaboration at this point.

Uncertainty refers to lack of knowledge regarding the true value of a quantity. In practice, uncertainties are often expressed in the form of a probability distribution. A probability distribution describes the range and relative likelihood of different values of a quantity (e.g., emission factors, activity factors). A probability distribution can be described as either a probability density function (PDF) or a cumulative distribution function (CDF), as explained further in Box C.1 of Appendix C. As an example, Figure 8.1 shows a typical density function characterizing the uncertainty associated with an emission factor pertaining to some selected source category. A

Box 8.2. Terminology

Accuracy	Agreement between the true value and the average of repeated measured observations or estimates of a quantity. An accurate measurement or prediction lacks bias or, equivalently, systematic error.
Precision	Agreement among repeated measurements of the same quantity.
Precision vs. Accuracy	Figures a, b, c, and d illustrate the difference between precision and accuracy. Data may be accurate but not precise. In contrast, they may produce precise results but be systematically at variance with the true value.



(a) (b) (c) (d)

(a) Inaccurate but Precise; (b) Inaccurate and Imprecise; (c) Accurate but Imprecise; and (d) Precise and Accurate.

Bias	A bias exists when there is a discrepancy between the true value and the average result obtained from a model or observations. Bias is also referred to as constant error or systematic error.
Random Error	The deviation of individual measurements from the average of the measurements.
Sensitivity	The influence of one or more inputs to a system on the system's output.
Uncertainty	The lack of knowledge about the true value of a quantity.
Systematic Error	An error that causes the mean of measured or predicted values to differ from the true mean. Systematic error is also referred to as bias and is also described as a lack of accuracy.
Variability	Heterogeneity of a quantity over time, space or members of a population. Variability may arise, for example, due to differences in design from one emitter to another (inter-plant or spatial variability) and in operating conditions from one time to another at a given emitter (intra-plant variability).

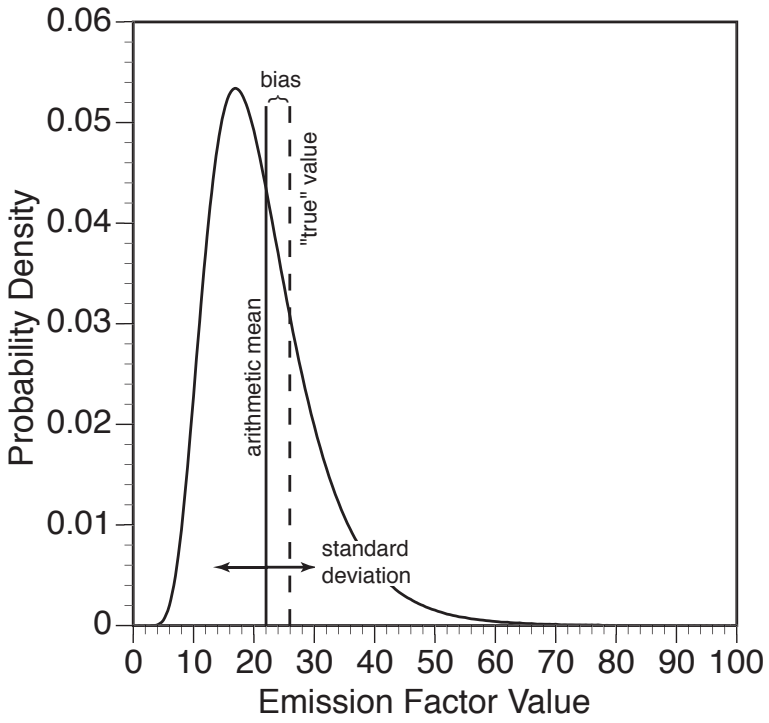


Figure 8.1. Example Probability Density Distribution, Characterizing Uncertainty of an Emission Factor for a Selected Source Category.

probability distribution can be summarized in terms of key statistics, such as the mean, standard deviation, skewness, or percentile values.

Figure 8.1 also indicates the possible presence of systematic error, or "bias" of the emission estimate in terms of the difference between the actual emission factor and the average of the estimated values. This may be compared directly with the target analogy given in Box 8.2. Bias is often difficult to quantify based upon statistical analysis of data; however, expert judgment can be used as a basis for identifying bias and developing a bias correction.

Probabilistic approaches usually begin by determining, to the extent possible, the unbiased ranges and relative likelihoods of values for individual inputs to the inventory (e.g., emission and activity factors for individual source categories), often using a variety of estimation methods, and making inferences in order to develop associated probability distributions, thus providing a quantitative mathematical characterization of uncertainty.

Once probability distributions are obtained for all cognizant sources or source classes, their collective effect on the total emission inventory's uncertainty can be calculated by propagating the ensemble of these distributions through the total system. Although numerous probabilistic techniques have been applied, the well-known Monte Carlo approach, which repeatedly takes random samples from the individual distributions and propagates them through the total inventory system, is most often used for this purpose.

Thus, uncertainty estimates are specified for the *inputs* to an inventory, and the resulting uncertainty for the *outputs* of an inventory are estimated. For this reason it is useful to consider the emission inventory output in terms of a "system" or a "model" which combines individual inputs to produce aggregated outputs, as indicated schematically in Figure 8.2. Here the model is depicted as the emission inventory computational framework, but one is not limited to this. One could for example depict the "model" as a composite of an emission inventory and an air quality model, having outputs of predicted ambient concentrations and global uncertainties associated with these predictions. Generally, uncertainties can pertain to inventory or model inputs such as emission factors, activity factors, or other inputs where the emission-factor/activity-factor paradigm is inapplicable such, for example, as the characterization of natural emissions.

Probabilistic emission inventory evaluation efforts often apply two highly complementary components: uncertainty analysis and sensitivity analysis. Within this context uncertainty analysis involves the propagation of uncertainties in various inventory inputs through the model to characterize uncertainty in model outputs. However, without additional analysis, uncertainty analysis by itself does not

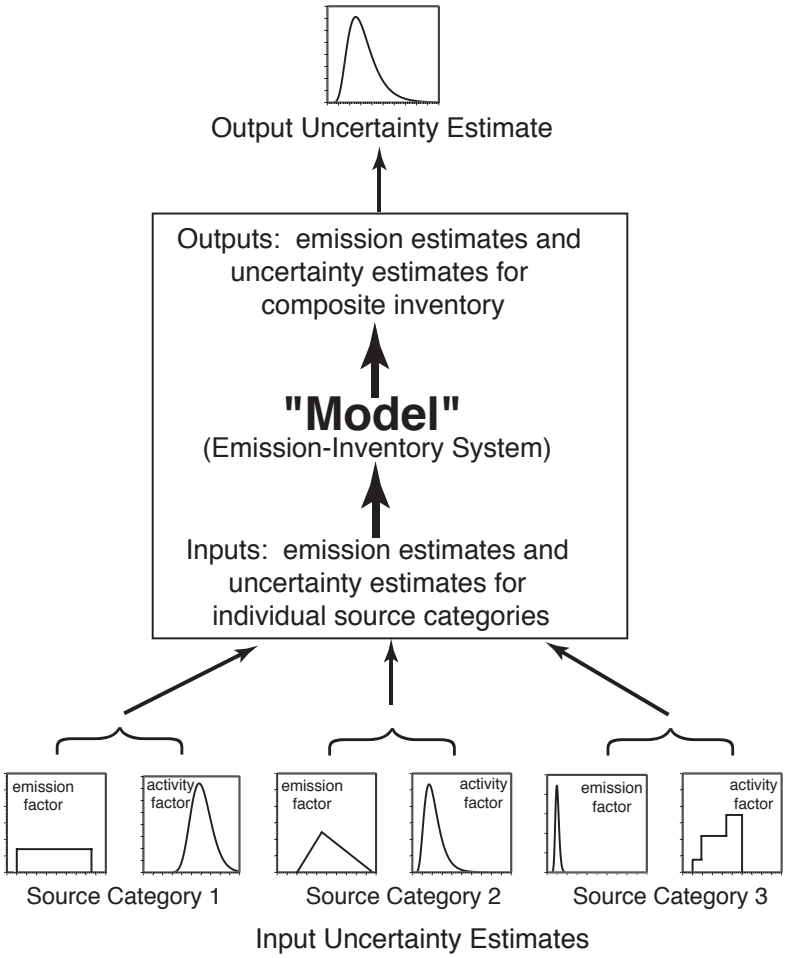


Figure 8.2. Conceptual Framework for Propagation of Uncertainty in Emission Inventory Inputs of Emission and Activity Factors for Each of k Emission Source Categories to Quantify the Uncertainty in the Estimate of Total Emissions. A variety of probability distribution models can be specified to represent uncertainty in inputs.

provide explicit information regarding which of the inputs contributed the most to the uncertainty in the output.

In contrast, *sensitivity analysis* quantifies the variation in model output that is caused by specific model inputs (e.g., Saltelli et al., 2000; Cullen and Frey, 1999). In this capacity sensitivity analysis can be used to answer the following types of questions:

- What is the rank order of importance among the model inputs?
- Are there two or more inputs to which the output has similar sensitivity, or is it possible to clearly distinguish and discriminate among the inputs with respect to their importance?
- Which inputs are most responsible for the best (or worst) outcomes of the output?
- Is the model response appropriate?

Methods of sensitivity analysis and metrics for measuring sensitivity are widely available. The most commonly used sensitivity analysis methods are often relatively simple techniques which evaluate the local linearized sensitivity of model response at a particular point in the input domain, as illustrated in Box C.2 of Appendix C. A simple type of sensitivity analysis

is to evaluate the sensitivity of the system output to its various inputs in terms of a partial derivative of the output with respect to the input in question. This derivative usually takes the form of a ***sensitivity coefficient***,

$$s_i = \left(\frac{\partial(\text{output})}{\partial(\text{input i})} \right)_{\text{inputs } j \neq i} \qquad (8.1)$$

where input i might be, for example, the emission factor for Source Category 2 in Figure 8.2, and the output the total emissions of some associated pollutant species.

The simplistic sensitivity coefficient type of approach is typically used if the model inputs are treated as point estimates, often representing the "best guess" as to the true but unknown value of each input. The sensitivity analysis of point estimates is often done for the purpose of evaluating how much the model would respond to a unit change in the input. A simple variation on this approach is to vary each input individual over a possible range of its values, rather than just for a small perturbation or a change of only one unit of measure. Although conceptually simple, local sensitivity-analysis techniques typically suffer from two key shortcomings: (1) they do not take into account the simultaneous variation of multiple model inputs; and (2) they do not take into account any nonlinearities in the model that create interactions among the inputs. For example, some emission-factor models, such as BEIS or MOBILE, have nonlinear responses over portions of their domain. In particular, emissions may respond in a nonlinear way to changes in ambient temperature. Thus, a linearized sensitivity coefficient at a local point would not accurately estimate how the model responds to a change in its inputs over the entire range of values of its inputs, when several inputs are varying simultaneously.

If uncertainty analysis is thought of as a forward propagation of distributions through the model, then sensitivity analysis could be conceptualized as looking back from the output to the inputs to determine which of the inputs is most important to the range and likelihoods of the final result. For a probabilistic analysis based upon Monte Carlo simulation, a variety of statistically based methods can be used to ascertain what portion of the variation in the model output can be attributed to each of the model inputs. Depending on the functional form of the model, the resulting measures of sensitivity may be exact or may be approximate; however, even in the latter situation they are typically highly informative with regard to management and planning needs. For example, because uncertainty arises from lack of perfect knowledge of the true but typically unknown value of actual emissions, uncertainty can be reduced by obtaining better information. Therefore, insights regarding key sources of uncertainty can be used to assess priorities for collecting additional data or information in order to reduce uncertainty.

8.3 UNCERTAINTY ANALYSIS: SOURCES, TECHNIQUES, AND APPLICATIONS

This section briefly describes the key sources of uncertainty, techniques for analyzing uncertainty, and examples of uncertainty analyses applied to emission inventories, emission sub-models, and air quality models.

8.3.1 Sources of Uncertainty

Uncertainties typically derive from a number of sources, including:

- *Precision and Accuracy in Measurement Methods*. Lack of precision (random error) is usually associated with imperfections in measurement techniques or with processes that are random or statistically independent of each other. Lack of accuracy (systematic error, or bias) may originate from sources such as imperfect calibration of equipment, simplified or incorrect assumptions, and any other errors introduced in the selection and implementation of methodologies for collecting and utilizing data.
- *Variability and Sample Size*. Variability of emission sources can lead to uncertainty. For example, for vehicle or equipment emission factors, emissions from any one unit vary from time to time and place to place. Some portion of the variability might be explainable based upon factors such as age, design features, fuel

characteristics, duty cycles, ambient conditions, and others. However, even for a specific category of vehicles or equipment, such as light duty gasoline vehicles equipped with three-way catalysts, there is intra-vehicle variability over time and inter-vehicle variability within a fleet. The variability of emissions within a category and the limited sample size of measurements give rise to random sampling errors in estimation of the mean emission factor (NRC, 2000). The average emission factor, which is typically based upon the small data set available when an emission inventory is developed, is therefore subject to uncertainty (NRC, 2004b). If the emission inventory includes a large sample of specific units within a source category, then the uncertainty analysis should typically focus on uncertainty in the mean emission rate (e.g., Frey and Zheng, 2002b). However, if an emission inventory includes only one unit from a given source category, and if no site-specific emission data are available, then an assumption might be made that the individual unit is a random sample from the population of all similar units. In this latter situation, the distribution of inter-unit variability would be the appropriate estimate of uncertainty.

- *Representativeness of Data*. In the development of emission inventories, data measured from a limited number of sources may not be representative of the entire population of sources (NRC, 2000; 2004b) or the study objectives. In such situations, several judgments must be made in order to use available data to make estimates of emissions for presumably similar sources. For example, when comparing emissions sources from which test data are available to the emission sources that are within the scope of a particular inventory, judgment is needed regarding whether the feedstocks, processes, ambient conditions, operating conditions, maintenance history, and averaging time (e.g., such as for a process facility or combustion source) are sufficiently similar. This judgment will introduce uncertainty. Furthermore, emissions measured for a different duty cycle or for a different averaging time (e.g., hourly, daily, weekly, monthly, annual, etc.) may not be a reliable basis for estimating uncertainty in a particular inventory without additional analysis or judgment.

- *Dependence and Correlations*. When there is more than one uncertain quantity, it may be possible that the uncertainties are statistically or functionally dependent. Failure to properly model the dependence between the quantities can lead to uncertainty in the emission estimation, in terms of improper prediction of the variance of output variables. However, correlations typically matter only if they are sufficiently strong between two or more quantities each of which has a significant impact on the overall uncertainty of the inventory. Thus, it is not always essential to properly account for correlations even though correlations may be known to exist. It is only necessary to account for correlations if they would alter the insights provided by the analysis.

- *Lack of Empirical Basis*. This situation occurs when relevant data for inferring emissions for the source or situation of interest are absent; it can also describe situations in which emission sources or processes are overlooked because data are not available. This situation also exists when there is a need to make predictions or estimates for future emissions. Depending on the time horizon, estimates of future emissions may have to contend with the possibility of technology changes, thereby involving the need for estimates about something that has yet to be built, tested, or measured. Although it is not possible to make statistical inferences from directly relevant data in these situations, uncertainties can be represented using technically-based judgments about the range and likelihood of possible outcomes. For example, estimates of uncertainty for future emission scenarios will typically require expert judgment.

- *Disagreement Among Experts*. Expert opinion is often used to select appropriate values or distributions for input into an emission inventory model. For example, experts may suggest the most appropriate emission factor for a certain pollutant, or, in a Bayesian analysis, experts may supply a subjective prior distribution. Often different experts' opinions on these data and

distributions may differ. Thus, there may be disagreement regarding the most appropriate values or distributions to use. Various methods are used to deal with potentially conflicting judgments regarding uncertainties. Examples include: (1) conducting the uncertainty analysis separately with each alternative set of judgments in order to determine whether insights from the analysis differ; (2) assigning weights to each judgment and performing one analysis in which the judgment is weighted; or (3) iterating the judgment and attempting to reach a consensus among experts before proceeding with an analysis.

- *Aggregation and Disaggregation.* In general, any kind of modeling involves decisions regarding aggregation or lack thereof. Aggregation refers to situations in which details are combined, such as by representing several processes or emission sources by one numerical value. Typically, aggregation results in the loss of some information regarding the details of assumptions upon which the aggregated numbers are based. Another practical example of aggregation is when emission estimates are combined from different agencies into one inventory, resulting (potentially) in loss of information regarding the source and basis of each numerical estimate that enters the inventory. In contrast, disaggregation may be required in order to convert a long-term emission estimate for a large geographic area into a shorter term estimate for a smaller area. An example of this is the development of hourly, gridded inventories for air quality modeling. To the extent that the process of aggregation results in loss of information, the range of uncertainty would typically increase, especially if the inventory was later applied to a purpose for which it was not originally developed. Similarly, the process of disaggregation may involve various assumptions and judgments, each of which is subject to uncertainty, thereby producing additional uncertainty in the disaggregated inventory.

Examination of the above features leads to the conclusion that development of probability distribution functions for inventory inputs requires a large measure of judgment and subjectivity. In addition there are several features that are not directly associated with the inputs but nevertheless affect the composite uncertainty estimates for a model output or aggregated inventory. These include:

- *Model Uncertainty.* Model uncertainty arises from model structures and inappropriate assumptions regarding emission scenarios. For example, a model based upon standardized duty cycles for mobile sources may fail to accurately and precisely estimate real-world emissions. Alternatively, structural problems could occur if emission sources are counted more than once because of ambiguity in scenario definitions. For example, a lack of clarity regarding the categorization of evaporative emissions during refueling of onroad vehicles might result in emissions being double-counted as both part of the vehicle emission inventory and part of the stationary source inventory that includes fuel service stations. Conversely, emission processes might not be counted at all if the scenario definition does not include them, such as emissions associated with startup, process upsets, and shutdown procedures. The NRC (2004b) pointed out that a major contributor to the large uncertainties in current emission inventory is the emission models used to derive the inventories. Emission models can include component models used to estimate emissions for specific source categories as well as modeling approaches for managing data in the entire inventory. Model uncertainty can be significant and is typically poorly characterized or not characterized at all (NRC, 2004b).

- *Scenario Uncertainty.* A scenario is the set of assumptions regarding the structure of the inventory and scope of geographic area, temporal averaging time, source categories, emission processes, and pollutants that are included. An emission scenario that fails to include all relevant emission sources and pollutants necessary for the desired assessment objectives would be subject to data gaps, thereby introducing uncertainty in the emission inventory (e.g., if swimming pools were omitted from an inventory of chlorine emissions). This source of uncertainty is known as scenario uncertainty (Cullen and Frey, 1999) and typically results in a bias in emission

estimates. The sources of scenario uncertainty include descriptive errors, errors in professional judgment, and incomplete specification of the scenarios (U.S. EPA, 1997).

Other possible uncertainty sources include the incorrect entry or reading of emission data, misclassification of emission source categories, and improper assumptions regarding model input distributions and model formations. All of these may lead to additional uncertainty in emission estimation. Although data-entry mistakes and misclassification errors can be sources of uncertainty, these can be avoided or minimized by application of appropriate QA/QC techniques. In contrast, other types of uncertainties described above can exist even with the implementation of appropriate QA/QC procedures. This variety of sources, which are usually exceedingly difficult to characterize in mathematical form, again lead to the conclusion that good judgment is mandatory, and considerable subjectivity is involved, in establishing input uncertainties and interpreting associated global output. This is a major challenge in emission-inventory uncertainty analysis.

8.3.2 Techniques for Uncertainty Analysis

Quantitative methods for characterizing the combined effect of uncertainties in inputs on the output of a model or inventory range from relatively simple approaches to more rigorous techniques such as Monte Carlo methods and bootstrap simulation. While it is beyond the scope of this chapter to go into the details of these methods, Section C.2 of Appendix C provides an overview of the more commonly used techniques and discusses some frameworks for conducting quantitative uncertainty analysis.

As noted above, quantitative methods typically involve specifying probability distributions for inputs to an inventory, and propagating the distributions through the inventory in order to estimate the distribution of uncertainty for the total inventory. Methods for developing input distributions typically are based on empirical data, encoding of expert judgment, or some combination of both. In situations where relevant and appropriately sampled empirical data are available, a variety of statistical techniques can be used to fit a distribution to the data (e.g., Cullen and Frey, 1999). In cases where relevant data are not available, accepted protocols for encoding expert judgment can be used (e.g., Morgan and Henrion, 1990). Bayesian statistical techniques can combine information from both empirical data and expert judgment.

Once uncertainties in the inputs to the inventory have been specified, a variety of techniques can be selected to propagate the uncertainties to the inventory output. Depending on the type of input information and the model used for the inventory, an analyst may be able to choose from exact analytical solutions, approximate solutions based upon error propagation using Taylor series expansions, or numerical methods. Of the various numerical methods, Monte Carlo simulation is popular because of its flexibility. Monte Carlo simulation can be used with a wide variety of input distribution assumptions and with a wide variety of models.

Guidelines for quantification of uncertainty in emission inventories have not been developed at the national scale in the U.S., Canada, or Mexico. However, the U.S. EPA has developed guidelines for probabilistic analysis in the context of human exposure assessment (e.g., U.S. EPA, 1997). A general framework for uncertainty analysis of emission inventories has been recommended by Frey et al., 1999. Furthermore, the Intergovernmental Panel on Climate Change has developed good practice guidance for quantification of uncertainty in national greenhouse gas emission inventories (IPCC, 2000). This guidance incorporates methods for dealing with empirical data, methods for encoding expert judgment, and methods for propagating uncertainty in inventory inputs to estimate uncertainty in the total inventory.

8.3.3 Example Applications of Uncertainty Analysis

This section provides a survey of representative case study applications of uncertainty analysis to different aspects of emission estimation. For this purpose, the example applications are classified as follows: (1) direct applications refer to estimation of uncertainty for an emission inventory; (2) application for inventory sub-models refers to

estimation of uncertainties for models that produce estimates of emissions for specific source categories that, in turn, are entered into an emission inventory calculation; and (3) combined emission inventory and air quality modeling refers to examples in which uncertainties in emission inventories are quantified and propagated through air quality models in order to estimate uncertainty in estimates of ambient concentrations. The key insights from these case studies are summarized.

Direct Applications

Several examples of the use of relatively simple approaches for estimation of uncertainty in emission inventories are reported by Chang et al. (1996), Van Amstel et al. (2000), Lee et al. (1997), NRDC et al. (2002), El-Fadel et al. (2001), Gschwandtner (1993), and Hanna and Wilkinson (2004). Simple approaches are typically based on limited information about input uncertainties (e.g., only the mean and standard deviation) and on approximate methods for propagating uncertainties through a model, such as using Taylor series expansion-based techniques. More complex for uncertainty estimation and propagation have also been used. For example, Frey and Zheng (2002a&b) quantified variability and uncertainty in highway vehicle emission factors based upon data used in MOBILE5b and developed probabilistic 6-month and 12-month emission inventories for a utility NO_x emission inventory for North Carolina. In these examples, empirical and parametric distributions were used to quantify variability while bootstrap simulation was employed to characterize uncertainty in emissions. Other examples are reported by Winiwarter and Rypdal (2001), Frey and Tran (1999), Allen et al. (2004), Frey and Bammi (2002), and Frey and Li (2003). Chi et al. (2004) employed bootstrap sampling, expert elicitation and Monte Carlo techniques to characterize uncertainty of nonroad emissions for Georgia, based upon the use of the U.S. EPA's NONROAD model.

Frey and Zhao (2004) characterized variability and uncertainty in urban toxic air pollutant emission inventories for Jacksonville, Florida, and Houston, Texas. Maximum likelihood estimation was used to deal with censored (non-detected) values in emission data, and bootstrap simulation in combination with maximum likelihood estimation was used to estimate uncertainty in the mean emission factors based upon data that included non-detects. An overview of this example is given in Appendix C.2.4.

Other statistical methods to quantify uncertainty in emission estimation include the use of analysis of variance (ANOVA) and time-series approaches (Abdel-Aziz and Frey, 2003; Sharma and Khare, 2000; Gleit, 1987). Bortnick and Stetzer (2002) applied ANOVA to emission inventories where they quantified uncertainty in ambient toxic air pollutant concentration data. These authors partitioned the variance of the monitored data into four components (temporal, spatial, sample collection and laboratory analysis) and concluded that temporal variability contributed most to the overall uncertainty. Khalil (1992) employed a statistical approach to estimate uncertainties in total global budgets for trace gases. Confidence limits for the total emissions were estimated.

The significance of these examples is two-fold. First, they demonstrate that a wide range of methodologies can be applied, depending on study objectives and availability of information. Second, the information produced in these examples is useful in answering the types of questions posed by decision makers described in Section 8.1. For example, each of these case studies provides insight regarding the quantifiable range of uncertainty in emission estimates for individual sources and for inventories and regarding the pedigree and quality of emission estimates.

Applications for Inventory Sub-Models

Frequently composite emission inventories contain sub-model components such as, for example, mobile-source emission models and natural emission models (e.g., MOBILE, NONROAD, BEIS3). Although current sub-models of this type rarely incorporate online uncertainty analysis, a few examples exist to illustrate that uncertainty analysis can be incorporated as an integral technique with such emission inventory components.

One of these efforts, which is currently in an emerging stage, is the MOVES mobile-source sub-modeling framework, which is being designed to incorporate an uncertainty analysis component (U.S. EPA, 2002). MOVES is expected to replace

both MOBILE and NONROAD, neither of which contain online uncertainty analysis. This effort is considered to be particularly timely and appropriate because several studies of MOBILE have identified significant ranges of uncertainty in fleet-average emission estimates (Guensler, 1993; Guensler and Leronard, 1997; Chatterjee et al., 1997). Frey and Zheng (2002a) derived estimates of uncertainty in basic emission rates, speed correction, temperature correction, and Reid vapor pressure for a specific MOBILE 5b LDV technology group (port-fuel and throttle body injection vehicles). Uncertainty in the-fleet average emission factor was as much as -90% to +280% when correction factors for alternative driving cycles, temperature, and Reid vapor pressure were applied. Although most of the reported efforts have dealt with onroad emissions sources, Frey and Bammi (2002) have characterized uncertainty in nonroad vehicle and equipment emission factors.

A second effort to incorporate uncertainty analysis into a sub-model component is the Integrated Environmental Control Model (IECM) developed by Carnegie Mellon University for the U.S. Department of Energy (Rubin et al., 1997). The IECM incorporates a probabilistic simulation capability, and provides performance, emission, and cost estimates for user-specified power-plant configurations using site-specific plant parameters and fuel characteristics. The IECM has the capability to explicitly quantify uncertainty in calculated results including emission estimates. The IECM enables the user to accept default specifications of uncertainty for inputs or to provide user-specified probabilistic inputs. The IECM allows the user to choose either Monte Carlo simulation or Latin hypercube sampling to propagate uncertainties through the model in order to estimate uncertainty in emission rates and other outputs.

Combined Emission Inventory and Air Quality Modeling

Emission inventories are often used as inputs to air quality models, and it is well known that errors in emission inventories can have a significant influence on model-predicted pollutant concentrations (e.g., Guenther et al., 2000; Placet et al., 2000; Russell and Dennis, 2000; Sawyer et al., 2000). Because of this, several past studies have examined the uncertainties of air quality model predictions as influenced by uncertainties in their emission-inventory inputs.

Hanna et al. (1998), for example, used expert elicitation to estimate typical uncertainties in 109 input parameters for the Urban Airshed Model (UAM-IV) including emissions, meteorological conditions, boundary conditions, and chemical rate constants; they propagated uncertainties using Monte Carlo simulation to quantify uncertainty in ozone predictions for the 6-8 July 1998 episode in New York City. The results indicate that the variability in anthropogenic VOC emissions had most impact on the uncertainty in predicted ozone concentrations. Hanna et al. (2001) later applied a similar analysis to the Ozone Transport Assessment Group domain. They addressed uncertainties in 128 input variables including emissions, initial and boundary conditions, meteorological variables, and chemistry. Through the use of sensitivity analysis, the authors were able to pinpoint key sources of uncertainty and to estimate the effect of control strategies on ambient ozone levels in the face of uncertainty. Simulation results include base-case uncertainty estimates for ozone concentrations and estimates of differences in ozone concentrations resulting from emission reduction strategies. Uncertainty was lower for estimates of differences in concentration than for absolute estimates of total concentration, thus implying more confidence in estimating changes than in estimating absolute values.

Moore and Londergan (2001) applied a probabilistic approach to quantify uncertainties in the differences of predicted ozone between a base and a control scenario in which Latin hypercube sampling was employed. They propagated uncertainties in 168 model inputs for emissions, chemistry, meteorology and boundary conditions. Lognormal and normal distributions were used based on expert judgment to describe the input uncertainties. Assessment of the uncertainty in the difference between two alternatives enables assessment of the likelihood that one alternative will perform better than another in the face of uncertainty. Bergin et al. (1999) used Monte Carlo simulation with Latin hypercube sampling to propagate uncertainties in 51 model parameters through the California/ Carnegie Institute of Technology air quality model. Uncertainties in onroad CO emissions were quantified based on remote sensing measurements.

Uncertainties for other emissions were estimated based on expert judgment. The study concluded that uncertainties in motor vehicle emissions contributed most to uncertainties in ozone concentrations. This example illustrates that uncertainty analysis can help pinpoint priorities where reductions in uncertainty (e.g., via more or better data collection) would be most useful.

Abdel-Aziz and Frey (2004) propagated uncertainty of hourly utility NO_x emissions through a photochemical air quality model to estimate the uncertainty in the maximum 1-hour and 8-hour ozone concentrations for Charlotte, North Carolina, modeling domain using a Monte Carlo simulation. They took into account statistical dependencies between power plant units (inter-unit variability) as well as temporal autocorrelation for each individual unit (intra-unit variability). Simulation results included the probability of exceeding each of two different ambient air quality standards in each grid cell during the time frame of a simulated air quality episode. This case study illustrates the ability to deal with complex dependencies among inputs while producing results that could inform decisions regarding whether addition emission control is needed, despite the existence of uncertainty in the estimates.

Key Insights from Uncertainty Analysis

Several key insights can be gleaned from the various analyses and studies described above. One of the most important of these is that it is usually far more efficient and less resource-intensive to conduct uncertainty analyses when they are incorporated directly into the emission inventory methodology, rather than conducted after the fact (e.g., Frey and Zheng, 2002a,b). A key difficulty in this respect is finding the original data used to develop a point estimate inventory or estimate average emission factors. The time required to assemble databases when original data could not be found is substantial. When data are found, they are typically poorly documented.

Because emission inventories typically involve inputs that must be nonnegative, uncertainties in inputs often are positively skewed (cf. Figure 8.1), and in these cases normality assumptions are not valid. Thus, the mean of the distribution is often greater than the mode and median. When positively skewed distributions are propagated through a model, especially one that involves multiplication, the output also tends to be positively skewed. Thus, interactions among inputs, plus the positive skewness of inputs, can lead to situations in which the mean emission rate is larger than the point estimate of emissions from a point estimate analysis. This suggests that failure to consider the interactions among simultaneous uncertainties can be a source of bias (underestimation) in some emission models.

Visualization of data used to develop an inventory is highly informative to choices of empirical or parametric distribution models for quantification of variability or uncertainty. It is important to correctly determine whether inter-unit variability or uncertainty in the mean is the relevant basis for characterizing uncertainty, since the range can differ substantially between the two. Uncertainty estimates based upon fitting parametric distributions to data might be sensitive to the choice of parametric distribution models if there is variation in the goodness-of-fit among the alternatives. However, in such cases, there is typically a preferred best fit. When several alternative models provide equivalent fits, results are not sensitive to the choice of the model. The quantifiable portion of uncertainty attributable to random sampling error can be large and should be accounted for when using emission factors and inventories.

The ranges of variability and uncertainty are typically much greater as averaging time decreases. Intra-unit dependence in hourly emissions is significant for some sources (e.g., power plants), including hourly and daily lag effects. Inter-unit dependence in emissions is important for some sources, such as multiple units at one power plant. These types of dependencies can be quantified statistically, such as with time series models. Even for sources with CEMS data, there is uncertainty regarding predictions of future emissions that can be informed by analysis of historical data.

Many of the case examples demonstrate that it possible to combine multiple methods (e.g., statistical analysis, expert elicitation) into one assessment,

and that there are varying levels of detail and sophistication from which to choose a methodology appropriate to a particular assessment objective.

Typically, analysts who have conducted uncertainty analysis report that systematically thinking about uncertainties leads to a better understanding of the strengths and weaknesses of an assessment. Overall, uncertainty analysis helps improve the characterization of the state of knowledge of emissions, thereby better informing decisions and avoid unpleasant surprises that would have occurred had uncertainty been ignored.

8.4 SENSITIVITY ANALYSIS

Sensitivity analysis is useful for answering several of the key questions given in Section 8.1.3, and can play an important role in emission inventory development and analysis (e.g., Russell and Dennis, 2000). This section briefly describes the roles of sensitivity analysis, techniques for sensitivity analysis, and example applications.

8.4.1 Roles of Sensitivity Analysis

The roles of sensitivity analysis include: (1) evaluation and verification of emission inventory models; (2) identification of key sources of variability and uncertainty; and (3) evaluation of the importance of key assumptions in the inventory structure.

Emission inventory model verification is a process of making sure that the model properly calculates emissions from various sources. If a model responds in an unacceptable way to changes in one or more inputs, then troubleshooting efforts can be focused to identify the source of the problem. For example, if a significant increase in activity factor does not lead to appropriate increase in the emission inventory, efforts need to be focused on fixing problems with the emission-inventory model structure. Model validation ideally involves comparison of model results to independent observations from the system being modeled. Generally, complete validation is not possible because of lack of sufficient observational data. Cullen and Frey (1999) discuss partial validation of a model when observational data are available for only a part of the modeling domain. Sensitivity analysis can be used to help develop a "comfort level" with a particular model. If the model response is reasonable from an intuitive or theoretical perspective, then the model users may have some comfort with the qualitative behavior of the model even if the quantitative precision or accuracy is unknown. Saltelli (2002) discusses the role of sensitivity analysis in model evaluation and how to make use of sensitivity analysis to verify or validate a model. Russell and Dennis (2000) discuss the application of sensitivity analysis to air quality model evaluation and verification.

Identification of key variability and uncertainty sources often can be aided by application of sensitivity analysis methods, in combination with probabilistic analysis techniques. Even though an emission inventory may involve many uncertain inputs, it is often the case that only a few of these contribute substantially to total uncertainty. Therefore, as a means for conserving resources devoted to an analysis, sensitivity analysis can be used concurrently with the process of developing input assumptions to continually refine the identification of key uncertainty sources and to prioritize information-gathering efforts for the most important inputs.

Evaluation of key assumptions in the inventory structure can also be aided by sensitivity-analysis applications. For example, independence among model inputs is a commonly employed assumption. Using sensitivity analysis, it is possible to evaluate whether the assumption is reasonable. For example, bounding analyses can be performed in which the inputs of interest are assumed to be independent versus assumed to be completely correlated. If the results and insights from the analysis do not change irrespective of which assumption is made, then the issue of correlation is unimportant. Frey and Zhao (2003) demonstrated that correlation between uncertain emission factors for hazardous air pollutants was typically unimportant for several inventories. Furthermore, sensitivity analysis can be used to determine whether simplifying assumptions or judgments in the absence of empirical data have a significant influence on results. Frey and Zhao (2003) demonstrated, for example, that assumptions regarding weighting factors for emissions of different processes within a source category were unimportant

to an overall assessment of urban-scale emissions because the source categories were also unimportant to the overall uncertainty estimate.

8.4.2 Techniques for Sensitivity Analysis

Methods of sensitivity analysis and metrics for measuring sensitivity are widely available. They can be classified as *screening methods* or *refined methods* depending on their level of accuracy, and as *local* or *global*, depending on their scope of coverage of the sample space for model inputs. Some methods are model-dependent in that they involve assumptions regarding model form, whereas other methods are model-independent. Although refined, global, and model-independent methods typically provide the most robust insights regarding key sources of uncertainty, they are often more difficult to apply than screening and local sensitivity analysis methods. Section C.3 of Appendix C provides an overview of methods for sensitivity analysis. Saltelli et al. (2000, 2004), Cullen and Frey (1999), and Frey, Mokhtari, and Zheng (2004) provide more detail regarding sensitivity analysis methods.

There are simple sensitivity analysis methods that work well for linear models, such as nominal range sensitivity analysis, but that may not be robust to model characteristics such as nonlinearity, thresholds, interactions, and different types of inputs (e.g., categorical, continuous). These latter characteristics may be present in some kinds of emissions models. In the context of a probabilistic simulation of uncertainties using Monte Carlo or similar methods, typically used methods for sensitivity analysis include correlation coefficients, regression techniques, ANOVA, and categorical and regression trees (CART).

The choice of an appropriate sensitivity analysis method depends on the objectives of the analysis, the characteristics of the model, and other considerations such as ease of implementation and resource availability to conduct the analysis (e.g., Frey, Mokhtari, and Zheng, 2004). For example, when the objective of sensitivity analysis is to identify key sources of uncertainty and apportion variance in an output to individual inputs, the choice of methods further depends on model characteristics. If a model is linear, correlation methods and regression analysis methods are appropriate. If the model is nonlinear, ANOVA or other methods capable of dealing with interactions are better choices. When there are categorical inputs, CART may be more appropriate. When the objective of sensitivity analysis is to identify factors contributing to high emissions in order to develop control strategies, ANOVA and CART should be considered since these methods can provide insight into conditions that lead to high emissions.

Although no guidance is available specifically for the application of sensitivity analysis to emission inventory development and air quality modeling, guidance documents are available on sensitivity analysis applied to other quantitative analysis fields such as risk assessment. For example, the U.S. Department of Agriculture sponsored work to identify and evaluate methods for sensitivity analysis (e.g., Frey and Patil 2002; Frey, Mokhtari, and Danish, 2003) and development of a guidance document on the application of sensitivity analysis methods to food-safety risk process models (Frey, Mokhtari, and Zheng, 2004). The latter study discusses the various objectives for performing sensitivity analysis, identifies key factors to be considered in the selection and application of sensitivity analysis methods, and discusses the interpretation and communication of results from sensitivity analysis.

The U.S. EPA (2001) provides guidance on how sensitivity analysis can be applied to identify important exposure or risk factors as part of risk assessment of Superfund sites. The role of sensitivity analysis in probabilistic risk assessment is discussed. Common sensitivity analysis methods such as correlation and regression methods, graphical methods such as scatter plots, and the use of these methods in the risk assessment are introduced via example case studies.

Saltelli et al. (2004) provide a guide regarding application of sensitivity analysis methods to scientific modeling. A review of the state-of-the-art in sensitivity analysis is presented and a guide regarding selection of appropriate methods for evaluating model performance and key inputs is provided with example applications.

8.4.3 Example Applications

Sensitivity analysis has been used to evaluate emission models. For example, Kear and Niemeier (2002) evaluated the sensitivity of exhaust emission rates to vehicle population and mileage accrual data for the CARB mobile source emission model, EMFAC 2001 V2.08. Sensitivity analyses also have been performed to evaluate the relative importance of model inputs in MOBILE models such as average speed, ambient temperature, fuel property and I/M parameters. Heiken et al. (1994) assessed the sensitivity of model outputs to alternative fuel formulations for exhaust emission rate, evaporative system pressure and evaporative basic emission rates. Fox (1996) evaluated the contributions of key model inputs (e.g., temperature, Reid vapor pressure, average speed) to emission factor estimates for MOBILE 6. Chatterjee et al. (1997) analyzed key travel-related inputs (e.g., speed, VMT, vehicle classification, operating-model fraction) and assessed the sensitivity of model outputs to these variables.

Sensitivity analysis has been applied to the development of emission inventories to identify key sources of variability and uncertainty. For example, Frey and Zheng (2002a,b) used sensitivity studies to identify key sources of variability and uncertainty in developing a probabilistic emission inventory for utility NO_x emissions and key contributors (e.g., speed correction factor, temperature correction factor, base emission rate and Reid vapor correction factor) to the uncertainty in highway vehicle emission factors. Frey and Zhao (2003) performed sensitivity studies to identify key source of uncertainty in developing probabilistic a toxic air pollutant emission inventory for Houston, Texas, and Jacksonville, Florida. Sax and Isakov (2003) used sensitivity analysis to determine the importance of different roadway classifications, speed, emission factor and other sources contributing to uncertainty of onroad emission estimates. In most of these example applications, sample or rank correlations and regression were the most commonly used methods to identify key contributors to uncertainty in the emission estimates.

Sensitivity analysis also has been used in air quality modeling to investigate how emission-control strategies affect atmospheric air quality and to quantify the sensitivity of air quality model results to uncertainty in emission input or other input parameters (e.g., chemical reaction rates). For example, Morris et al. (2004) investigated how ozone concentration is sensitive to emission-reduction scenarios for controlling anthropogenic VOC versus NOx emissions. Odman et al. (2002) calculated sensitivities of modeled air quality concentrations and deposition fluxes to various emission inputs. Bullock et al. (1998) used scatter plots to analyze model sensitivity to uncertainties in mercury emissions. Bergin et al. (1999) evaluated the effects of uncertainty in air parcel trajectory, emissions, rate constants, deposition affinities, mixing height, and atmospheric stability on the predictions from a photochemical air pollution model by using regression analysis, with the help of scatter plots to determine the relationship (linear or nonlinear) between the model output variables and uncertain inputs. Mendoza-Dominguez and Russell (2000) linked sensitivity analysis of air quality models with an inverse modeling technique to help identify improvements in estimates of emission strength, pattern, and composition of various source categories. Chock et al. (1995) investigated the sensitivity of UAM results for test fuels to uncertainty in light-duty vehicle and biogenic emissions and alternative chemical mechanisms. Jiang et al. (1997) evaluated the sensitivity of ozone concentrations to VOC and NO_x emissions in the Lower Frasier Valley. Other examples include investigations of the sensitivity of model-predicted predicted ozone concentrations to rate parameters of chemical mechanisms (e.g., Gao et al., 1996; Yang et al., 1996), and the sensitivity model-predicted pollutant concentrations to key model inputs, particularly emissions and meteorology (e.g., Kumar and Russell, 1996; Kuklin and Seinfeld, 1995; Seinfeld, 1988).

Many of the case study examples indicate that a relatively small number of inputs often contribute substantially to uncertainty in a model output. This observation can be used to limit debate over inputs that are of little consequence to an assessment objective, and to enable time and effort to be devoted to more fruitful discussions on those inputs that matter the most. Similarly, when basing inputs on expert judgments, only those disagreements that really matter to the decision need become the focus of further discussion and evaluation.

The examples mentioned here illustrate the diversity of objectives, methods, and applications of sensitivity analysis in the context of emission inventories. Sensitivity analysis is shown to provide useful insights regarding model behavior, key sources of uncertainty, emission control strategies, and priorities for reducing uncertainties.

8.5 CONCLUSIONS AND RECOMMENDATIONS

The discussions within this chapter combine with those of preceding chapters to produce three important conclusions with regard to emission-inventory uncertainties, their analysis, and their application. These conclusions are directly related to key recommendations of this Assessment, and are discussed sequentially below.

1. A well designed uncertainty analysis should be an essential part of the design and assessment of alternative air quality management strategies. Any decision process is more robust when uncertainties are acknowledged and taken into account. Application of uncertainty and sensitivity analysis becomes increasingly important when modern, risk-based protocols are applied to air quality decision analysis. Accordingly, this Assessment strongly recommends incorporation of quantitative uncertainty estimation into the development of all future emission inventory and air quality management strategies.

2. Most current emission inventories and emission-inventory components do not contain embedded uncertainty or sensitivity analyses, nor do they include quantified measures of uncertainty. In view of the previous conclusion this is not an acceptable situation, and this Assessment recommends that it be corrected, particularly in future inventories. It is important to note that uncertainty analysis is less resource-intensive when it is incorporated into emission inventory development, rather than conducted post hoc.

3. Although numerous techniques for uncertainty and sensitivity analysis are available, no clear guidance for application of these techniques exists for the specific case of emission inventories. Such guidance is badly needed, in order to provide a consistent and systematic basis for developing the embedded uncertainty analyses recommended above. Accordingly, this Assessment strongly recommends that Canada, the United States, and Mexico cooperate to create a central guidance document for emission inventory uncertainty analysis, including a definitive framework for applying such analyses.

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CHAPTER 9

RECOMMENDATIONS AND CONCLUSIONS

Chapter 9 Objective: ***To summarize the findings, recommendations, and conclusions of this Assessment, and to outline a proposed plan for future progress.***

Over the past three decades, local, state, and national regulatory programs have significantly reduced and will further reduce emissions from the source categories responsible for the majority of criteria air pollutants. These continuing emission reductions have significant implications for emission inventories. When ambient concentrations are high and emissions are dominated by a few source categories, air quality management strategies are fairly insensitive to errors resulting from the neglect of extraneous sources. In many current circumstances, however, ambient concentrations are falling, atmospheric chemistry regimes have changed, and emissions are more evenly distributed across a larger number of source categories. In this evolving situation, contributions from diverse sources can have proportionately greater consequences. These include wrongly identifying the pollutant to be controlled (as in the case of ozone) and designing control strategies that miss the most cost-effective reductions because of erroneous information about relative contributions of source categories. This greater sensitivity of air quality management strategies to errors in emission inventories emphasizes the increasing pressure to improve the inventories' timeliness, completeness, and accuracy.

The preceding chapters reflect these evolving issues in documenting the current state of North American emission inventories and their supporting technologies, and note several needs for inventory improvement. Particularly important for supporting air quality management and pollution modeling, these needs can be summarized in terms of the following key shortcomings:

- Quality assurance and quality control procedures are not strictly applied in the development of most emission models and inventories, and the documentation of uncertainties and data sources in emission inventories are not adequate.
- There are significant uncertainties in mobile source inventories particularly regarding the speciation of VOCs, the magnitude of CO emissions, and the temporal trend of NO_x emissions.
- Emissions for many important categories such as fine particulates and their precursors, biogenic emissions, toxic air pollutants, ammonia, fugitive emissions, open biomass burning, and many other area sources are uncertain and inadequately characterized.
- Emission estimates are frequently based on a small number of emission measurements that may not be representative of real world activity; accordingly, the precision and accuracy of estimates developed from these measurements are limited.
- The process for developing information on emissions with the kinds of spatial and temporal resolution needed for location-specific air-quality modeling is problematic and a source of unquantified uncertainty in model results.
- Current emission inventories are not developed and updated in a timely manner.
- Methods used to estimate emissions of individual chemical species in many emission models are out of date and produce estimates that are not reliable.
- Differences in current emission inventories in the three countries create difficulties for jointly managing air quality.

To address these shortcomings, this Assessment has developed eight findings and recommendations, which are described in the following subsections. A plan for implementing the recommendations follows their description.

Priorities and categories of the recommendations are indicated in Figure 9.1. As shown, the highest priority is given to uncertainty reduction for specific emission categories that are currently undercharacterized but are becoming increasingly significant with the noted evolution of North American air-quality management (9.1.1). The next seven recommendations are of equal importance from a broad North American perspective. These can be roughly divided into categories associated with emission data production (9.1.2, 9.1.3, 9.1.4, and 9.1.8) and those associated with data processing and management (9.1.5, 9.1.6, and 9.1.7). Although individual agencies may have specific needs and opportunities that would give priority to one or more of these second-tier recommendations, NARSTO encourages agencies to address each recommendation to as great an extent as possible during the normal emission inventory update cycle. For example, as agencies collect data for emission inventories, they should collect speciated data where possible, apply the most capable measurement technologies, and take measurements to ensure that the uncertainties and variabilities associated with the measurements are quantified. Agencies should also collect and process these data so that they are compatible and comparable to other emission and ambient measurements, accessible, and collected and reported in as timely a manner as possible.

9.1 FINDINGS AND RECOMMENDATIONS

9.1.1 Reduce Uncertainties in Emission Estimates of Key Undercharacterized Sources

Finding: **Comparisons of national emission inventories with ambient measurements and other independent measures indicate that emission inventories for certain source categories and pollutants, particularly gaseous emissions from electric utilities in the United States, are well characterized and reported. Emission inventories for other source categories and pollutants are much more uncertain. Of particular concern are nonpoint sources including fugitive emissions and transportation categories, as well as sources of organic compounds, carbonaceous PM, ammonia, and HAPs.**

The emission inventory community has years of experience in developing data for inventories, and has identified associated areas of greatest uncertainty. The first step in improving North American inventories is to address key uncertainty areas, which will differ for different countries, states, and provinces. Priorities will differ for inventories in different stages of

First Tier	**9.1.1 Reduce Uncertainties in Emission Estimates of Key Undercharacterized Sources**	
	Data Production Activities	**Data Management Activities**
Second Tier	**9.1.2 Improve Speciation** **9.1.3 Improve and Develop Tools** **9.1.4 Quantify and Report Uncertainty** **9.1.8 Assess and Improve Projections**	**9.1.5 Increase Compatibility and Comparability** **9.1.6 Improve Accessibility** **9.1.7 Improve Timeliness**

Figure 9.1. Prioritization and Classification of Recommendations.

development, such as inventories for specific HAPs or black carbon, or specific political domains (states, provinces or countries).

Recommendation: **Focus immediate measurement and development efforts on areas of greatest known uncertainty within current emission inventories. Systematically continue to improve emission inventories by applying sensitivity and uncertainty analyses and by comparing them to independent sources of measured data. Such comparisons will help identify subsequent improvement priorities.**

Resources must be targeted to reduce the most important uncertainty sources in emission inventories, especially for those source categories whose control will be most effective in terms of cost and health risk reduction, in making progress toward air quality goals. Considerations in the previous chapters of this Assessment, combined with recommendations from other reports (NRC, 2004a,b; NARSTO, 2004), lead to the following recommended list of topics for initial action within this first-priority recommendation:

- Size-segregated, speciated emissions of fine particles and their precursors, including black and organic carbon emissions
- Toxic and hazardous air pollutants
- Emissions from the onroad vehicle fleet
- Emissions from agricultural and other area sources, especially ammonia
- Speciated, spatially and temporally resolved organic emissions from biogenic sources
- Emissions of VOCs and organic HAPs at petrochemical and other industrial facilities
- Emissions from offroad mobile sources including farm and construction equipment aircraft and airport ground equipment, commercial marine facilities, and locomotives
- Emissions from open biomass burning, including agricultural and forest prescribed burning, wildfires, and residential backyard burning
- Residential wood combustion, including woodstoves and fireplaces
- Paved and unpaved road dust.

9.1.2 Improve Emission Inventory Speciation Estimates

Finding: **Contemporary air quality issues such as PM and ozone nonattainment, and identification of "hot spots" of HAP concentrations require detailed information about the species being emitted from sources.**

Stakeholders increasingly require speciated emission estimates as inputs for the ever-more sophisticated models used to predict air quality, human exposure, and health effects. The species needed for each of these applications may differ; even so, the need for improved and updated speciated emission factors and speciation profiles is critical for making well-informed air quality management decisions. As an example, speciated emission estimates for PM and its precursors are needed to apply source apportionment methods as one means to help link adverse health effects to emissions from specific source types.

Recommendation: **Develop new and improve existing source speciation profiles and emission factors plus the related activity data needed to more accurately estimate speciated emissions for particulate matter and its precursors, volatile organic compounds, and hazardous air pollutants.**

A high priority commitment should be made to develop, through measurements or other means, speciated source profiles, emission factors and activity data for important source categories of PM (especially carbonaceous compounds), VOCs (including a separation between high- and low-molecular-weight material), and HAPs. Critical to this effort is the need to develop temporally and spatially resolved and compound-specific estimates of emissions from biogenic sources. Progress in this area has occurred over the last several years in the United States and Canada, but further effort is needed to develop more complete knowledge of

emitted chemical constituents. The most pressing speciation needs are for organic compounds, from both anthropogenic and biogenic sources.

The National Research Council recognized this as one of seven overarching scientific challenges for air pollution research (NRC, 2004b). Emission inventories are now being used to help link emissions from specific source categories with specific measures of health. As health research identifies specific compounds of importance to public health, the emission inventory community should be ready to respond positively. Work to improve emission inventory speciation will form a solid foundation for any future efforts to include species that may be identified by health researchers as important for better understanding the links between emissions and health.

9.1.3 Improve, Develop, and Apply Emission Inventory Tools

Finding: **Technical advances in instrumentation and computation have allowed measurements and analyses that were not previously possible; continuing development of these and other technologies is likely to further improve emission inventory measurements and analyses. Improvements in modeling and data processing capabilities provide the basis for more detailed and more accurate emission models and processors.**

Advances in instrumentation capability continue to encourage more extensive measurements at lower cost than previous technologies. Increases in computational capabilities are providing new tools for comparing emissions and ambient concentration data and developing more detailed models of emissions, especially from non-point sources. Continuing development of these technologies and concepts holds substantial promise for improving emission inventory measurements, applications, and evaluations.

Recommendation: **Continue the development of new and existing measurement and analysis technologies to enable expanded measurements of emissions and ambient concentrations. Apply these technologies in developing emission model and processor capabilities to allow models to more closely approximate actual emissions in time and space.**

Support for improving current measurement technologies and developing innovative measurement concepts must be continued so that emissions and ambient concentrations can be measured more frequently and more cost effectively. To be of greatest value to air quality managers, new emission models and processors must continue to be developed to ensure that future inventories achieve the required levels of temporal and spatial resolution and composition detail.

Open path laser-based technologies, CEMS for pollutants previously considered to be "trace" species (such as mercury), and aircraft plume measurements are among the techniques that have shown considerable promise in providing more accurate source measurements. Use of dilution sampling systems coupled with detailed organic speciation methods will help to develop more comprehensive emission inventories of potential biologically active compounds. The use of satellites for identifying sources of wildfires or dust, or for measuring ambient levels of pollutants across a broad area, provides information about times and locations of emissions that would otherwise be unavailable. These measurements need to be combined with improvements in emission models and processors and other tools to create an emission inventory system that functions as a coherent whole rather than as a collection of parts.

The application of appropriate technologies and approaches for estimating speciated emissions and incorporating them into emission inventories is likely to require more resources than the other recommendations.

9.1.4 Quantify and Report Uncertainty

Finding: **The emission inventories, processors, and models of Canada, the United States, and Mexico are poorly documented for uncertainties; as a result, the reliability of the emission estimates cannot be quantified.**

Quantifying uncertainties results in a clearer understanding of the reliability of emission estimates and the robustness of policy decisions that are based upon those estimates. Given the level of resources that are allocated to maintaining and improving air quality, it is critical to provide information to decision makers that clearly identifies the uncertainties associated with technical analyses.

Recommendation: **Develop guidance, measures, and techniques to improve uncertainty quantification, and include measures of uncertainty (including variability) as a standard part of reported emission inventory data.**

Greater attention should be given to improving quantification and reporting of uncertainty in emission estimates. The most effective emission inventories are those that provide the appropriate levels of accuracy as well as the temporal, spatial, and compositional resolution needed to address the issue at hand. In order to most fully characterize the "appropriate" levels of accuracy, resolution and completeness needed for an emission inventory, methods to quantify uncertainty and evaluate accuracy must be applied where possible and developed where needed. Guidance on applying these methods is needed by emission inventory developers at all levels. Definitive guidelines are especially required for characterizing the means by which uncertainties propagate from emission and activity measurements through to final emission rate estimates and into final air quality projections and predictions. Such guidance will serve to minimize confusion about terms, methods, and results, allowing a more informed and accurate comparison of uncertainty across different emission inventories.

Quantifying variability, documenting data sources, and comparing results with other, independent measurements can, and should, be done as emission or activity measurements are taken. The results of uncertainty analyses should be made available concurrently with the primary measurement results. In Chapter 8, several methods of quantifying uncertainty in a "top-down" manner were presented and can be applied practically in many cases. Crucial to many of these methods are independent tests of emission estimates, many of which involve comparing ambient data to emission estimates. Innovative options are being developed to test or evaluate emission inventories that involve innovative applications of emerging measurements and techniques (e.g., those described in Chapter 6). Where resources are available and uncertainties in emissions are significant, every effort should be made to use these techniques to improve emission estimates that have a significant bearing on determining investments in emission controls.

Generating this information retroactively for developed inventories will be expensive – possibly as expensive as developing the initial emission estimate. On the other hand it should be relatively inexpensive when incorporated as a routine part of emission estimation. In the long run, including uncertainty information will provide users with a greater degree of confidence in the reliability of decisions supported by emission inventories. This increased confidence can lead to more effective allocation of millions of dollars for control strategies, and could well outweigh any incremental costs for including uncertainty information in databases and models.

9.1.5 Increase Emission Inventory Compatibility and Comparability

Finding: **Numerous emission inventories have been developed by different organizations for different purposes and covering different spatial domains. Although substantial improvements have been made in reporting national emission inventories in a mutually consistent way by categories, estimation methods, and chemical constituents, further efforts are needed to make these diverse emission inventories more comparable across organizations, purposes, geographies and time periods.**

Emission inventories for different countries, states, and regions have followed different developmental paths. Although emission inventories in Canada and Mexico use techniques similar to those in the United States, coordination among nations and among different organizations still needs to be fostered to improve comparability across emission inventories.

Recommendation: **Define and implement standards for emission inventory structure, data documentation, and data reporting for North American emission inventories.**

Efforts to use mutually acceptable and consistent data formats for reporting and processing data have significantly improved the ability to apply emission inventory data across regional and political boundaries in all three countries, as well as trends over time. Further efforts are needed to make emission inventories as comparable as possible given the unique needs of each emission inventory developer.

Comparability of the emission inventories is essential for effective joint analyses, air quality modeling, and reporting. At a minimum, a standard reporting format is needed for units, chemical names, industries, and similar fundamental data through use of common coding schemes [e.g., source classification codes (SCC), European industrial classifications (NACE), and pollutant codes] and data interchange formats such as the NIF. Within the United States, harmonization of the NEI, TRI, and Greenhouse Gas Emission Inventories is needed.

It is appropriate to convene a panel of experts from across the North American emission inventory development and user communities to define and implement standards for emission inventories, perhaps under the umbrella of ongoing coordination by the Commission for Environmental Cooperation. Achieving this recommendation requires that the current cross-border interactions and collaborations be maintained and enhanced.

9.1.6 Improve User Accessibility

Finding: **The accessibility of emission inventories or emission models is presently very limited because of the sheer size of the databases, and the cumbersome manner in which the data have been reported and archived. Improved accessibility to emission data is critical to meet the diverse needs of the user community.**

Many data enhancement methods and improvements are not utilized by the community due in part, to the difficulty in accessing the data. This results in inefficiencies in effort or utilization of inferior data.

Recommendation: **Improve user accessibility to emission inventory data, documentation, and emission inventory models through the Internet or other electronic formats.**

High priority attention needs to be given to substantially improve user accessibility to emission inventory data and associated supporting documentation. An investment is needed in all three nations and at different governmental levels to improve accessibility, through the Internet or other electronic formats. For instance, the creation of a file transfer protocol site (ftp) to host the detailed emission inventory and related modeling files for the three countries could address some of the accessibility requirements of the air quality modeling community. The information concerning the data sources, methods by which they were collected, and where possible, the raw data from which the final emission inventory values were developed should be as easily available as the emission inventory values themselves. Accessibility also means that inventory data will be readily available to all those who need access to it, ranging from interested members of the general public to experienced air quality modelers.

Application of modern data management techniques can provide significantly improved user accessibility to emission inventory data, and can also improve the ability of emission inventory developers to incorporate new information into emission inventories as they are developed and updated. It should be noted that accessibility cannot be achieved by simply applying the appropriate technology. Data handling procedures and agreed-upon data formats and protocols (see Recommendation 9.1.4 on compatibility) are equally important to achieving effective user accessibility.

These approaches will likely require substantial additional investment in information technology infrastructure, including investment in personnel. In some cases, the necessary infrastructure is in place, while in others, investments are needed in adequate high-speed network access, modern computer systems, and dedicated information

technology support. Expertise in data management techniques, database development and maintenance, and related topics will also be needed. A combination of distributed control and centralized maintenance yields significant opportunities for pooling resources at the regional level. Such pooling may well be an effective approach to obtaining the resources to design, implement, and maintain improved emission inventory data systems.

9.1.7 Improve Timeliness

Finding: **Timely and historically consistent emission inventories are crucial elements for stakeholders to assess current conditions and estimate progress in improving air quality.**

The current emission inventory cycle is not short enough to capture changes in emissions caused by increasingly rapid economic and technical changes. Shorter update cycles will ensure that inventory estimates are more accurate in describing actual conditions. Shorter cycles also make it easier to identify trends that provide feedback about the effectiveness of air quality management strategies. Long emission inventory cycle times have inhibited the ability of all three nations to link emission changes with trends in ambient air quality.

***Recommendation*: Create and support a process for preparing and reporting national emission inventory data on a yearly basis.**

Efforts are needed to accelerate the preparation and reporting of annual, self-consistent national emission inventories. If historical estimates need to be changed to incorporate method improvements or for other technical reasons, updated historical inventories also must be reported in a timely way to ensure that such changes are clearly communicated to users. It may be necessary to create "draft" and "final" emission inventories or other means of version control that differentiate by level of quality review so that new data can be incorporated into inventories as rapidly as possible.

The emission inventory development community should strive for continual improvements in inventory responsiveness, using an annual emission inventory update cycle as their goal. Canada and California, for instance, have demonstrated approaches that significantly reduce the length of the inventory update cycle. However, there are limits to cycle time reduction, as data collection and reporting often must follow a detailed multi-step process, including legally mandated reviews of data in some instances. In addition, shortening the inventory cycle will require the cooperation of many organizations at the federal, provincial, and state levels. For the United States to accomplish this goal, the various federal agencies that collect and report data needed for compilation of emission inventories must provide this data in a more timely manner. This includes, for example, Department of Energy data on fuel use, Department of Agriculture data on acreage and livestock populations, Department of Transportation data on vehicle miles traveled, and NASA data on fires and ground cover. Achieving this goal may also require investments in personnel or data processing capacity to more rapidly collect and report inventory data.

The ability to quickly incorporate and report new information without significantly increasing uncertainty will provide a more up-to-date picture of the current emission situation and will therefore be of much greater value to policy development efforts. However, as the level of data quality assurance increases, the time required to report the final emission inventory results will also increase. Inventory users will need to balance the desire for rapid response with the need to apply the required level of data quality assurance.

9.1.8 Assess and Improve Emission Projections

Findings: **Emission projections are critical to developing control strategies for attaining air quality standards and goals, and for evaluating future year impacts associated with regulatory development.**

Current approaches for projecting emissions have not received the same level of attention as development of base-year emission inventories. However, they have a critical impact on the regulatory process. With the exception of the electric utility and some mobile source sectors, limited effort has been applied

to capture the societal and technological changes that will impact emissions in the future. Most source categories have only had limited evaluation and the emission projection procedures may not be applicable to the range of emitted compounds being recommended for inclusion in emission inventories.

Recommendation: **Emission projection methodologies for all emission inventory sectors in North America should be evaluated to determine the accuracy of past projections and identify areas of improvement for future projections.**

Publicly available models or approaches for estimating future emission changes should be developed for all emission sectors. It is preferable from a scientific perspective to make the models widely available and to encourage further model development through comparisons of modeled results in technical literature. However, development of alternative models could be expensive and have a limited market. These factors can limit the ability of researchers and others to conduct studies of projected emissions using different assumptions.

A retrospective analysis of practical growth estimation techniques should be undertaken to understand how well past projections have predicted actual emissions. Retrospective evaluations can also identify areas in which projections can be improved. However, combining or comparing nation-, state-, or province-specific projections requires agreement among future conditions, including projection year or years and control and economic scenarios.

Uncertainties associated with projections (both forecasts and backcasts) should be explicitly quantified and reported based on backcasting and assessment of alternative demographic and technological scenarios. Uncertainties can be presented in terms of probabilistic assessments, upper and lower bounds, or comparison with other projections, but information on projection uncertainties is needed to ensure that decisions based on forward (or backward) projections are able to account for the possibility of other outcomes. For instance, some comparisons of Economic Growth Analysis System projection results with alternative approaches have taken place or are underway.

Projections for greenhouse gases are necessarily different from those associated with air quality management, due to the time scales involved and the key role of fundamental technology changes in greenhouse gas emission mitigation. Projections that account for technology innovation and diffusion involve fundamental differences from short-term projections of emissions related to air quality, and need to be considered in a complementary way.

9.2 IMPLEMENTING THE RECOMMENDATIONS

The eight recommendations are an ambitious list of items, and will clearly require money, expertise, and time to implement. Unfortunately, the resources now available may not be adequate to meet current requirements, let alone an ambitious new agenda. Nevertheless, guidance and approaches for policy makers to consider when faced with decisions about resource allocations are provided below.

The implementation of these recommendations must be considered within the context of existing requirements. It is understood that inventories are developed because of existing legislative and regulatory requirements. Even so, implementing these recommendations will ensure that inventories are able to meet air quality management needs well into the future.

Four actions were considered to be common to the three North American countries in implementing the recommendations:

- The implementation efforts should be led by Environment Canada, the U.S. EPA, and SEMARNAT over the next 10 years. Interim milestones for emission inventory improvement should be developed to support regulatory deadlines in each country.
- Federal support for regional, state, and provincial emission inventory development and improvement needs to be continued to ensure that emission inventories are able to provide the expected quality of information.

- The interactions and collaborations among and across Canada, the United States, and Mexico should be maintained and enhanced.
- Increased training of agency staff at federal, state and provincial, and local levels and industrial stakeholders (regulated sources, testing organizations, etc.) will be required to effectively implement these recommendations.

Outlined below is a series of first steps toward a full implementation of the eight recommendations for each of the three countries. These action plans are intended to provide initial guidance; each lead agency should develop more detailed steps to fully implement the above recommendations across all governmental levels in all three countries.

The cost estimates in the action plan were developed based upon the experience of the Assessment's combined authors, with the understanding that these are preliminary planning estimates that must be further refined for each issue. These cost estimates are intended as a starting point for additional discussion.

The call for increased funding should not be construed to mean the current emission inventories are inadequate to support current regulatory activities; rather, the need for increased investments is a recognition that future emission inventory improvement needs to be accelerated to enhance the effectiveness of air quality management and more clearly assess both ongoing progress and remaining air quality issues.

9.2.1 Action Plan for Canada

1. Improve the emission inventory for $PM_{2.5}$ and its precursors. The adverse health effects of $PM_{2.5}$ due to exposure to ambient air pollution are well documented. The requirements for Canadian jurisdictions to meet the new ambient air quality standards for $PM_{2.5}$ by the year 2010 provide an additional incentive to reduce the uncertainties associated with the current emission inventory for $PM_{2.5}$ and its precursors, for the development of provincial implementation plans. The national inventory will be improved through the development of new emission factors using the latest measurement techniques, and the compilation of activity statistics through detailed surveys. These activities should be conducted for industrial and non-industrial sources, including particulate matter and ammonia emissions from the agricultural sector. **Estimated Cost:** $1.5 million (US) per year.

2. Improve speciation profiles for PM and VOCs. Many of the speciation profiles currently available are based on measurements and information compiled a number of years ago reflecting mainly industrial and non-industrial activities in the United States. The use of the latest measurement techniques will allow the current speciation profiles to be expanded to provide a more accurate representation of the Canadian emission sources, taking into account the differences in the climate, fuel characteristics, processes and activities. These new profiles will improve the characterization of the Canadian emission sources providing better information for air quality models and air quality management. **Estimated Cost:** $2 million (US) per year.

3. Improve the point source emission estimates. The point source emissions collected in Canada through programs such as the NPRI are currently of variable quality for selected sectors. There is a need to collect more information on the emission sources for each facility to more easily assess the completeness and accuracy of the reported emissions. The implementation of an enhanced verification program conducted in conjunction with technical studies and source measurements would provide additional support to the industries to improve their emission estimates. Performed in collaboration with the industries and the industrial associations, this program would improve the accuracy of the emission inventories, and more precisely monitor the progress of different emission reduction programs and initiatives. **Estimated Cost:** $1.5 million (US) per year.

4. Improve the timeliness for the dissemination of the emission inventory trends and projections. The dissemination of the emission inventory trends and projections in a more timely fashion

is required to meet the reporting requirements of domestic programs, international agreement and protocols, the air quality modelers and the public. With the current efforts in Canada to compile and disseminate the national emission inventory on an annual basis, there is a need to increase the current capacity to produce the required reports, and data files. The emission trends and projections should also be reviewed on a regular basis to ensure their accuracy and consistency with the latest emission inventory. An increase in personnel and an update of the national emission inventory database system are required to meet these requirements. **Estimated Cost:** $0.6 million (US) per year.

5. Engage appropriate stakeholder groups to develop a national strategy to implement the eight recommendations of the Assessment. The compilation and the improvement of the national emission inventory are performed in collaboration with the federal, provincial, territorial, and regional governments, and with industries, industrial associations, academia, and nongovernmental organizations. Consultations with these stakeholder groups should be held to discuss the eight recommendations of this Assessment, identify their priorities, and develop a national strategy with specific timelines for implementation. **Estimated Cost:** $60,000 (US) for the first two years to conduct the consultations with the stakeholder groups.

The cost to implement these initial steps as part of a national strategy is estimated to be approximately $6 million (US).

9.2.2 Action Plan for United States

1. Enhance the emission inventories and associated tools (such as SPECIATE) for $PM_{2.5}$ and its precursors, especially for carbonaceous particles. From a public health perspective, $PM_{2.5}$ has been associated with premature mortality and appears to be the single greatest contributor to public health risk due to exposure to ambient air pollution. Furthermore, of the ten highest-priority source categories identified as needing immediate attention, nine are directly relevant to $PM_{2.5}$. **Estimated Cost:** An additional $5 million per year at the federal level for additional measurements, plus $0.1 million per year (ongoing) to maintain SPECIATE. Development of improved mobile emission models and data should continue at current levels for the foreseeable future.

2. Establish emission inventory reporting requirements for HAPs and integrate data into the National Emission Inventory. No requirement currently exists for sources or state agencies to report emissions of HAPs in the same way as criteria pollutants and their precursors. Under Title V of the *Clean Air Act* and the requirements of the Toxic Release Inventory, many of these data are being reported to the states on regular basis, but are not necessarily transferred to the national emission inventory system. **Estimated Cost:** Initial, short-duration costs to implement a rule would be on the order of $0.5 million per year for three years. Development of a data management system to facilitate harmonization and stakeholder accessibility of these data could be $10 million.

3. Improve the capacity of state, local, and tribal agencies to develop inventories to meet State and Tribal Implementation Plan and other regulatory requirements. As inventories become more complex, the resources required by state, local, and tribal agencies to meet their regulatory requirements increase tremendously. Much of the investment made by these agencies is in the form of personnel expenses. Many actions can be taken to increase the capacity of these agencies to meet the needs of increasingly complex inventories. Changing the data collection process to allow facilities to submit data online, providing additional and more in-depth training, and consolidating data reporting requirements (see item 2 above) can all improve the ability of state, local, and tribal agencies to meet inventory development challenges. **Estimated Cost:** Investments in state/local/tribal personnel should be doubled from the current estimated expenditures of $10 million/year.

4. Engage appropriate stakeholder groups to develop action plans to implement the full range of recommendations. Considerable effort is underway to improve U.S. emission inventories across the federal government, by state governments, and by affected industries. Coordination of efforts toward addressing the eight recommendations would provide the greatest return on those inventory investments and would ensure that the recommendations of greatest importance to the stakeholder communities are being addressed. The appropriate stakeholders will vary depending upon the location and the type of inventory (criteria, toxic air pollutants, mercury, greenhouse gases, etc.), but will include the following general groups: the U.S. EPA (Office of Air and Radiation, Office of Research and Development), the Committee on Environment and Natural Resources Research (to coordinate across federal agencies), STAPPA/ALAPCO, industry experts, environmental and other nongovernmental groups, and academic researchers. **Estimated Cost:** $0.25 million per year for two years to support stakeholder meetings. Resources to implement these plans should be provided in concert with these planning resources. To get the process underway, it is estimated that $10 to 20 million would provide the necessary initial support for critical programs to address the Assessment's recommendations. The stakeholder groups will determine appropriate base level funding for future years.

5. Increase support of research to develop and improve emission inventories. Several of the Assessment's recommendations call for improved technologies, tools, methods, and guidance. These improvements can only occur if the research necessary to develop them is adequately supported. Inventory-related topic areas should be regularly included in federal competitive grants programs and technology development programs such as the Small Business Innovative Research program. **Estimated Cost:** A minimum of 10 percent of the base budget for implementing these recommendations (as determined by the stakeholder groups discussed above) should be allocated to stimulate research activities by academic, institutional, and governmental researchers on the science and technology of emission inventory development and improvement.

9.2.3 Action Plan for Mexico

1. Complete the National Emission Inventory for Mexico. The most critical need is to complete the initial NEI for Mexico. Mexico's NEI is nearing completion, and when done it will represent a major accomplishment in Mexico's air quality management program. Not only will completion of this inventory provide a comprehensive overview of air pollutant emissions in Mexico, but it will also set the foundation upon which improved inventories will be developed in the coming years. **Estimated Cost:** $0.6 million (US) per year for two years.

2. Develop and implement a communications strategy to disseminate the results of the NEI. Upon completion of the NEI, it is critical to get the information out to other federal agencies, states, localities, industries, researchers, and the general public in Mexico. As the value of the inventory is recognized by stakeholders, support for future inventories will increase. This support may take the form of measurements from industrial sources or access for such measurements, as well as sustained funding from both Mexico and outside sources. **Estimated Cost:** $80,000 (US).

3. Develop and fulfill requirements at the national level to enable emission inventory updates on a three-year cycle. As the NEI nears completion, data gaps and lessons learned can be evaluated and used to develop requirements for the next cycle. In conjunction with the communications strategy above, discussions with stakeholder groups can provide valuable input to facilitate the update of the NEI. **Estimated Cost:** $85,000 (US) per year for three years.

4. Build emission inventory development capacity among state environmental agencies. In order to maintain and update the NEI, state environmental authorities require basic emission inventory

development capacity. Intensive training is required for state government officials and technicians in the areas of information retrieval, emission factor use, QA/QC activities, and inventory compilation in general. Interaction with SEMARNAT to integrate the NEI will be facilitated if all state agencies act upon the same technical baseline. **Estimated Cost:** $1 million (US) per year for three years.

5. Expand capabilities among Mexican agencies. Mexican agencies at the federal and state level often have access to data and facilities that will significantly expand the ability of SEMARNAT to develop emission inventories and updates. Expanding the capabilities of these other agencies to measure and collect emission and activity data will substantially facilitate future NEI development. **Estimated Cost:** $80,000 (US) per year for three years.

6. Continue to improve the capabilities to develop emission inventories through interactions with the U.S. and Canada. Partnerships to enhance Mexico's emission inventory development capacity have been of enormous value to both Mexico and the US and need to be continued. Where appropriate, such efforts should be expanded across North America through NARSTO, the Commission for Environmental Cooperation, and similar multinational entities. Partnerships at the state level, such as with the Western Governors' Association, are also highly beneficial to states on both sides of the border. Areas requiring special attention include training for Mexican inventory developers at the federal and state levels, and emission measurement pilot-project activities to develop Mexico-specific emission factors. **Estimated Cost:** $0.3 million (US) per year for three years

7. Improve programs to conduct direct emission measurements by identifying sources needed to develop Mexico-specific emission factors and by developing vehicle fleet characterization data for mobile sources. Many of the emission estimates in the current draft of the NEI are based upon U.S. data. Although these data provide a meaningful starting point, it is important to improve the emission estimates by conducting emission measurements on Mexican sources to reflect differences in activity patterns, technology use, and fuels. Equally important is the need to develop Mexico-specific vehicle fleet data. Differences in vehicle mix, age, emission controls, and use patterns will have significant impacts on the estimated emissions from mobile sources. **Estimated Cost:** $3 million (US) per year for five years.

8. Develop a national data system. A common data system for reporting and analyzing emission data is critical to the long-term ability of SEMARNAT to maintain and update emission inventories. Data processing hardware and software are needed to handle the increasing amounts of data that will be collected as emission inventories are updated and improved. Expanding the emission inventory data system infrastructure to states will further enhance the capabilities for developing and updating emission inventories. **Estimated Cost:** $1 million.

9. Increase human resources available at federal and local levels for emission inventory compilation, maintenance and update. The first ever National Emission Inventory is being compiled by the limited personnel available at federal and state agencies with the help of a consulting team. However, to effectively follow up on the most pressing next steps, more personnel are needed for the compilation, maintenance and update of data. This would assure continuity of present efforts. **Estimated Cost:** $1 million (US) per year.

9.2.4 Additional Commentary on Cost

It is estimated that the U.S. federal government currently invests approximately $25 million per year to develop and update emission inventories. In Canada, approximately $6 million (US) per year is invested for the compilation of the national emission inventory. Mexico has invested approximately $600,000 (US) per year in the development of the NEI in Mexico. As a basis for comparison, the U.S. EPA's total budget for air programs, not including climate change, was nearly $600 million in 2003. Investments in emission inventory research, preparation, and reporting will

need to increase substantially to achieve emission inventories that provide the quality and quantity of information expected by air quality management decision makers, the regulated community, and the general public. Increases ranging from double to an order of magnitude may be required, depending upon the specific area and current levels of investment. Although additional resources are being invested by state, provincial, and local agencies (an estimated $10 million per year in the United States), the total available resources are not sufficient to achieve the desired improvements in emission inventory programs.

The cost of developing emission inventories is strongly dependent upon their purpose. The relatively low cost to develop Mexico's NEI is a consequence of a relatively low data detail level and the use of previously existing information. At the upper end of the cost scale, the Electric Power Research Institute invested $50 million to quantify emissions of hazardous air pollutants from utility boilers (EPRI, 1994). The American Petroleum Institute, the U.S. Department of Energy, and other contributors have spent approximately $6 million to measure combustion emissions from refinery equipment. These more expensive examples reflect the higher cost of collecting highly detailed information, including quantification of speciated organic and metal compounds that are normally present in flue gases at concentrations as low as part-per-billion levels.

These examples indicate the reasons for such disparity in costs, but they also illustrate that as the demands for detailed data increase, inventories become increasingly expensive. This need for more detailed emission information to adequately support the development of air quality management decisions is driving the need for more accurate and more expensive emission inventories. In this context, estimates of an order-of-magnitude increase in resource needs are not as extreme as they may initially appear, and in some cases may even be conservative.

Investment in emission inventories is roughly $40 million per year across North America. This substantial sum can be put into context. It has been estimated that the United States spent about $19 billion in 1999 to meet the requirements of the *Clean Air Act*. Thus, approximately $2 out of every $1,000 spent to meet the *Clean Air Act* requirements was spent on emission inventories. A doubling of the investment in emission inventory development can significantly improve well-informed air quality management decisions, and may in fact reduce the total amount that spent on *Clean Air Act* compliance if more targeted air quality strategies can be developed.

9.3 CONCLUSIONS

Emission inventories are the foundation upon which air quality management strategies are built. Substantial progress has been made over the past three decades in improving air quality across North America due to the application of good scientific and technical information by air quality managers. However, emission inventories are now expected to provide high-quality data for applications for which they were not designed, and to provide those data more rapidly, more transparently, and more broadly.

Several scientific advisory groups in the United States recently have underscored these expectations. The National Research Council reports on air quality management and PM research, the recent NARSTO Ozone and PM Assessments, and the Clean Air Act Advisory Committee have all identified emission inventories as needing additional attention (CAAAC, 2005). These groups have each pointed to the importance of accurate, timely, and complete emission inventories as the foundation for scientifically sound air quality management decisions.

Experience in Texas, California, and elsewhere has shown that well focused cooperative efforts among government, industry, and academia can facilitate the development of improved emission inventories. Although such concerted efforts initially appear costly, it is much more costly to embark upon a control strategy that is ineffective in solving the environmental problem at hand. In short, the return on investment in accurate and timely emission inventories can be more than offset by the savings derived from more cost-effective control strategies.

The ambitious vision described in Chapter 2 – "all significant emissions from all sources, time periods, and areas with quantified uncertainties and timely accessibility" – provides a long-term target for emission inventory improvement. The progress made to date by the three countries of North America to develop and improve emission inventories represents a clear success for the field of air quality management. To build on this success and to achieve the quality of environment the people of North America expect, allocation of management attention and resources to emission inventories continues to be critical. The recommendations above are an important step toward ensuring that the progress of the past is maintained and that future progress is achieved.

REFERENCES FOR CHAPTER 9

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NRC. 2004b. Research Priorities for Airborne Particulate Matter (IV). Continuing Research Progress. National Academies Press, Washington, DC. ISBN 0-309-09199-3.

U.S. EPA. 2001. Final Report to Congress on Benefits and Costs of the Clean Air Act. EPA-410-R-99-009, Office of Air and Radiation, Washington, DC.

APPENDIX A

LISTS OF AGENCIES AND CONTACTS

Table A.1. Contacts for Obtaining Local and Regional Canadian Emission Inventories (3 pages)					
Province (P) Territory (T)	Department	Name	E-mail	URL	Address
Newfound-land (P)	Department of Environment & Conservation	Jeff Fillier	JFillier@mail.gov.nf.ca	http://www.gov.nf.ca/env/	Jeff Fillier Nfld. Dept. of Environment 4th Floor, West Block Confederation Building P.O. Box 8700 St. John's, NF A1B 4J6
Prince Edward Island (P)	Department of Fisheries, Aquaculture and Environment	Todd Fraser	ktfraser@gov.pe.ca	http://www.gov.pe.ca/af/agweb/in-dex.php3	K. T. Fraser PEI Dept. of Fisheries, Aquaculture and Environment Jones Building, 11 Kent Street P.O. Box 2000 Charlottetown, PEI C1A 7N8
Nova Scotia (P)	Department of the Environment and Labour	Barbara Bryden	brydenba@gov.ns.ca	http://www.gov.ns.ca/enla/	Barb Bryden Resource Management and Environmental ProtectionNova Scotia Department of Environment & Labour. P.O. Box 2107 Halifax, NS B3J 3B7
New Brunswick (P)	Department of Environment and Local Government	Sean Fortune	sean.fortune@gnb.ca	http://www.gnb.ca/0009/index.htm	Sean Fortune Acid Rain Program Specialist New Brunswick Department of the Environment 364 Argyle Street P.O. Box 6000 Fredericton, New Brunswick E3B 5H1

Table A.1. Contacts for Obtaining Local and Regional Canadian Emission Inventories (3 pages)					
Quebec (P)	Environnement Québec	Gérard Houle	gerard.houle@menv.gouv.qc.ca	http://www.menv.gouv.qc.ca/accueil/plan.htm	Gérard Houle, ing, Ministère de l'Environnement 675 Boul. René-Lévesque est, 9ième étage Boite 71 Quebéc City, Québec G1R 5V7
Ontario (P)	Ministry of the Environment	Peter Wong	wongpe@ene.gov.on.ca	http://www.ene.gov.on.ca/environet/onair/splash.htm	Peter Wong Ontario Ministry of Environment 125 Resources Road, East Wing Etobicoke, Ontario M9P 3V6
Manitoba (P)	Manitoba Conservation	Jean Van Dusen	jvandusen@gov.mb.ca	http://www.gov.mb.ca/conservation/index.html	Jean Van Dusen Manitoba Conservation 123 Main Street, Suite 160 Winnipeg MB R3C 1A5
Saskatchewan (P)	Saskatchewan Environment	Chris Gray	cgray@serm.gov.sk.ca	http://www.se.gov.sk.ca/	Chris Gray Environmental Protection Branch Saskatchewan Environment and Resource Management Rm 224, 3211 Albert St. Regina, Saskatchewan S4S 5W6
Alberta (P)	Alberta Environment	David Slubik	dave.slubik@gov.ab.ca	http://www3.gov.ab.ca/env/air/EMR/index.html	Dave Slubik Alberta Environment 9820-106 Street Edmonton, Alberta T5K 2J6

Table A.1. Contacts for Obtaining Local and Regional Canadian Emission Inventories (3 pages)					
British Columbia (P)	B.C. Ministry of Water, Land and Air Protection	Tony Wakelin	Tony.Wakelin@gems5.gov.bc.ca	http://wlapwww.gov.bc.ca/air/industrial/index.html	Tony Wakelin B.C. Ministry of Environment, Lands & Parks Air Resources Branch P.O. Box 9341, Stn. Prov. Govt. Victoria, B.C., V8W 9M1
British Columbia (GVRD) (Local Government)	Greater Vancouver Regional District	Kelly Der	kelly.der@gvrd.bc.ca	http://www.gvrd.bc.ca/air/emissions.htm	Kelly Der Greater Vancouver Regional District Air Quality Department 4330 Kingsway Burnaby, British Columbia V5H 4G8
Yukon Territory (T)	Department of Environment	Pat Paslawski	pat.paslawski@gov.yk.ca	http://www.environmentyukon.gov.yk.ca/main/index.shtml	Pat Paslawski A/Manager, Standards and Approvals Environmental Protection and Assessment Branch Yukon Environment Box 2703 Whitehorse, Yukon Y1A 2C6
Northwest Territories (T)	NWT Resources, Wildlife & Economic Development	Graham Veale	graham_veale@gov.nt.ca	http://www.rwed.gov.nt.ca/RWED/	Graham Veale Northwest Territories Resources, Wildlife & Economic Development 7th Floor Scotia Centre 5102 - 50th Ave. Yellowknife, NWT X1A 3S8
Nunavut (T)	Department of Sustainable Development			http://www.gov.nu.ca/sd.htm	

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Alabama	Alabama Department of Environmental Management, Air Quality Division	http://www.adem.state.al.us/AirDivision/AirDivisionPP.htm	Huntsville Jefferson County	http://ci.huntsville.al.us/NatRes/ http://www.jcdh.org/
Alaska	Alaska Department of Environmental Conservation, Division of Air and Water Quality	http://www.state.ak.us/local/ akpages/ENV.CONSERV/dawq/dec_dawq.htm/	Anchorage, Fairbanks North Star Borough	http://www.ci.anchorage.ak.us/healthesd/air.cfm http://www.co.fairbanks.ak.us/transportation
Arizona	Arizona Department of Environmental Quality, Air Quality Division	http://www.adeq.state.az.us/environ/air/index.html	Maricopa County Pima County Pinal County	http://www.maricopa.gov/envsvc/Airqual.asp http://www.deq.co.pima.az.us/air http://co.pinal.az.us/AirQual/
Arkansas	Arkansas Department of Environmental Quality, Air Division	http://www.adeq.state.ar.us/air/default.htm	No Local Agencies	No Local Agencies
California	California Air Resources Board	http://www.arb.ca.gov/homepage.htm	Amador County Antelope Valley Bay Area Butte County Calaveras County Colusa County El Dorado Count Feather River Glenn County Great Basin Imperial County Kern County Lake County Lassen County Mariposa County Mendocino County Modoc County Mojave Desert	http://www.amadorapcd.org, http://www.avaqmd.ca.gov http://www.baaqmd.gov http://www.dcn.davis.ca.us/go/bluesky/ http://www.co.calaveras.ca.us/departments/env.html http://www.dcn.davis.ca.us/go/bluesky http://co.el-dorado.ca.us/emd/apcd/index.html http://home.jps.net/fraqmd/ http://www.dcn.davis.ca.us/~bluesky http://www.co.kern.ca.us/eh/ehs.htm http://www.co.mendocino.ca.us/aqmd http://www.mdaqmd.ca.gov http://www.mbuapcd.org

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
California (cont.)	California Air Resources Board	http://www.arb.ca.gov/homepage.htm	Monterey Bay North Coast Northern Sierra Northern Sonoma County Placer County Sacramento San Diego County San Joaquin Valley San Luis Obispo County Santa Barbara County Shasta County Siskiyou County South Coast Tehama County Tuolumne County Ventura County Yolo-Solano	http://www.northcoast.com/~ncuaqmd http://www.nccn.net/~nsaqmd http://www.placer.ca.gov/airpollution/airpolut.htm http://www.airquality.org http://www.sdapcd.co.san-diego.ca.us http://www.valleyair.org http://www.slocleanair.org http://www.sbcapcd.org http://www.co.shasta.ca.us/Departments/Resourcemgmt/drm/aqmain.htm#top http://www.aqmd.gov http://www.vcapcd.org http://www.ysaqmd.org
Colorado	Colorado Department of Health, Air Pollution Control Division	http://www.cdphe.state.co.us/ap/aphom.asp	Boulder County Boulder Fort Collins Denver Denver Regional Air Quality Council El Paso Jefferson County Larimer County Mesa County Pueblo Tri-County Weld County	http://www.ci.boulder.co.us/environmentalaffairs/air_quality/aq_clear_air.html http://www.denvergov.org/Environmental_Protection http://www.raqc.org http://www.co.el-paso.co.us/health http://206.247.49.21/ext/dpt/health/ehs/environm.htm http://www.co.larimer.co.us/depts/health/ehs/air1.htm http://www.co.mesa.co.us/health http://www.tchd.org/environmental.html http://www.co.weld.co.us/departments/enviropublichealth.html

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Connecticut	Connecticut Department of Environmental Protection, Bureau of Air Management	http://dep.state.ct.us/air2/prgacti.htm	Bridgeport Bristol-Burlington Greenwich Milford New Haven Stamford Stratford	http://ci.bridgeport.ct.us/departments/ health/environmental_health.aspx http://www.ci.bristol.ct.us/BBHealth/BBHmain.htm http://www.greenwichct.org/services/Health%20department.htm http://www.ci.milford.ct.us/health.html http://www.cityofnewhaven.com/govt/gov21.htm#4 http://www.cityofstamford.org/HealthDepartmentEnvironmentalHealth/main.htm http://www.townofstratford.com/depts/health.htm
Delaware	Delaware Department of Natural Resources and Environmental Control, Division of Air & Waste Management	http://www.dnrec.state.de.us/air/aqm_page/aqm_nets.htm	No local agencies	No local agencies
District of Columbia	Department of Health, Environmental Health Administration, Air Quality Division	http://dchealth.dc.gov/services/ administration_offices/environmental/services2/air_quality/ index.shtm	No local agencies	No local agencies
Florida	Florida Department of Environmental Protection, Division of Air Resource Management	http://www.dep.state.fl.us/air/	Broward County Dade County Hillsborough County Jacksonville Manatee County Orange County	http://www.co.broward.fl.us/air.htm http://www.miamidade.gov/derm/air/home.asp http://www.epchc.org/air.htm http://www.coj.net http://www.co.manatee.fl.us http://www.orangecountyfl.net/dept/CEsrvcs/epd

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Florida (cont.)	Florida Department of Environmental Protection, Division of Air Resource Management	http://www.dep.state.fl.us/air/	Palm Beach County Pinellas County Polk County Reedy Creek Improvement District Sarasota County	http://www.doh.state.fl.us/chdpalmbeach/env/airqual/airquality.html http://www.co.pinellas.fl.us/BCC/ Environ/default.htm#Air%20Quality http://www.polk-county.net/Environment_Services/Natresources/index.htm http://www.state.fl.us/rcid Sarasota County
Georgia	Georgia Department of Natural Resources, Environmental Protection Division, Air Protection Branch	http://www.dnr.state.ga.us/dnr/environ	No local agencies	No local agencies
Hawaii	Hawaii Department of Health, Clean Air Branch	http://www.state.hi.us/health/eh/cab	No local agencies	No local agencies
Idaho	Idaho Division of Environmental Quality, Air Quality Program	http://www2.state.id.us/deq/air/air1.htm	No local agencies	No local agencies
Illinois	Illinois Environmental Protection Agency, Bureau of Air	http://www.epa.state.il.us/air	Bedford Park Chicago Cook County East St. Louis McCook	http://www.ci.chi.il.us/Environment/AirToxPollution/ http://co.cook.il.us/agencyDetail.php?pAgencyID=7
Indiana	Indiana Department of Environmental Management, Office of Air Quality	http://www.in.gov/idem/air	Anderson Evansville Gary Hammond Indianapolis Lake County St. Joseph County Vigo County	http://www.ci.hammond.in.us.environmental/index.htm http://www.indy-enviro.org/air.htm http://www.vigocountyin.com/air.htm

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Iowa	Iowa Department of Natural Resources, Air Quality Bureau	http://www.iowacleanair.com	Polk County Linn County	http://www.airquality.co.polk.ia.us http://www.air.linn.ia.us
Kansas	Kansas Department of Health and Environment, Bureau of Air and Radiation	http://www.kdhe.state.ks.us/bar	Johnson County Shawnee County Wichita Wyandotte County	http://www.sharetheair.com http://www.wichitaenvironment/air_quality.asp http://www.toto.net/daq/
Kentucky	Kentucky Department for Environmental Protection, Division for Air Quality	http://www.air.ky.gov	Louisville Metro	http://www.apcd.org
Louisiana	Louisiana Department of Environmental Quality, Office of Environmental Services	http://www.deq.state.la.us	No local agencies	No local agencies
Maine	Maine Department of Environmental Protection, Bureau of Air Quality	http://www.state.me.us/dep/air/homepage.htm	No local agencies	No local agencies
Maryland	Maryland Department of the Environment, Air and Radiation Management Administration	http://www.mde.state.md.us/arma	Allegany County Anne Arundel County Baltimore Baltimore County Carroll County Frederick County Garrett County Harford County Montgomery County	http://www.hereintown.net/~dressman/achd/environmental.html http://www.dhmh.state.md.us/ http://www.co.ba.md.us/p.cfm/agencies/deprm/index.cfm http://frederickhealth.org/environment/community.htm http://www.garretthealth.org http://www.co.ha.md.us/health/ER/solidwaste.htm http://www.co.mo.md.us/services/dep/AQ/home.html

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Maryland (cont.)	Maryland Department of the Environment, Air and Radiation Management Administration	http://www.mde.state.md.us/arma	Prince George's County Washington County	http://www.goprincegeorges.com/Government/AgencyIndex/Health/environmental.asp?h=20&s=&n=20 http://www.washhealth.org/html/ehair.htm
Massachusetts	Department of Environmental Protection, Bureau of Waste Prevention	http://www.state.ma.us/dep/bwp/planeva.htm#air	Boston Fitchburg	http://www.ci.boston.ma.us/environment/pollution.asp http://www.ci.fitchburg.ma.us
Michigan	Department of Environmental Quality, Air Quality Division	http://www.michigan.gov/deq	Grand Rapids Macomb County	http://www.grand-rapids.mi.us/departments/epsd/default.asp
Minnesota	Minnesota Pollution Control Agency, Policy and Planning Division, Major Facilities, Air Quality Section	http://www.pca.state.mn.us/air/index.html	Bloomington Minneapolis Richfield St. Louis Park	http://www.ci.bloomington.mn.us/cityhall/ dept/commdev/envserv/envserv.htm/ http://www.ci.minneapolis.mn.us/citywork/city-coordinator/environment/air.html http://www.ci.richfield.mn.us/officials/ commissions/advisoryboardofhealth.html http://www.stlouispark.org/index.html
Mississippi	Mississippi Department of Environmental Quality, Office of Pollution Control, Air Division	http://www.deq.state.ms.us/newweb/opchome.nsf/pages/air	No local agencies	No local agencies
Missouri	Missouri Department of Natural Resources, Division of Environmental Quality, Air Pollution Control Program	http://www.dnr.state.mo.us/deq/apcp/homeapcp.htm	Independence Kansas City Springfield St. Louis St. Louis County	http://www.indepmo.org/ http://www.kcmo.org/health.nsf/web/environ?opendocument http://springfield.missouri.org/gov/health/air_qual.htm http://stlouis.missouri.org/citygov/airpollution/ http://www.stlouisco.com/doh/environ/airpolut.html#airpollut

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Montana	Montana Department of Environmental Quality, Air and Waste Management Bureau	http://www.deq.state.mt.us/pcd/awm/index.asp	Cascade County Missoula Yellowstone County	http://www.co.missoula.mt.us/ http://ci.billings.mt.us/government/boards/pollution.htm
Nebraska	Nebraska Department of Environmental Quality, Air Quality Division	http://www.deq.state.ne.us/AirDivis.nsf/Pages/Air/	Lincoln Omaha	http://www.ci.lincoln.ne.us/city/health/environ/pollu/index.htm http://www.ci.omaha.ne.us/
Nevada	Nevada Division of Environmental Protection, Bureau of Air Quality	http://www.ndep.state.nv.us/bapc/index.htm	Clark County Washoe County	http://www.co.clark.nv.us/air_quality http://www.co.washoe.nv.us/Health
New Hampshire	New Hampshire Department of Environmental Services, Air Resources Division	http://www.des.state.nh.us/ard_intro.htm	No local agencies	No local agencies
New Jersey	New Jersey Department of Environmental Protection, Division of Air Quality, Air Quality Management	http://www.state.nj.us/dep/aqm/	Essex Elizabeth Hudson Middlesex County	http://www.essexregional.org http://www.elizabethnj.org/cityroster/ deporg/departmenthealth.htm
New Mexico	New Mexico Environment Department, Air Quality Bureau	http://www.nmenv.state.nm.us/aqb	Albuquerque	http://www.cabq.gov/airquality/index.html
New York	New York Department of Environmental Conservation, Division of Air Resources	http://www.dec.state.ny.us/website/dar/index.html	Albany County Erie County Interstate Sanitation Commission Nassau County New York	http://www.albanycounty.com/departments/health/programs/home.htm#Environmental http://www.erie.gov/environment/compliance/compprog.phtml http://www.ci.nyc.ny.us/html/dep/home.html

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
New York (cont.)	New York Department of Environmental Conservation, Division of Air Resources	http://www.dec.state.ny.us/website/dar/index.html	Niagara County Onondaga County Rockland County Suffolk County Westchester County	http://www.healthyniagara.com/environmental/index.htm http://www.ongov.net/other http://www.co.rockland.ny.us/health/ envmiss.htm#BureauofAirPollutionControl http://www.co.suffolk.ny.us/health/eq http://www.co.westchester.ny.us/health/environ%20health.html
North Carolina	North Carolina Department of Environment and Natural Resources, Division of Air Quality	http://daq.state.nc.us	Cleveland County Cumberland County Forsyth County Guilford County Mecklenburg County Western Counties	http://publichealth.sr_ahec.org/cumberland http://www.co.forsyth.nc.us/envaffairs/ http://www.co.guilford.nc.us/governent/ publichealth/envhealth/hhhome.html http://www.co.mecklenburg.nc.us/coenv/air/aqhmpg.htm http://www.wncair.org/
North Dakota	North Dakota Department of Health, Division of Air Quality	http://www.health.state.nd.us/ndhd/environ/ee	No local agencies	No local agencies
Ohio	Ohio Environmental Protection Agency, Division of Air Pollution Control	http://www.epa.state.oh.us	Akron Canton Cincinnati Cleveland Dayton (RAPCA) Hamilton County Lake County Mahoning-Trumbull Portsmouth Toledo	http://156.63.18.80/ http://www.cantonhealth.org/serv03.htm http://www.rcc.org/oem/aq.html rogers@city.cleveland.oh.us http://rapca.org http://www.hcdoes.org/airqmd.htm http://www.lcghd.org/eh/apc.htm http://www.ychd.com/airpollution.html
Oklahoma	Oklahoma Department of Environmental Quality, Air Quality Division	http://www.deq.state.ok.us/air1/air.html	No local agencies	No local agencies

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Oregon	Oregon Department of Environmental Quality, Air Quality Division	http://www.deq.state.or.us/aq/index.htm	Lane County	http://www.lrapa.org/
Pennsylvania	Pennsylvania Department of Environmental Protection, Bureau of Air Quality	http://www.dep.state.pa.us/dep/deputate/airwaste/aq/default.htm	Allegheny County Philadelphia	http://www.achd.net http://www.phila.gov/health/units/ams/index.html
Rhode Island	Rhode Island Department of Environmental Management, Office of Air Resources	http://www.state.ri.us/dem/programs/benviron/air/index.htm	No local agencies	No local agencies
South Carolina	South Carolina Department of Health and Environmental Control, Bureau of Air Quality	http://www.scdhec.gov/baq	No local agencies	No local agencies
South Dakota	South Dakota Department of Environment and Natural Resources, Air Quality Program	http://www.state.sd.us/denr/DES/AirQuality/airprogr.htm	No local agencies	No local agencies
Tennessee	Tennessee Department of Environment and Conservation, Division of Air Pollution Control	http://www.state.tn.us/environment/apc/index.html	Chattanooga Knox County Memphis Nashville	http://www.apcb.org/ http://aqm.co.knox.tn.us http://www.co.shelby.tn.us/county_gov/divisions/health_serv/environ_health/index.htm/ http://healthweb.nashville.org/env/env_air_pollution.html
Texas	Texas Commission on Environmental Quality, Policy and Regulations Division	http://www.tnrcc.state.tx.us	Austin Dallas El Paso	http://www.ci.austin.tx.us/airquality http://www.dallasair.org http://www.ci.el-paso.tx.us/city_resources/health/index.htm

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
Texas (cont.)	Texas Commission on Environmental Quality, Policy and Regulations Division	http://www.tnrcc.state.tx.us	Fort Worth Galveston County Harris County Houston Lubbock San Antonio	http://www.fortworthgov.org/dem/airpg.htm http://www.gchd.org/pages/pollution_ctl/index.htm http://www.hd.co.harris.tx.us/pcd/pcd.htm http://www.ci.houston.tx.us/departme/health/airqualitypage.html http://healthdept.ci.lubbock.tx.us http://www.ci.sat.tx.us/pubwrks/ envsvcs/air_quality_home_page.htm
Utah	Utah Department of Environmental Quality, Division of Air Quality	http://www.eq.state.ut.us/eqair/aq_home.htm	Salt Lake City	http://www.slvhealth.org/html/airpol.html
Vermont	Vermont Department of Environmental Quality, Air Pollution Control Division	http://www.anr.state.vt.us/dec/air/	No local agencies	No local agencies
Virginia	Virginia Department of Environmental Quality, Air Quality Division	http://www.deq.state.va.us/air/	Alexandria Arlington County Fairfax County Roanoke	http://ci.alexandria.va.us/city/ health/environmental_health.html http://www.co.arlington.va.us/des http://www.co.fairfax.va.us/gov/dpwes/environmental/air.htm http://www.ci.roanoke.va.us/engineer/index.html
Washington	Washington Department of Ecology, Air Quality Program	http://www.ecy.wa.gov/programs/air/airhome.html	Benton County Northwest Counties Olympic Region Puget Sound (Seattle) Southwest Counties Spokane County Yakima County	http://www.bcaa.net http://www.nwair.org http://www.orcaa.org http://www.pscleanair.org http://www.swcleanair.org http://www.scapca.org/ http://co.yakima.wa.us/cleanair/default.htm

Table A.2. U.S. State and Local Agencies from STAPPA/ALAPCO (11 pages)				
State	**State Agency**	**State Agency URL**	**Local Agency**	**Local Agency URL**
West Virginia	West Virginia Department of Environmental Protection, Division of Air Quality	http://www.dep.state.wv.us/daq/index.html	No local agencies	No local agencies
Wisconsin	Wisconsin Department of Natural Resources, Bureau of Air Management	http://www.dnr.state.wi.us/org/aw/air/index.htm	Eau Claire Madison Milwaukee County	http://www.ci.eau-laire.wi.us/Departments/home.html http://www.ci.madison.wi.us/health/envhlth.htm No URL listed
Wyoming	Wyoming Department of Environmental Quality, Air Quality Division	http://deq.state.wy.us/aqd.htm	No local agencies	No local agencies

Table A.3. U.S. RPO Emission Inventories (2 pages)

Name	URL	Sponsor	Pollutants	Geographic Coverage	Spatial Resolution	Temporal Resolution
MANE-VU Point and Area Sources	http://www.marama.org/visibility	MANE-VU	Criteria pollutants	MANE-VU RPO	County level	Annual averages, monthly, weekly, and daily profiles
MANE-VU RWC	http://marama.org/visibility/	MANE-VU MARAMA	Criteria and HAP from Residential Wood Combustion (indoor and outdoor equipment)	MANE-VU RPO	County level (based on census tract level estimates)	Annual averages, monthly, weekly, and daily profiles
MANE-VU Mobile Sources	http://marama.org/visibility/	MANE-VU MARAMA	Criteria Pollutants from Onroad and Nonroad Sources	MANE-VU RPO	County-level	Annual averages, monthly, weekly, and daily profiles
MANE-VU Open Burning	http://marama.org/visibility/	MANE-VU MARAMA	Criteria and HAP from Open Burning (Residential waste burning, yard waste burning, land clearing debris burning)	MANE-VU RPO	County level (based on census tract level estimates)	Annual averages, monthly, weekly, and daily profiles
MANE-VU Misc. Ammonia	http://marama.org/visibility/	MANE-VU MARAMA	Ammonia from cement plants, industrial refrigeration, POTWs, composting.	MANE-VU RPO	County level (POTWs, cement plants, based on point level data)	Annual averages
VISTAS Mobile Sources	http://www.vistas-sesarm.org/	VISTAS	Criteria Pollutants for onroad and nonroad sources	VISTAS RPO	County-level	Annual averages, monthly, weekly, and daily profiles
VISTAS Point and Area	http://www.vistas-sesarm.org/	VISTAS	Criteria Pollutants for point and area sources	VISTAS RPO	County-level	Annual averages, monthly, weekly, and daily profiles

Table A.3. U.S. RPO Emission Inventories (2 pages)						
Name	**URL**	**Sponsor**	**Pollutants**	**Geographic Coverage**	**Spatial Resolution**	**Temporal Resolution**
Midwest RPO	http://www.ladco.org/	MRPO	Criteria Pollutants ("Base E" inventory includes all sectors)	U.S. National and southern Canada	36-km grid (national) 12-km (regional)	Hourly
Midwest RPO	http://www.ladco.org/mrpo.html	MRPO	Criteria Pollutants (ongoing projects for nonroad sources, ammonia from livestock, wildfires)	Midwest RPO	County-level	Annual averages, monthly, weekly, and daily profiles
CENRAP	http://www.cenrap.org/	CENRAP	Criteria Pollutants (ongoing projects for Ag & prescribed burning, mobile sources, agricultural dust, and ammonia)	CENRAP RPO	County-level	Annual averages, monthly, weekly, and daily profiles
WRAP	http://www.wrapair.org/	WRAP	Criteria Pollutants (for point sources)	WRAP and CENRAP RPOs (22 States)	Point	Annual, hourly
WRAP	http://www.wrapair.org/	WRAP	Criteria Pollutants plus EC/OC (for onroad, nonroad, road dust)	WRAP RPO	County-level	Annual average week-day, seasonal average weekday
WRAP	http://www.wrapair.org/	WRAP	Criteria Pollutants (for area sources)	WRAP and CENRAP (22 States)	County-level	Annual average
WRAP	http://www.wrapair.org/	WRAP	Criteria Pollutants (for area sources)		Point and county-level	

Table A.4. Contacts for Obtaining Local and Regional Mexican Emission Inventories (6 pages)				
State	**Institution**	**Address**	**E-mail**	**URL**
Aguascalientes	Secretaría de Desarrollo Social	Colon 110 3er. Piso Zona Centro C.P 20000 Aguascalientes, Ags. Tel: 910 21 20 Dir., 910 21 21 Conm.	subecoags@infosel.com	http://www.aguascalientes.gob.mx/
Baja California	Dirección General de Ecología	Av. Rápida Oriente No. 10252-106 Col. Zona Del Rio, Tijuana (Centro De Gobierno) C.P. 22320 Tijuana, Baja California Tel. 01664 624 20 95 Fax 01664 624 20 96	evillegas@baja.gob.mx	http://www.bajacalifornia.gob.mx/ecologia/entrada.htm
Baja California Sur	Secretaría de Planeación Urbana, Infraestructura y Ecología	Isabel La Católica Entre Nicolás Bravo E Ignacio Allende Edificio Central 2° Nivel Palacio De Gobierno Col. Los Olivos C.P. 23040 La Paz, Baja California Sur Fax Y Tel. 01 612 12 294 61	sepui@latinmail.com	http://www.gbcs.gob.mx/
Campeche	Secretaría de Ecología	Plaza Comercial Ah-Kim-Pech Local 517 Col. Centro C.P. 24000 Dir: 01-981-611-42 Tel. Y Fax: 619-08/674-41	ecologia@campeche.gob.mx	http://www.campeche.gob.mx/Gobierno/Secretarias/ecologia.htm
Chiapas	Instituto de Historia Natural y Ecología	Calzada A Cerro Hueco S/N Col. El Zapotal Ap No. 6, Tuxtla Gutiérrez, Chis. Tels: 01 961 44701, 6144765, 6144778	ihne@chiapas.gob.mx	http://www.chiapas.gob.mx/funcionarios/estatal.asp?Id=e06162203200207

Table A.4. Contacts for Obtaining Local and Regional Mexican Emission Inventories (6 pages)				
State	**Institution**	**Address**	**E-mail**	**URL**
Chihuahua	Secretaría de Desarrollo Urbano y Ecología	Calle 15 Y Aldama No. 1317 Col. Centro C.P. 31000 Chihuahua, Chih Tels: 410 64 40	not available	http://www.chihuahua.gob.mx/default.asp
Coahuila	Instituto Coahuilense de Ecología	Victoria N° 608 1° Piso Zona Centro C.P. 25000 Saltillo, Coah. Tel. 01 844 4 12 56 22	sergio.aviles@ecoah.org	http://servidor.seplade-coahuila.gob.mx/portal/page?_pageid=34,68247,34_73288&_dad=portal&_schema=PORTAL
Colima	Direccion de Ecología	Blvd Camino Real N° 435 C.P.28010 Colima, Colima Tel. 01 312 - 310 79 00 / 312 02 94	not available	not available
Distrito Federal	Secretaría de Medio Ambiente	Plaza De La Constitución N0. 1 Col. Centro. Piso 3 Delegación Cuauhtémoc C.P. 06068. México, D.F. Tel: 55 21 35 28/ 55 10 36 63/ 55 42 09 83 Fax: 55 21 26 88	sheinbaum@dgpa.df.gob.mx	www.sma.df.gob.mx
Durango	Secretaría de Recursos Naturales	Blvd. Armando Del Castillo Franco No. 99 P.B. Plaza Guadiana C.P.34050 Durango, Durango Dir: 813-39 02 Tel: 812 97 77 / 825 69 71 / 825 69 72	secretariaderecursosnaturales@durango.gob.mx	http://www.durango.gob.mx/depe/ver.asp?id=10

Table A.4. Contacts for Obtaining Local and Regional Mexican Emission Inventories (6 pages)				
State	**Institution**	**Address**	**E-mail**	**URL**
Estado de México	Secretaría de Ecología	Parque Orizaba No. 7 P.H. Col. El Parque, Edif. Auris Naucalpan De Juarez C.P. 53390 Estado De Mexico Dir. 5576 73 10, 5576 89 72 Tels. 5576 28 55 Fax: 5576 00 26	gemse@edomex.gob.mx	http://www.edomexico.gob.mx/portalgem/se/
Guanajuato	Instituto de Ecología	Calle Aldana N° 12 Esq. Con Calle Republica Mexicana Zona Xiv Del Barrio Pueblito De Rocha Guanajuato, Guanajuanto C..P. 36040 Tel. 01473 7327887	institut@guanajuato.gob.mx	http://www.guanajuato.gob.mx/index.html
Guerrero	Procuraduría de Protección Ecológica	Av. Miguel Alemán N° 68 Col. Centro C.P. 39000 Chilpancingo Guerrero Tel. 01 747 471 4015 Fax 01747 49 378 01	not available	not available
Hidalgo	Dirección General del Consejo Estatal de Ecología	José María Iglesias No. 100 Col. Centro C.P. 42000 Pachuca, Hgo. Tel: 71 410-56	aduran@prodigy.net.mx	http://www.hidalgo.gob.mx/gobierno/entidades/entidad.asp?entidadID=8
Jalisco	Secretaría del Medio Ambiente para el Desarrollo Sustentable	Av. Cubilete 2955 Col. Jardines Del Sol Zapopan , Jalisco C.P. 55050 Tel 01 33 36 47 05 65 Fax: Ext.55791	not available	http://semades.jalisco.gob.mx/site/index.htm

Table A.4. Contacts for Obtaining Local and Regional Mexican Emission Inventories (6 pages)				
State	**Institution**	**Address**	**E-mail**	**URL**
Michoacán	Secretaría de Urbanismo y Medio Ambiente	Escarcha 272, Frac. Prados De Campestre C.P. 58290 Morelia, Mich. Dir. 01 443 314 01 75 Tels. 01 443 314 09 55, 01 443 314 07 01 Fax 314 09 55	suma@michoacan.gob.mx	http://www.michoacan.gob.mx/gobierno/dependencia/suma.htm
Morelos	Comisión Estatal del Agua y Medio Ambiente	Palacio de Gobierno 2º. Piso Col. Centro C.P. 62000 Cuernavaca, Mor Tels. Y Fax: 01 773- 329-22- 66 / 329 22 68	ceama@morelos.gob.mx	http://www.edomorelos.gob.mx/e-gobierno/DirCEAMA/
Nayarit	Instituto Nayarita para el Desarrollo Sustentable	Av. México 191 Sur Col. Centro C.P. 63000 Tepic, Nayart Tel.01 311 210 35 70 Y 71	not available	not available
Nuevo León	Agencia de Protección al Medio Ambiente y Recursos Naturales	Av. Alfonso Reyes No. 1000 Norte Interior Del Parque De Los Niños Héroes Colonia Regina C. P. 64290 Monterrey, Nuevo León. Tel: 01 81 - 20 20 74 03 / 20 20 74 01	emilio.rangel@mail.nl.gob.mx	http://gobierno.nl.gob.mx/EstructuraOrganica/SectorParaestatal/Organigramas/AgenciaProteccion
Oaxaca	Instituto Estatal de Ecología	Calle Libre 511 Letra “A” C.P. 68000 Oaxaca, Oax Dir. 01-951 5185 600, 01-951 5185 601 Fax: 01-951 5185 600, 01-951 5185 601	ecologiaoax@prodigy.net.mx	http://www.oaxaca.gob.mx/ecologia/

Table A.4. Contacts for Obtaining Local and Regional Mexican Emission Inventories (6 pages)				
State	**Institution**	**Address**	**E-mail**	**URL**
Puebla	Secretaría de Desarrollo Urbano, Ecología y Obras Públicas	K.M. 5.5 Recta A Cholula-Puebla S/N San Andrés Cholula C.P. 72810 Puebla, Pue. Tels: 01-22 2247 24 34 Fax: 01-22 2247 07 87	subecol@yahoo.com	http://www.sedurbecop.pue.gob.mx/
Querétaro	Secretaría de Desarrollo Sustentable	Blvd Bernardo Quintana N° 204 Col. Carretas C.P. 76050 Tel. 01442 211 68 00	sedesu@queretaro.gob.mx	http://www.queretaro.gob.mx/sedesu/
Quintana Roo	Secretaría de Desarrollo Urbano y Medio Ambiente; Subsecretaría de Medio Ambiente	Km 2.5 Carretera Chetumal-Bacalar, Chetumal, Quintana Roo, C.P. 77000 Tel: 01983 8322646, 01983 8322747 Ext. 227 Fax: 01983 8322747 Ext. 227	simapqro@prodigy.net.mx	http://www.quintanaroo.gob.mx/nuestrogobierno/flash/ng1.htm
San Luis Potosí	Secretaría de Ecología y Gestión Ambiental	Cuauhtémoc No. 1205 Esq. Vista Hermosa Fraccionamiento Capitán Caldera 78250, San Luis Potosí, S.L.P. Tel. (48) 11 30 80	segam_rtrevino@slp.gob.mx	http://www.segam.gob.mx/
Sinaloa	Subsecretaría de Desarrollo Urbano y Ecología	Av. Insurgentes S/N Col. Centro Sinaloa C.P.80200 Culiacán, Sinaloa Fax. 01 6677 17 51 88 / 01 6677 58 70 35	gabriel_yaez@yahoo.com.mx	http://laip.sinaloa.gob.mx/LAIP/Secretaria/SPD/
Sonora	Secretaría de Infraestructura Urbana y Ecología	Blvd. Hidalgo y Comonfort N° 35, 3° Piso Col. Centenario C.P. 83260 Hermosillo, Sonora Tel. Y 01 6622 17 02 17.	siue@hmo.megared.net.mx	http://www.siue.gob.mx/

Table A.4. Contacts for Obtaining Local and Regional Mexican Emission Inventories (6 pages)				
State	**Institution**	**Address**	**E-mail**	**URL**
Tabasco	Secretaría de Desarrollo Social y Protección del Medio Ambiente	Av. Paseo de la Sierra Nº 425 Col. Reforma C.P. 86080 Villahermosa, Tab. Tels. Dir. 01 993 315 0821 Fax 01 993 15 47 10	secretario@sedespa.gov.mx	http://www.sedespa.gob.mx/
Tamaulipas	Secretaría de Desarrollo Urbano y Ecología	Carretera a Soto La Marina Km. 5.6 Ciudad Victoria C. P. 87130 Tamaulipas Tel: 01 834 318 34 00	sdu@tamaulipas.gob.mx	http://www.tamaulipas.gob.mx/sedue/default.asp
Tlaxcala	Coordinación General de Ecología	Camino Real a Ixtulco Jardín Botánico Tizatlan, Tlaxcala C.P. 90110 Tel. 01246 46 50 900 Ext. 1704	ecologia_titular@tlaxcala.com.mx ecologia@tlaxcala.com.mx	not available
Veracruz	Coordinación Estatal de Medio Ambiente	Fco. I. Madero, Esquina Juárez Planta Alta S/N Zona Centro C. P. 91000 Xalapa, Veracruz Tel: 01 228 817 22 95, 817 75 88.	medioambiente@sdmaver.gob.mx	not available
Yucatán	Secretaría de Ecología	Calle 64 #437 Por 53 Y 47 Letra A, Col. Centro, Mérida, Yucatán Tel: 01999 9303385, 01999 9303380 Ext. 44013 / 44005 Fax: 019999303385, 01999 9303380Ext. 44013 / 44005	luis.morales@yucatan.gob.mx	http://www.yucatan.gob.mx/index.htm
Zacatecas	Instituto de Medio Ambiente	Blvd. Lopez Portillo N° 30 2°. Piso Col. La Florida Guadalupe, Zacatecas Tel. 01 492 89 91 304 Fax 01 492 899 13 05	vikybg@mail.com.mx	http://www.zacatecas.gob.mx/

APPENDIX A

APPENDIX B

SOURCE TEST METHODS

This appendix provides information on source test methods for the Canada, the United States, and Mexico. Source test methods used nationally by Canada are presented in Table B.1, and methods used by Canadian provinces are presented in Tables B.2 and B.3. Source test methods used in the United States are presented in Table B.4. Source test methods used by Mexico are presented in Table B.5.

Source test procedures have been developed to quantify emissions from point and nonpoint sources. In addition to producing emission data for individual sources to determine compliance with emission regulations, source test data are used to develop emission factors which in turn, as described in Chapter 2, are used to prepare emission inventories.

In the United States, source test methods are available nationally through the U.S. EPA. In addition, various states (e.g., California and Pennsylvania) have developed their own source test methods, some of which are more stringent than the EPA test methods. Source test method numbers or Performance Specifications between 1 and 100 are for New Source Performance Standards (NSPS). These methods, which apply to criteria pollutants, are found in 40 CFR Part 60, Appendix A. Similarly, method numbers in the 100 series are for National Emission Standards for Hazardous Air Pollutants (NESHAPs). These methods are found in 40 CFR Part 61, Appendix B. Method numbers in the 200 series are used to develop data for SIPs. These methods are found in 40 CFR Part 51, Appendix M. Method numbers in the 300 series are for the Maximum Achievable Control Technology (MACT) based NESHAPs. These methods are found in 40 CFR Part 63, Appendix A.

Both Canada and Mexico have developed their own source test methodologies. In both Canada and Mexico, source test methods developed by the U.S. EPA were used as building blocks for the country-specific methods. Consequently, some methods used by Canada and Mexico are identical to those employed by the United States. As in the United States, source tests are used by both Canada and Mexico to quantify emissions from sources for determining compliance with applicable rules and regulations. Canada has national source test methods and two provinces have also developed their own source test methods.

Table B.1. Environment Canada Reference Methods for Stationary Sources.	
Method	**Parameter**
EPS 1-AP-74-3	Sulfur Dioxide from Stationary Sources (absorption in H_2O_2 followed by Ba thorin titration)
EPS 1-AP-75-1 EPS 1-AP-75-1A	Asbestos from Asbestos Mining and Milling Operations S-3, Sampling of Drill Baghouse Exhaust Emissions (Isokinetic sampling followed by optical phase-contrast microscopy)
EPS 1-AP-75-2	Opacity of Emissions from Stationary Sources (Trained observer and transmissometer versions)
EPS 1-AP-77-1	Vinyl Chloride from Vinyl Chloride and Polyvinyl Chloride Manufacturing (Tedlar bag sampling followed by GC/FID analysis)
EPS 1-AP-77-3	Nitrogen Oxides from Stationary Sources (grab sample followed by colorimetric wet chemical analysis)
EPS 1-AP-79-1	Arsenic from Gold Roasting Operations
EPS 1/RM/1	Gaseous Hydrogen Chloride from Stationary Sources (impinger absorption followed by IC analysis)
EPS 1/RM/2	Selected Semi-volatile Organic Compounds from Stationary Sources (isokinetic sampling with XAD /Ethylene Glycol Impingers)
EPS 1/RM3	Analysis of PCDDs, PCDFs and PCBs (high resolution GC/MS analysis)
EPS 1/RM/4	Carbon monoxide Emission from Stationary Sources (Tedlar bag sampling follow by NDIR determination)
EPS 1/RM/5	Mercury Emissions from Mercury Cell Chlor-Alkali Plants (permanganate impinger sampling followed by analysis by CVAA)
EPS 1/RM/6	Total Reduced Sulfur Compounds from Pulp and Paper Operations (dried Tedlar bag sample followed by GC/FPD analysis)
EPS 1/RM/7	Lead in Particulate from Stationary Sources (isokinetic sampling followed by aqua regia digestion and AA analysis)
EPS 1/RM/8	Particulate matter from Stationary sources, Traverse Points, Molecular Weight, Moisture (isokinetic sampling followed by gravimetric determination)
EPS 1/RM/15	Gaseous Emissions from Fossil Fuel-fired Boilers (electrochemical analyzer method for NO_x, SO_2, CO and O_2)
EPS 1/RM/23	Internal Quality Assurance Requirements for the Analysis of Dioxins in Environmental Samples
EPS 1/PG/7	Protocols and Performance Specifications for Continuous Emission Monitoring of Gaseous Emissions from Thermal Power Generation
	(CEMS summary equivalent to CFR part 60 and CFR part 75)

Table B.2. Alberta's Emission Test Methods for Stationary Sources.	
Method	Parameter
1	Traverse Points
1a	Traverse Points, Small Ducts
2	Stack Gas Velocity & Flow Rate
2c	Flow, Small Duct, Standard Pitot
3	Stack Gas Molecular Weight
4	Moisture Content
5	Particulate Emissions
5a	Condensible Particulate Emissions
7	NO_x Emissions
7a	NO_x Emissions: Ion Chromatography
7c	NO_x Emissions: Colorimetric
8	Sulfuric Acid Mist &/or SO_2 Emissions
10	CO Emissions
18	Gaseous Organic Emissions
25	Nonmethane Organic Emissions
26	Hydrogen Halide & Halogen Emissions
26a	Isokinetic Hydrogen Halide & Halogen Emissions
	Total Reduced Sulfur, Pulp & Paper
	Total Reduced Sulfur, Sour Gas Plants
	Chlorine & Chlorine Dioxide Emissions
	Vinyl Chloride Monomer Emissions
	Lead Emissions
	Volatile Organic Compound Emissions
	Semi-volatile Organic Compound Emissions
CEMS Code	Continuous Emission Monitoring System Code

Table B.3. Ontario's Emission Test Methods for Stationary Sources.	
Method	**Parameter**
1	Traverse Points
2	Stack Gas Velocity and Flow Rate
3	Stack Gas Molecular Weight
4	Moisture Content
5	Particulate Emissions
	Odour Emissions (dynamic dilution sampling on Tedlar bags followed by forced choice sensory panel)
	Total Hydrocarbon Emissions (heated continuous FID)

Table B.4. U.S. EPA Test Methods.			
Pollutant	**EPA Promulgated Test Methods**	**EPA Proposed Test Methods**	**EPA Conditional Test Methods (numbers not assigned)**
Carbon Dioxide and Oxygen	3, 3A, 3B, 3C		CTM-034
Methane	3C		
Particulate Matter	5, 5A, B, D, E, F, G, H, 5I, 17, 201, 201A, 202, 315		CTM-002
$PM_{2.5}$, PM_{10}	201, 201A, 202		CTM-039
Sulfur Dioxide	6, 6A-6C, 8		
Nitrogen Oxides	7, 7A-7E, 20		CTM-022
Sulfuric Acid Mist	8		
Opacity	9, 22	203, 203A-C	CPS-001
Carbon Monoxide	10, 10A, 10B		
Hydrogen Sulfide	11, 15		
Lead	12, 29		
Fluoride	13A, 13B. 14, 14A		
Carbonyl Sulfide, Carbon Disulfide	15		
Total Reduced Sulfur	15A, 16A, 16B		
Sulfur	16		
Volatile Organic Compounds	18, 21, 25D, 204A-F, 305, 307		CTM-028
CTM 042			
Dioxin and Furan	23		
Nonmethane Organic Compound	25, 25C		CTM-035
Gaseous Organics	25A		
Metals (Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, P, Se, Ag)	29		
Hydrogen Chloride, Halides, Halogens	26, 26A, 321	322	
Mercury	29, 101, 101A, 102, 105	324	
Beryllium	29, 103, 104,		
Vinyl Chloride	106, 107, 107A		

Table B.4. U.S. EPA Test Methods (Concluded).			
Pollutant	**EPA Promulgated Test Methods**	**EPA Proposed Test Methods**	**EPA Conditional Test Methods (numbers not assigned)**
Arsenic	29, 108, 108A, 108B, 108C		
Polonium-210	111		
Radionuclides	114		
Radon-222	115		
Chromium	29, 306, 306A		
Methanol	308		
Hexane	310A, 310C		
HAPS	311		not assigned
Styrene	312A-C		
Formaldehyde	316	323	CTM-027
Isocynates		207	
Butadiene			CTM-001
Acrylonitrile			CTM-008
Halogenated Organics			CTM-011
Benzene			CTM-014
Ammonia			CTM-027
Methylene Diphenyl Isocyanate (MDI)			CTM-031
Phenol and Cresol			CTM-032
Hydrogen Cyanide			CTM-033
Toluene Diisocynate			CTM-036

Table B.5. Mexico's Reference Test Methods for Stationary Sources.		
Method No.	**Parameter**	**U.S. EPA Equivalent**
NMX-AA-009-1993-SCFI	Stack gas flow (pitot tube method)	Method 2
NMX-AA-010-SCFI-2001	Particulate Matter (Isokinetic sampling with in-stack filter)	Method 5
NMX-AA-035-1976	CO_2, CO and O_2 (Orsat analysis of combustion gases)	Method 3
NMX-AA-054-1978	Stack gas Moisture (Gravimetric impinger method)	Method 4
NMX-AA-055-1979	SO_2 (midget impinger absortion in H_2O_2 solution, followed by Ba-thorin titration)	Method 6
NMX-AA-056-1980	SO_2, SO_3 and H_2SO_4 mist (isokinetic sampling, hot filtering, isopropanol absorption of SO_3 and H_2SO_4 , thorin titration)	Method 8
NMX-AA-069-1980	H_2S (absorption in $CdSO_4$ solution, followed by iodometric titration)	Method 11
NMX-AA-070-1980	Chlorides and Cl_2 (chlorides absorbed in water impinger. Chlorine absorbed in arsenite solution. Followed by photocolorimetric determination of chlorides)	-
NMX-AA-085-1986	Calibration of dry gas meter with wet gas meters or spirometer	Method 5 QA/QC
NMX-AA-086-1986	Rotometer calibration	-
NMX-AA-090-1986	Phosphoric acid mist (Isokinetic sampling without filter, color development with Mo-Va reagent, followed by spectrophotometric determination)	-
NMX-AA-095-1986	Cyanides (Isokinetic sampling in dilute Zn acetate solution, followed by buffering and by pyridine-pyrazolone addition. Spectrophotometric determination)	-
NMX-AA-096-1986	Benzene, Toluene, Xylene and Styrene (Colorimetric determination of benzene absorbed in a concentrated formaldehyde/H_2SO_4 solution. Colorimetric determination of toluene+xylene in a concentrated KIO_4/ H_2SO_4 solution. Colorimetric determination of styrene in a concentrated H_2SO_4 solution)	-
NMX-AA-097-1986	NH_3 (Absorption in dilute H_2SO_4 solution followed by phenol-nitroferrocyanide addition and colorimetric determination)	-
NMX-AA-098-1996	Trichloroethylene (Absortion in pyridine impingers. Colour development by hot-mixing with sodium hydroxide/ethanol solution. Colorimetric determination)	-
NMX–AA-114-1991	Opacity by smoke stain in a filter	-

APPENDIX C

CONCEPTS AND METHODS FOR UNCERTAINTY AND SENSITIVITY ANALYSIS OF EMISSION INVENTORIES

This appendix supplements Chapter 8 and provides additional detail regarding concepts and methods for uncertainty and sensitivity analysis of emission inventories.

C.1 CONCEPTS FOR UNCERTAINTY AND SENSITIVITY ANALYSIS

Figure C.1 gives an example of a probability distribution that quantitatively describes uncertainty in an emission or activity factor that is input to an inventory. The probability distribution in the figure is shown in the form of a probability density function (PDF). A probability distribution quantifies the range of possible values, as well as the probability of obtaining a value within any defined range. Box C.1 provides additional information regarding graphical techniques for displaying probability distributions and defines commonly used terminology.

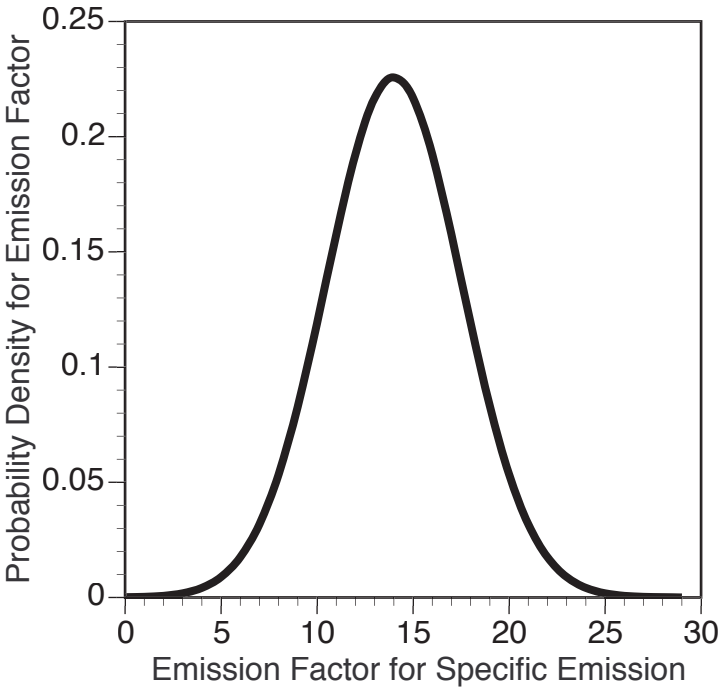


Figure C.1. Example Probablility Distribution Describing Quantitative Uncertainty in an Emission or Activity Factor.

Figure C.2 provides a schematic representation of the process of quantifying uncertainties in the inputs to an emission inventory and estimating uncertainty in the output, which represents the total inventory.

Box C.2 defines some basic concepts pertaining to sensitivity analysis. Methods of sensitivity analysis and metrics for measuring sensitivity are widely available. The most commonly used sensitivity analysis methods are often relatively simple techniques that evaluate the local linearized sensitivity of model response at a particular point in the input domain, as illustrated in Box C.2. This type of approach is typically used if the model inputs are treated as point estimates, often representing the "best guess" as to the true but unknown value of each input.

Sensitivity analysis becomes more challenging when many model inputs are varied simultaneously over each of their possible ranges. Figure C.3 provides conceptual illustrations of three scenarios that imply different challenges for sensitivity analysis. In one case, all model inputs are assigned point estimates. This type of model simulation implies either that the analyst believes that no uncertainty exists in the inputs, that uncertainties are negligible, or that uncertainties are being ignored. A local sensitivity-analysis method could be

Box C.1. Probability Distribution Models

A probability distribution can be depicted several ways. Two of the most common depictions are shown here: (1) a probability density function (PDF); and (2) a cumulative distribution function (CDF). The PDF is useful for indicating the central tendency, range, and shape of the distribution. The CDF is more useful for inferring specific numerical values associated with specific levels of cumulative probability. For example, the CDF can be used to infer the median (50th percentile) and the 95 percent probability range (which is enclosed by the 2.5th and 97.5th percentiles). The CDF also provides some indication of the shape of the distribution, such as if the upper tail of the distribution appears to be longer than the lower tail of the distribution.

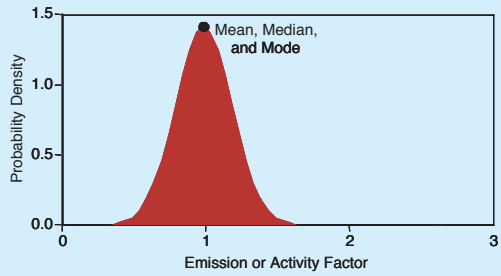


Figure a. PDF for Symmetric Distribution

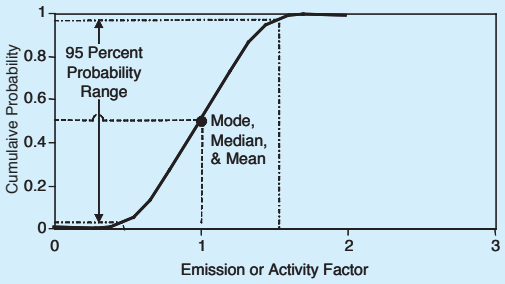


Figure b. CDF for Symmetric Distribution

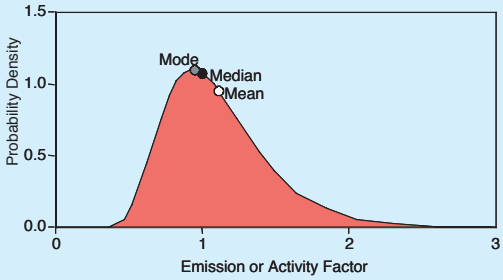


Figure c. PDF for Asymmetric (Skewed) Distribution

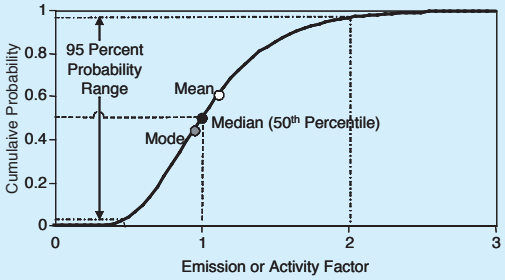


Figure d. PDF for Asymmetric (Skewed) Distribution

Cumulative distribution function: Relationship between cumulative probability and values of a random variable

Cumulative probability: The probability associated with a random variable being less than or equal to a specific numerical value, referred to as a fractile.

Mean: the arithmetic average of all possible outcomes of the random variable. Typically cannot be inferred by visual inspection of a PDF or CDF unless the distribution is symmetric. Also referred to as the "expected value."

Median: the numerical value of the random variable associated with a cumulative probability of 0.50; also referred to commonly as the 50th percentile. Can be read directly from the CDF.

Mode: a local maximum of the Probability Density Function. Can be read directly from the PDF.

Probability Density Function (PDF): Relationship between probability density and values of a random variable. The area under the function is equal to one. The shape of the PDF provides insight regarding whether the distribution is symmetric or skewed, and can be used to identify the mode(s) (if they exist).

Probability Distribution: a general term that refers to a probability distribution model for a random variable. A probability distribution can be visualized in various formats, such as the PDF or CDF. Probability distribution models may be parametric (e.g., normal, lognormal), empirical, or combinations of both.

Skewness: refers to departures from symmetry. A positively skewed distribution, such as a lognormal distribution, has an "upper tail" that is longer than its "lower tail."

Symmetric Distribution: A distribution that is symmetric with respect to its mean value. For this type of distribution, the mean, mode, and median coincide.

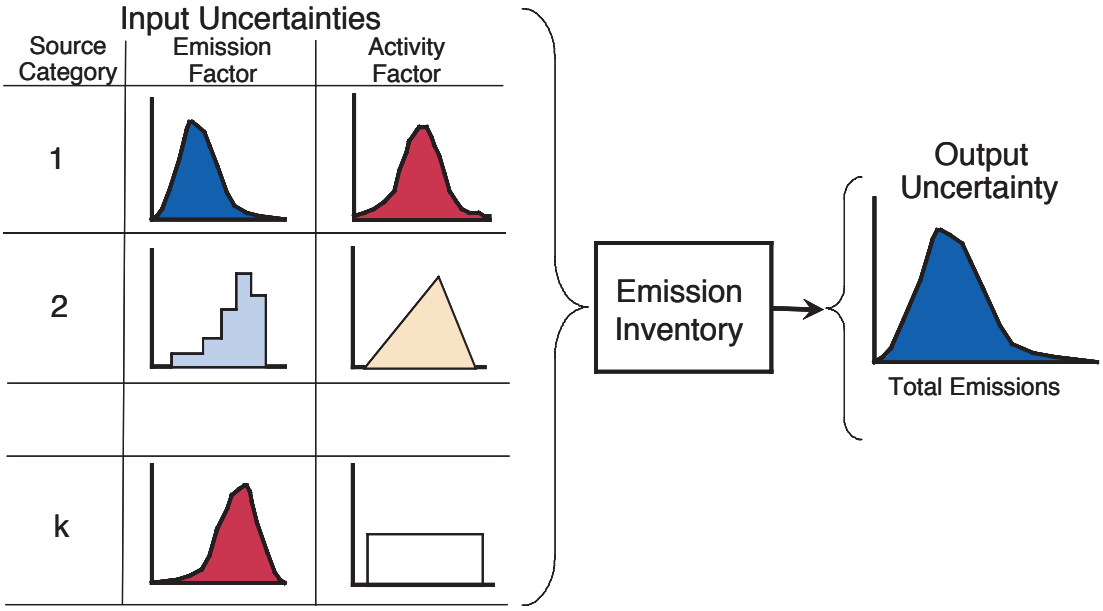


Figure C.2. Conceptual Framework for Propagation of Uncertainty in Emission Inventory Inputs of Emission and Activity Factors for Each of k Emission Source Categories to Quantify the Uncertainty in the Estimate of Total Emissions. A variety of probability distribution models can be specified to represent uncertainty in inputs.

applied to evaluate how the output would respond to a perturbation in each input.

In a second case, one of the inputs is assigned a probability distribution, and all others are assigned point estimates. The probability distribution for the model output is solely attributable to the probability distribution assigned to only one of the model inputs. Thus, it is clear how much uncertainty is induced in the model output because of uncertainty in only one input. One could alternatively assign each of the inputs a probability distribution, while keeping all others at their point values, in order to gain insight into the impact of uncertainty in each individual input on the output. However, simultaneous interactions among multiple uncertainties are not considered in such an approach.

In a third case, multiple inputs are assigned distributions. Although the distribution for the model output depends on the simultaneous propagation of uncertainties among the multiple inputs, the results of an uncertainty analysis do not, by themselves, provide insight as to which of the inputs caused the largest contribution to variation in the output. Thus, sensitivity analysis methods described in Section 8.3 and in Appendix C.3 are typically applied to identify key sources of uncertainty.

C.2 APPROACHES FOR CHARACTERIZING UNCERTAINTY IN EMISSION INVENTORIES

Techniques for characterizing uncertainty in emission inventories include qualitative, semi-quantitative, and quantitative methods.

C.2.1 Qualitative Methods

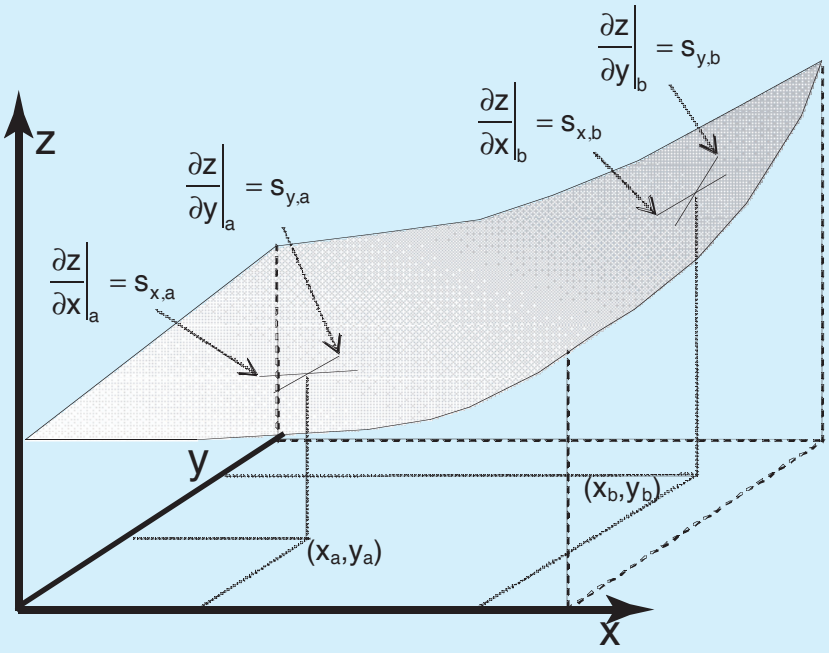
Qualitative methods used for uncertainty assessment typically involve listing and discussing sources of uncertainty. Each emission factor or activity factor is described in terms of the direction of any bias (i.e., whether they are judged to be over- or underestimates). An example of a qualitative method is the Data Quality Rating method in which

Box C.2. Local Sensitivity Analysis

The term "sensitivity analysis" evokes the concept of evaluating how a model output, Z, responds to a perturbation in any one its inputs, in this case either X or Y. One way to evaluate sensitivity is to estimate the partial derivative of the model output with respect to an individual input for a specific point in the input domain, as depicted in the figure below. For example, the sensitivity of the output at point a = (xa,ya) is given by the partial derivatives (slopes) of the model response at this specific point. This is a form of local sensitivity analysis. However, if the model is nonlinear, then the value of the slope will be conditional on what point is selected. For example, the slopes at point b = (xb,yb) are quite different than those at point a. The use of slopes at a local point implicitly assumes that the model response is linear or approximately linear at the local point. However, over a wide range of variation for each input, the model response for either X or Y is nonlinear in this example.

Local sensitivity analysis has many variations, such as estimation of slopes, relative percentage changes, or elasticities at local points. Variations of this type of analysis may involve evaluating how the model responds to a large change in its inputs. For example, nominal range sensitivity analysis (NRSA) involves estimating how Z changes as X varies over a large range, such as from xa to xb.

Sensitivity analysis can be generalized to include methods that deal with simultaneous variation in multiple inputs over wide ranges or based upon probability distributions. These are examples of global sensitivity analysis. Such methods are discussed in more detail in Section C.3.



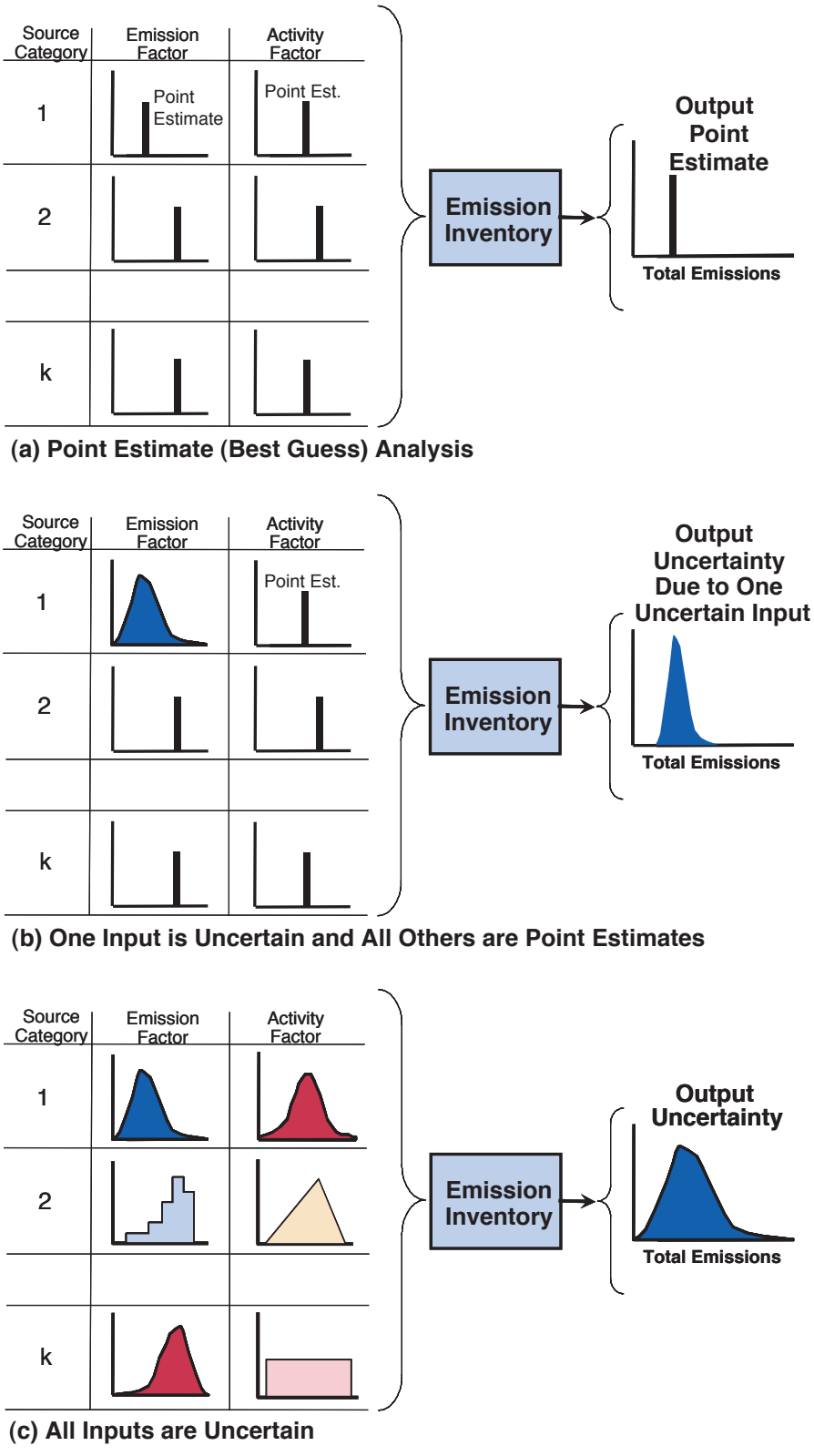


Figure C.3. Conceptual Diagram Illustrating the Propagation of Point Estimates and Probability Distributions for Inputs Through the Model and Their Effect on the Model Output. Each model input is shown as a probability density function.

qualitative A through E ratings are used to address the errors in the estimation of emission factors (U.S. EPA, 2005). However, the use of these ratings is somewhat subjective and depends to an extent on the individual reviewer (Roads, 1993). An example using qualitative methods for development of an inventory was done by Steiner et al. (1994) for emissions from offshore oil production facilities. Although qualitative methods do not require substantial resources, they have the significant drawback of not being able to produce quantitative insight regarding uncertainty. As a result, it is not possible to estimate the overall uncertainty in an inventory or to attribute uncertainty in an inventory to specific key source categories.

C.2.2 Semi-quantitative Methods

Semi-quantitative methods involve the explicit use of judgment and typically can be used to provide numerical scores that help to characterize the level of confidence in different parts of the inventory. An example of a semi-quantitative method is the Data Attribute Rating System (DARS). DARS is a method for combining data quality scores for both emission factor and activity data to develop an overall quality score for an emission inventory. DARS provides a numerical confidence rating for emission inventories. The numerical result is called the DARS score. DARS assigns the numerical scores to the various components of the emission inventory based upon their qualities, and allows numerical manipulation of the uncertainty estimates of the system. One advantage of DARS is to provide a quick evaluation of the effect of national-level or surrogate factors and activity data relative to local source specific factors (EIIP, 1996). However, although DARS can provide useful insight regarding the quality of an inventory, it does not provide quantification of the range of uncertainty in the inventory nor regarding the key sources of uncertainty in the inventory. DARS is not currently supported nor is it undergoing any further development, but it is a useful case study example of a semi-quantitative method.

C.2.3 Quantitative Methods

Both qualitative and semi-quantitative methods suffer from many shortcomings including: restrictive assumptions about the shape of probability distribution models; failure to deal with dependences between uncertainty estimates; failure to distinguish between variability and uncertainty estimates; inappropriate averaging times; improperly analyzed small sample data; and failure to use proper protocols in eliciting expert judgments (Frey et al., 1999)

Due to the limitations of qualitative and semi-quantitative methods, quantitative probabilistic methods for dealing variability and uncertainty in emission inventory are becoming more widely recognized and recommended. Quantitative methods for dealing with uncertainty in emission estimates involve the characterization of uncertainty in emission factors or activity factors and propagation of uncertainty in emission factors and activity factors to a total emission inventory.

The characterization of uncertainty in emission or activity factors may be based on statistical analysis of empirical data or expert judgment. Statistical analysis of empirical data is appropriate if there is a random sample of relevant data. Of course, the need for such data is no different with respect to developing a point estimate based upon an average value versus a distribution of uncertainty, such as for an emission factor. Data that are used to estimate emission factors typically are obtained from measurements on multiple facilities (or units) within a source category. Thus, the range of values in such data represents the inter-unit variability in emissions. If an estimate of the emissions for one unit for which no data are available is needed, and if it was reasonable to assume that the one unit was a random sample from the same population as those for which measurements are available, then the distribution of inter-unit variability could be used to estimate a range that would enclose the true-but-unknown emission rate with a specified degree of confidence.

However, if an estimate of emissions for many units within a source category is needed, then the appropriate measure of uncertainty is not the inter-unit variability, but rather the uncertainty in the mean emission rate. Box C.3 provides a case study example of the distinction between uncertainty in the mean versus inter-unit variability. Box C.4 discusses two methods for estimating uncertainty in a mean: (1) analytical estimates based upon the standard error of the mean; and (2) numerical estimates based upon bootstrap simulation. Bootstrap simulation, introduced by Efron in 1979 (Efron and Tibshirani, 1993), is a numerical simulation technique originally developed for the purpose of estimating confidence intervals. The advantage of bootstrap simulation is that it can provide solutions in situations where exact analytical solutions may be unavailable and in which approximate analytical solutions are incorrect. Bootstrap simulation has been widely used in the prediction of confidence intervals for a variety of statistics, such as the mean of emission factors (e.g., Frey and Zheng, 2002a&b; Frey and Zhao, 2003; Zhao and Frey, 2004).

However, in some cases, empirical data are not available for model inputs in emission estimation, especially for activity factors, or the available data are not representative of the scenario of interest. For example, emission factor data might be available for operation at full load under well-controlled steady-state conditions, but not for transient loads or process upsets. The mean emission rate in the latter cases may differ substantially from the mean emission rate in the former cases. In these situations, either data are not available or are likely to result in bias if they are used directly as the basis for statistical analysis. An alternative methodology for quantifying uncertainty in these situations is to elicit and encode expert judgment in the form of subjective probability distributions.

The EIIP has recommended that expert elicitation is an appropriate methodology for addressing data gaps and as a component of uncertainty analysis for emission inventories (EIIP, 1996). Box C.5 describes a typical procedure for encoding expert judgment, and details regarding elicitation methodologies can be found elsewhere (e.g., Morgan and Henrion, 1990). Expert elicitation has been used as the basis for several emission uncertainty analyses. Dickson and Hobbs (1989) estimated confidence intervals for a number of source categories based upon input via questionnaires filled out by a panel of emission inventory experts. Hanna et al. (2001) used expert elicitation as the basis for quantifying uncertainty in emissions, chemistry, and meteorology for an air-quality modeling simulation of ozone formation. In the process of making judgments, experts can make a judgment not only regarding the range of uncertainty, but also whether biases exist in available data or inference methods, and experts can make adjustments to attempt to counteract such biases. For example, if emission data are available only for full-load steady-state operation of a process, and if emissions from transients and process upsets are believed to be important, an expert can account for the likelihood of higher average emissions by estimating that the mean of the uncertainty distribution is larger than that of the available data. Thus, the expert can quantify the bias in the mean if a bias is believed to exist. Expert elicitation is also useful for quantifying uncertainty in activity factors, for which sample data are typically not available (Zhao and Frey, 2004).

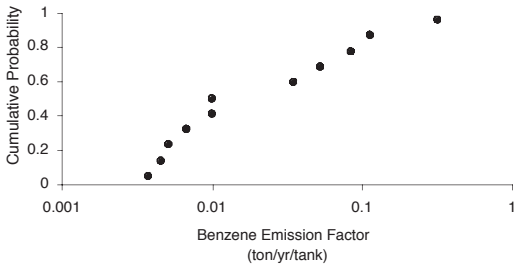
Key considerations regarding the credible use of expert judgment include: (1) follow a clear and appropriate protocol for expert elicitation; (2) for the conditioning step (as described in Box C.5), consider obtaining input via a workshop, but for the actual encoding, work individually with experts; (3) document (explain) the basis for each judgment; (4) compare judgments from different experts for the same or similar quantity and identify key similarities or differences; (5) evaluate the implications of apparent differences in judgments with respect to decision objectives, and do not "combine" judgments through some weighting scheme without first doing this; (6) where possible, allow for iteration.

There are techniques that allow an analyst to combine expert judgment and statistical analysis of empirical data. These techniques, known as Bayesian methods, can accommodate expert judgment in the form of a "prior" distribution that is updated with data, using Bayes' Theorem, to arrive at a "posterior" distribution that combines information from the judgment and the data. Bayesian methods can also deal with various complex situations, such as conditional probabilities (dependencies among multiple inputs) and combining information from multiple sources.

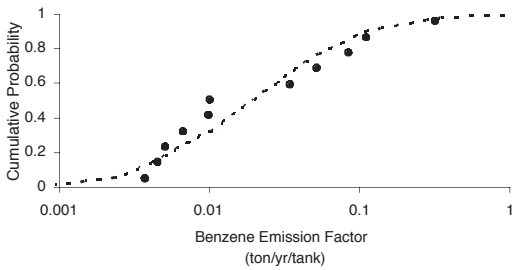
Box C.3. Variability and Uncertainty in Emission Factors: An Example

In situations for which emission factor data are available for a particular pollutant and source category, it is important to correctly distinguish between inter-unit variability in emissions versus uncertainty in the mean emission factor. For example, consider the case of benzene emissions from bulk storage terminals for gasoline, based upon work reported by Zhao and Frey (2004). There are 11 measurements within this source category, and the emissions vary from less than 0.01 to greater than 0.1 tons per tank per year. Figure (a) depicts an empirical distribution of these data points. For convenience, the data can be represented using a probability distribution model, such as the lognormal distribution depicted in Figure (b). Even if the observed data were truly a random sample from a lognormal distribution, some random deviations of the data from the model would be expected. Bootstrap simulation (described in another text box) was used to quantify uncertainty in our ability to estimate the true but unknown population distribution for inter-unit variability. The probability bands in Figure (c) represent confidence intervals for the fitted distribution. For example, the median of the distribution for inter-unit variability is uncertain, because we have only limited data from which to make an inference (estimate) of what the distribution might be. In this example, the 95 percent probability range of uncertainty for the median is from 0.008 to 0.05 tons per tank per year. Bootstrap simulation can also be used to estimate the uncertainty in the mean emission factor, as shown in Figure (d). In this case, the 95 percent probability range of uncertainty in the mean is from 0.016 to 0.18 tons per tank per year, or a range of -73% to +200% relative to the mean value of 0.06 tons per tank per year. Although this range may seem very large, it is substantially smaller than the range of inter-unit variability (the largest measured value is approximately 0.05 tons per tank per year).

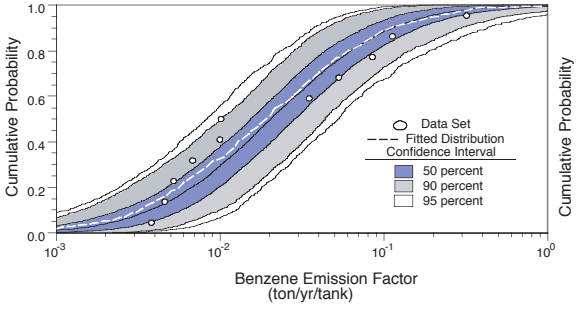
The inter-unit variability is the appropriate basis for estimating uncertainty when attempting to estimate emissions for only one emission source, if it can be assumed that the emission source is a random sample from the population of all such sources. The uncertainty in the mean is the appropriate basis for estimating uncertainty if there are many sources like this one in the inventory.



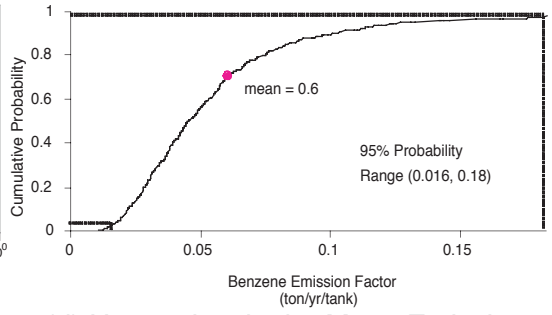
(a) Empirical Distribution of Inter-Unit Variability in Emissions



(b) Fitted Parametric Distribution for Inter-Unit Variability in Emissions



(c) Probability Bounds on Distribution for Inter-Unit Variability Due to Small Sample Size



(d) Uncertainty in the Mean Emission Factor Estimated Using Bootstrap Simulation

Box C.4. Estimating Uncertainty in a Mean:

Analytical Solution versus Bootstrap Simulation

For many emission inventory applications, it is necessary to know the uncertainty in the mean emission rate for a particular source category. However, the available data will typically represent inter-unit variability in emissions, as described in Box 5.5. A distribution of uncertainty for a statistic, such as the mean, is referred to as a *sampling distribution*. The standard deviation of the sampling distribution of the mean is referred to as the *standard error of the mean* (SEM). The SEM is estimated based upon the sample standard deviation, s, and the sample size, n: $SEM = s\ n^{-.5}$. If the available data are random, independent samples, and if the SEM is small enough, then the sampling distribution of the mean can be approximated as (or may exactly be) a normal distribution. Thus, the 95 percent probability range of uncertainty for the mean would be approximately -2 SEM to +2 SEM. However, if the SEM is more than approximately 30 percent of the mean value, then the normality assumption is typically inaccurate. In many practical cases, the SEM is sufficiently large that the use of a normality assumption would lead to the possibility of physically impossible values, such as negative emission rates for a particular source. In these cases, an alternative method is needed for estimating confidence intervals.

Bootstrap simulation is a numerical method for estimating confidence intervals in a statistic. There are many variations of bootstrap and this example is based upon the bootstrap-p technique (Efron and Tibshirani, 1993). Bootstrap simulation starts with an empirical sample of data of sample size n. A probability distribution model, such as a lognormal, could be fit to this sample of data. From the fitted distribution, n values are sampled at random with replacement to produce a sample of data referred to as a *bootstrap sample*. For a given bootstrap sample, a statistic of interest, such as the mean, is estimated. Each such estimate is referred to as a *bootstrap replicate* of the statistic. The bootstrap replicate can be saved, and then another bootstrap sample is created from which a second bootstrap replicate is estimated. This process is repeatedly typically 200 to 1,000 times to arrive at a distribution of bootstrap replicates, which is a numerical estimate of the sampling distribution of the statistic. The bootstrap replicates can be rank ordered and specifically ranked values can be used to describe confidence intervals. For example, the 95 percent confidence interval of the mean can be estimated by the range enclosed by the 25^{th} and 975th ranked values of 1,000 bootstrap replicates of the mean. The key advantage of bootstrap simulation is that it enables estimation of uncertainty in a mean value without imposing a normality assumption and taking into account that a quantity such as an emission factor cannot be negative.

While Bayesian methods are very flexible, they can be computationally complex. This complexity is considered by some to be a current barrier to their more widespread use.

Once uncertainties in the inputs to an inventory (or of models that are used as part of an inventory) have been specified, a variety of techniques can be selected to propagate the uncertainties to the model output. These methods range from analytical error propagation (e.g., Dickson and Hobbs, 1989; NRC, 1991; Balentine and Dickson, 1995) to numerical analysis based upon variations of Monte Carlo simulation (e.g., Frey and Zheng, 2002a, Abdel-Aziz and Frey, 2003a). Monte Carlo simulation methods are popular because they are flexible. They can accommodate many types of probability distributions for model inputs and they can be used with any model that can be simulated on a computer. For example, Monte Carlo simulation methods have been used to estimate uncertainty in inventories, such as for criteria pollutants, HAPs, and GHGs (e.g., Winiwarter and Rypdal, 2001; Gatz, 1995). Monte Carlo simulation and another commonly used method, Latin hypercube sampling, are described in Box C.6.

In the United States, a guideline for uncertainty analysis specifically in the context of emission inventories has not been established. However, the U.S. EPA has developed guidelines for probabilistic analysis in the context of human exposure assessment, including a 1997 Guideline on Monte Carlo Analysis,

Box C.5. Elicitation of Expert Judgment Regarding Probability Distributions

Expert elicitation is a formal process of encoding judgment in the form of probability distributions. Morgan and Henrion (1990) provide a useful overview and practical guidance. A typical five-step expert elicitation protocol is briefly described here, based upon the Stanford/SRI protocol. Similar protocols have been used in emissions and air quality work (e.g,. Hanna et al., 2001).

Step 1: Motivating the Subject: Establishing Rapport. The purpose of this step is for the elicitor to establish rapport with the expert. The elicitor should have some knowledge of the subject matter and the interview should be where the expert has full access to relevant materials (e.g., in the expert's office). The elicitor gives the expert context regarding the need for and planned use of their judgments.

Step 2: Structuring: Defining the Uncertain Quantity. Structuring typically consists of four steps: defining the variable; identifying the possible range of outcomes; disaggregating if necessary; and selecting an appropriate measurement scale. The elicitor seeks to arrive at an unambiguous definition of the quantity to be assessed. The definition should pass the "clairvoyance test"– the definition should be specific enough that a clairvoyant could look into the future (or the past, as appropriate) to discover the exact value of the quantity. The definition should also be stated in form in which the expert will most likely be able to provide reliable judgments, which may involve modifying the model.

Step 3: Conditioning: Get the expert to think about all evidence. The purpose of this step is get the expert to think about all relevant knowledge related to the uncertain variable. This includes thinking about available data, theoretical models for how the system of interest behaves, and how the expert plans to use the information. The expert typically will consider "case-specific" information, which relates directly to the quantity being assessed, and "surrogate" information, which relates to quantities similar to that being assessed. In the later case, the expert may draw on analogies with similar systems.

Step 4: Encoding: Quantifying the Expert's Judgment. The purpose of the encoding phase is to arrive at a quantitative description of the subjective probability distribution which best reflects the expert's beliefs about the possible range of outcomes, and their likelihood, for the uncertain quantity. To counter the tendency to be overconfident about uncertainty (i.e. produce too narrow a range), many elicitors recommend starting with extreme upper and lower values of the distribution. Then the elicitor would ask for scenarios that might lead to outcomes outside of these extremes until the expert indicates they are not possible. Some of the common elicitation methods include:

> **Fixed Value Method**. Estimate the probability that the actual value of a quantity is higher (or lower) than some arbitrary number.
>
> **Fixed Probability Method.** Estimate the value of a quantity such that the probability of higher or lower values is some specified amount. For example, what is the drycleaner VOC emission rate such that there is only a 10 percent change of a higher rate?
>
> **Interval Method.** For example, to assess the median of a distribution, the elicitor may ask the expert to react to an arbitrary value. The value is adjusted until the expert is indifferent as to whether the actual value of the quantity is higher or lower.

The selection of an appropriate approach often depends, at least in part, on the preferences of the expert.

Step 5: Verifying: Checking the Answer. The purpose of this phase is to test the probability distribution constructed in the encoding phases against the expert's beliefs to make sure that the distribution correctly represents those beliefs. The elicitor can form what appear to be equally likely outcomes based on the elicited distribution and ask the expert if they would be willing to make bets that one or the other outcomes are more likely to occur. If the distribution correctly reflects the expert's beliefs, then the expert should be indifferent between such bets. If not, then it may be necessary to iterate on previous steps, including conditioning and encoding, to obtain a better estimate of the distribution.

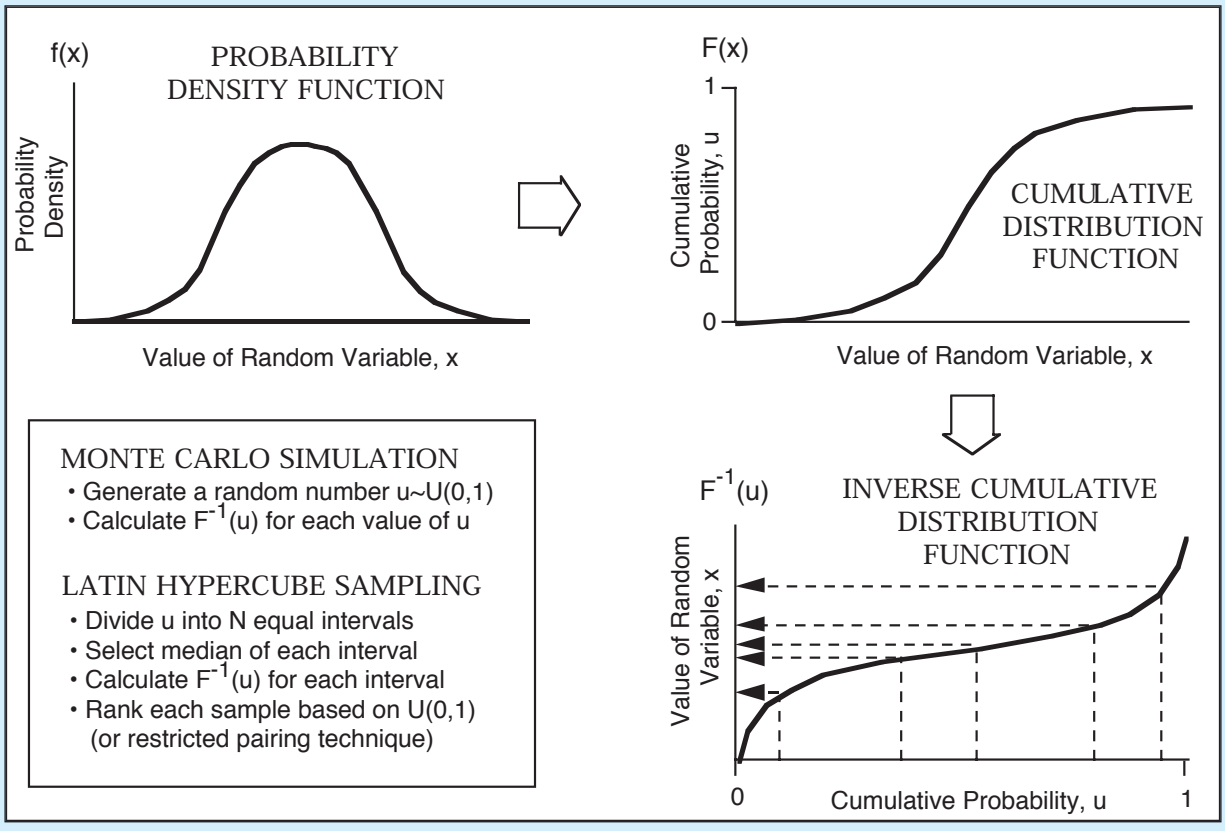
Box C.6. Monte Carlo and Latin Hypercube Simulation

Numerical methods for propagating distributions through models have gained wide acceptance and application because they are flexible. A commonly used numerical method is Monte Carlo simulation (MCS), and an often used alternative is Latin Hypercube Sampling (LHS).

The procedures for both MCS and LHS are depicted in the figure below. Both techniques involve the generation of sample values according to the probability distribution specified for each model input. One value is sampled for each model input, and one corresponding value of the model output is calculated using the user-provided model.

MCS involves generating pseudo-random values of the model inputs according to their probability distributions. One method for doing this is the use of the inverse cumulative distribution function, which depicts the values of the random variable on the y-axis and cumulative probability (which varies uniformly from 0 to 1) on the x-axis. The simplest pseudo random number generator algorithms simulate uniformly distributed independent random samples. Thus, if the inverse cumulative distribution function is known, it is possible to generate random values for any type of probability distribution model.

LHS differs from MCS in that the sampling is not random. Instead, each input distribution is divided into equal probability intervals and one sample is drawn, without replacement, from each interval. The pairing of sample values for multiple inputs is done randomly. For example, if a high value is selected for the first input to a model, x1, then it is possible that a high or low value could be independently selected for the second input, x2.



Source: Frey (1992)

as well as guidance on probabilistic methods applied to Superfund risk assessments. Although the problem area is different, many of the methodological principles are transferable to other fields. Authors such as Morgan and Henrion (1990) and Cullen and Frey (1999) provide general principles for the application of probabilistic techniques. An emission inventory is typically constructed based upon emission and activity factors. The U.S. EPA has sponsored the development of prototype software tools for quantifying uncertainty in emission inventories and other models (e.g., Frey et al., 1999; Frey et al., 2002). Thus, it is possible to create a general framework to quantify uncertainty in emission inventories. The general framework includes the following main steps (Frey et al., 1999):

Data preparation includes the assessment of data needs, data collection plans, and compilation or evaluation of existing databases for the specific source categories and emission processes that are included in the inventory.

Selection or development of emissions models, which may be as simple as a linear model that sums the products of emission and activity factors for each source category or which may involve complex models that are tailored to each source category. Uncertainty analysis and modeling should be concurrent activities; thus, the choice of model and the implementation of uncertainty analysis are closely related.

Statistical analysis of emission model inputs for which empirical data are available typically includes several key aspects: visualization of data using empirical cumulative distribution functions for model inputs; fitting, evaluation, and selection of alternative parametric probability distribution models for representing variability in model inputs.

Characterization of uncertainty using techniques such as bootstrap simulation, or if empirical data are not available or are imperfect in substantial ways (e.g., not representative of typical operating conditions, addition of missing key emissions processes (such as upsets) using expert judgment.

Propagation of uncertainty in model inputs through emission inventory models to estimate uncertainty in category-specific emissions and/or total emissions from a population of emission sources.

Sensitivity analysis to estimate the importance of uncertainty in specific inputs with respect to the uncertainty in the output. This is addressed in more detail in Section 8.3.

The IPCC has developed Good Practice Guidance recommending the use of Monte Carlo methods as part of a tiered approach to uncertainty estimates for greenhouse gas emissions (IPCC, 2000). The guidance document discusses the role of both statistical analysis of data as well as elicitation of expert judgment as means for quantification of uncertainty in emission and activity factors. The guidance has been used by many countries to prepare uncertainty estimates for GHG emission inventories (e.g., Winiwarter and Rypdal, 2001; El-Fadel et al., 2001; Van Amstel et al., 2000). There is a growing literature that includes uncertainty analysis of emission factors or emission inventories. Frey and Rhodes (1996) demonstrated the use of bootstrap simulation to quantify uncertainty in mean emission factors based upon inter-unit variability in emissions and sample size for situations in which normality assumptions are not valid, using a case study of HAP emissions from coal-fired power plants. Uncertainty was propagated using Monte Carlo simulation through an emission model to yield uncertainty in emissions for any given simulated averaging period. The quantitative methods based upon the use of bootstrap for characterizing uncertainty in emission factor or inventory have been applied to various emission sources, including power plants, nonroad mobile sources, natural gas-fired engines, and specific area sources (e.g., Frey et al., 1999; Frey and Zheng, 2002a&b; Frey and Bammi, 2002 and 2003; Abdel-Aziz and Frey, 2003a&b, 2004; Winiwarter and Rypdal, 2001).

C.2.4 An Uncertainty Analysis Example for an Emission Inventory

An example for developing a probabilistic emission inventory, by Zhao and Frey (2004), is presented here to demonstrate a comprehensive methodology for quantification of uncertainty in mean emissions or

activity factors as a fundamental basis for estimating uncertainty in emission inventories. The example quantified uncertainty of emission inventory for six selected urban air toxics (benzene, 1,3-butadiene, formaldehyde, mercury, arsenic and lead) for the urban area of Jacksonville, Florida.

This example follows the general framework and steps presented in Section C.3.3 to quantify uncertainty. The source categories considered in this example include: onroad and nonroad mobile; electric utility; and area sources. Specific source categories for each pollutant considered in the example case studies vary depending on the pollutant. Surrogate uncertainty data for emission factors are used for the situation where insufficient emission sample data are available for a particular source category, but for which data are available for a similar type of emission process. This example employed Maximum Likelihood Estimation to fit parametric distributions for inter-unit variability in emissions to sample data. Maximum Likelihood Estimation can be applied also to cases in which some data are below one or more detection limits. Bootstrap simulation was used to quantify variability and uncertainty in emission factors. Figure C.4 illustrates the results of analysis of variability and uncertainty for one of the emission factors used in the inventory for mercury. The figure shows the available sample data that represent inter-unit variability, a parametric probability distribution fit to the data, and probability ranges around the fitted distribution that were obtained from bootstrap simulation. The latter quantify uncertainty in the ability to infer the true but unknown population distribution of inter-unit variability. Furthermore, based upon the bootstrap results, uncertainty in the mean emission factor can be inferred. The advantage of the bootstrap approach over an analytical estimate of uncertainty in the mean is that the uncertainty in the mean can be positively skewed if there is a large amount of variability in the data and a small sample size. Bootstrap can capture such skewness, whereas analytical estimates of uncertainty in the mean typically are based upon a normality assumption. Skewness is an important property of a probability distribution and if inaccurately characterized can imply misleading insights.

Expert judgment was used to estimate uncertainty in activity factors. Monte Carlo simulation was applied to propagate uncertainty in emission factors and activity factors to total emission inventories. Table C.1 summarizes the relative range of uncertainty for the inventory for each of the six pollutants. The uncertainty estimates range from as little as minus 25 percent to plus 30 percent relative to the mean

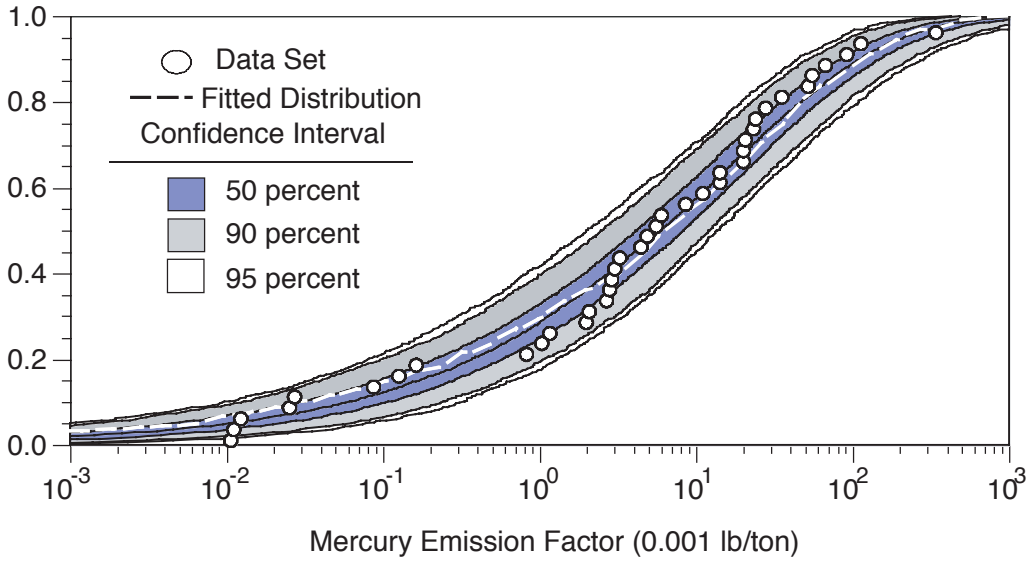


Figure C.4. Variability and Uncertainty in Mercury Emission Factor from Pathological Waste Disposal for Jacksonville, Florida, Estimated Based Upon a Weibull Distribution (n=40; B=500).

Table C.1. Normalized Estimates of Overall Uncertainty in Probabilistic Emission Inventories for 1, 3-butadiene, Mercury, Arsenic, Benzene, Formaldehyde and Lead: Comparative Analysis of Correlated and Uncorrelated Surrogate Emission Factor Uncertainties.	
Pollutant	**Relative Range of Uncertainty, Plus or Minus Percent Relative to Mean Inventory Estimate**
1,3-butadiene	(-46, 108)
Mercury	(-25, 30)
Arsenic	(-83, 243)
Benzene	(-54, 141)
Formaldehyde	(-42, 89)
Lead	(-52, 177)

estimate of the inventory to more than a factor of two. A factor of two uncertainty is when the lower end of the range is one-half of the mean and the upper end of the range is twice the mean (e.g., minus 50 percent to plus 100 percent). Correlation coefficients were used to identify key sources of uncertainty and important source categories. Typically only one to three source categories out of a dozen or more were found to be the key sources of uncertainty for each of the six pollutants.

The results of this example indicate that the overall range of uncertainty is approximately a factor of two or greater for five of the six pollutants. The results of this example also demonstrate that random sampling error and measurement error lead to substantial quantifiable uncertainty in the emission inventories of selected urban air toxics. The positively skewed ranges of uncertainty appropriately account for the fact that emissions must be non-negative. The identification of key sources of uncertainty in the inventory serves as an aid to prioritizing resources for additional data collection or research in order to reduce uncertainty.

C.3 METHODS FOR SENSITIVITY ANALYSIS

A variety of methods are available for performing sensitivity analysis; these methods can be classified in a variety of ways. Saltelli et al. (2000, 2004), Cullen and Frey (1999), and Frey, Mokhtari, and Zheng (2004) provide an overview of sensitivity analysis methods. For example, methods can be classified as screening versus refined depending upon the level of detail or sophistication. Screening methods are relatively simple to implement but may not be accurate, whereas refined methods provide more accurate or detailed insight but also are more challenging to apply and interpret. Local or global methods vary depending upon whether they measure sensitivity at a specific point in the model input domain or over a large input domain when many inputs are varying simultaneously. Some methods are model independent whereas others, such as linear regression, require assumption of a functional form. Methods can also be classified by type, such as mathematical, statistical, or graphical.

Screening methods are typically used to make a preliminary identification of the most sensitive model inputs. Scatter plots and nominal range sensitivity analysis are examples of such methods. However, such methods are often relatively simple and may not be robust to key model characteristics such as nonlinearity, thresholds, interactions, and different types of inputs (e.g., categorical, continuous). More refined methods, such as ANOVA, that can adequately deal with complex model characteristics typically require greater expertise or resources to implement and interpret.

Local sensitivity analysis concentrates on the impact of changes in values of inputs with respect to a specific point in the input domain. Nominal range sensitivity analysis and differential sensitivity analysis are examples of local sensitivity analysis methods. Global sensitivity analysis apportions the uncertainty in the output to the uncertainty in the

inputs when many inputs varying simultaneously and over large ranges of variation. Global methods are applicable to situations in which model inputs are varied simultaneously over large ranges of values, typically based upon probability distributions assigned to each input.

Some methods, such as correlation coefficients regression-based techniques, require assumption or specification of a model functional form and estimation of sensitivity coefficients that depend upon the assumed form. If the assumed form of the regression model does not adequately capture the response between an input and output, then insights obtained from the analysis may be subject to error. Other methods, such as Sobol's method, Fourier Amplitude Sensitivity Test, Categorical and Regression Trees (CART, also known as Hierarchical Tree-Based Regression) and ANOVA do not require a priori knowledge or specification of a function form and thus are typically more robust to model complexities. Such techniques are referred to as model-independent. However, such methods can be more challenging to use in practice than more commonly available correlation and regression methods.

Alternatively, methods can be classified as mathematical, statistical and graphical methods. The mathematical methods include nominal range sensitivity analysis and differential sensitivity analysis. Mathematical methods typically address the local or linear sensitivity of the output to perturbations or ranges of individually varied inputs and are helpful in eliminating unimportant inputs. However, they may not be reliable as a method for ranking and discriminating among important inputs. Furthermore, mathematical methods do not address the variance in the output due to the variance in the inputs. Statistical methods, such as correlation coefficients, regression, ANOVA, and CART, can be used to assess key sources of uncertainty when many inputs vary simultaneously. The selection of an appropriate technique will depend upon model characteristics and assessment objectives. Graphical techniques are often useful especially to help identify complexities in model responses and as an aid in selecting other sensitivity analysis methods or in interpreting results from other methods. Graphical methods can be used as complements to mathematical and statistical methods to better interpret sensitivity analysis results. More detail regarding the discussion and description of these methods is given by Frey, Mokhtari, and Danish (2003).

The most commonly used statistical methods typically are: (1) sample (Pearson) and rank (Spearman) correlation coefficients, and (2) sample and rank linear regression. The sample (Pearson) correlation method can evaluate the strength of linear association between output values and values sampled from probability distribution of an input; while the rank (Spearman) correlation can account for monotonic nonlinear relationships between two random variables (Siegel and Castellan, 1988). Sample regression uses a dataset for fitting a regression model including the output values from a model and sampled values from probability distributions of inputs. Sample regression can account for the linear associations between the inputs and output. Rank regression is based upon the ranks for the inputs and outputs. Rank regression is especially useful when there is high amount of variance or noise in the data or if the model is non-linear but monotonic.

In addition to the commonly used methods, there are advanced methods that are potentially useful for emission inventory modeling, including ANOVA and CART. ANOVA is a general statistical-based technique that can be applied to models that are linear, nonlinear, monotonic, or non-monotonic. ANOVA can address both qualitative and quantitative inputs (Steel et al., 1997). CART is a method for partitioning data. CART produces "classification rules" that specify specific cut-off values of selected inputs that lead to statistically significantly different mean values for an output. Hence, CART can provide insight into conditions that lead to high emissions. CART is applicable to linear or nonlinear models, including models with interactions and thresholds.

Selection of appropriate sensitivity analysis methods depends on objectives of the analysis, the characteristics of the model, and other considerations such as ease of implementation and resource availability to conduct the analysis (e.g., Frey, Mokhtari, and Zheng, 2004). For example, when the objective of sensitivity analysis is to identify key sources of uncertainty and apportion variance in an output to individual inputs, the choice of methods

further depends on inherent model characteristics. If a model is linear, correlation methods and regression analysis methods are appropriate. If the model is nonlinear, ANOVA or other methods capable of dealing with interactions are better choices. When there are categorical inputs, CART may be more appropriate. When the objective of sensitivity analysis is to identify factors contributing to high emissions in order to develop control strategies, ANOVA and CART should be considered since these methods can provide insight into conditions that lead to high emissions.

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