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EMISSIONS AND TRAFFIC CONTROL: AN EMPIRICAL APPROACH

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ABSTRACT

The purpose of this study is to evaluate the effect of traffic signal coordination and timing on real-world, on-road emissions. A portable instrument, the OEM-2100 manufactured by Clean Air Technologies International, Inc., was used to measure on-road tailpipe emissions of carbon monoxide (CO), nitric oxide (NO), hydrocarbons (HC), and carbon dioxide (CO_2) on a second-by-second basis during actual driving. Data have been collected for several vehicles, including two different 1996 Oldsmobile Cutlass and two different 1999 Ford Taurus light duty gasoline vehicles. The focus of data collection efforts to date has been on measuring emissions before and after signal coordination upgrades are implemented on two corridors in Research Triangle Park, North Carolina. The two corridors include NC 54 and Miami Boulevard. On each corridor, approximately 100 one-way trips have been made before upgrades of the signal coordination have been implemented. At this time, 100 additional one-way runs have been collected on Miami Boulevard after most of the signals have been coordinated. The emissions measurement work has involved: (a) development of data collection protocols; (b) development of a study design, including targeting specific peak periods, comparison of different vehicles, and comparison of different drivers; and (c) development of methods for analyzing the data. This paper presents some examples of the data collected from two of the vehicles and illustrates the key insights obtained to date from on-road emissions measurements. A key insight is that emissions during idling are generally low compared to emissions during acceleration. Another key insight is that emissions are substantially influenced by traffic signalization primarily because of the accelerations that occur after a red light, rather than because of deceleration or idling. These results have significant implications for traffic management, for example, in terms of making trade-offs between number of stops (and associated starts) versus total idling time. As demonstrated in this work, emissions may be analyzed also in terms of delay and non-delay events, for consistency with many transportation planning models. This project demonstrates the successful application of a portable on-road emissions measurement technique and its application to evaluation of the real world impact of traffic control methods on emissions. Future work includes additional data collection on the NC 54 and Miami Boulevard corridors as well as design and execution of a more extensive study on another corridor.

INTRODUCTION

On-board emissions measurement is widely recognized as the most desirable approach for quantifying highway vehicle emissions. However, in the past, on-board instrumentation has been prohibitively expensive. Thus, emission factor models, such as Mobile5b and EMFAC7F, rely on data collected in laboratory-based dynamometer tests (e.g, Kini and Frey, 1997). Dynamometer tests also underlie many current projects aimed at developing "modal" emissions models, which attempt to predict emissions due to microscale traffic events that lead to transients such as deceleration, idling, and acceleration at an intersection. Dynamometer tests have suffered from well-known shortcomings due to non-representativeness of actual driving conditions (e.g., Barth *et al.*, 1996; Kelly and Groblicki, 1993). For example, many tests under-represent short-term events that cause high emissions even for a properly functioning vehicle, such as high accelerations. Driver behavior can affect the duration of both cold starts and of events leading to enrichment operation, which in turn have substantial effects on emissions regardless of the total number of vehicle miles traveled.

Instrumented vehicle emissions studies have typically focused on a very small number (i.e. *one*) of vehicles (Kelly and Groblicki, 1993; Cicero-Fernandez *et al.*, 1997). Others have measured engine parameters only, and then used models to predict CO emissions based upon chemical equilibrium assumptions (e.g., LeBlanc *et al.*, 1994) or collected emissions data separately using dynamometers (e.g., West and McGill, 1997). Thus, there are limited emissions data based solely upon on-road measurements.

Remote sensing is capable of on-road emissions measurements for a large number of passing vehicles at selected sites (e.g., Stedman, 1989; Bishop *et al.*, 1989; Stephens and Cadle, 1991; Lawson *et al.*, 1990; Zhang *et al.*, 1996). The senior investigators on this project team have collected and analyzed remote sensing data as part of a recent Transportation Research Board (TRB)-funded project "ITS-44, ITS Integration of Real-Time Emissions Data and Traffic Management Systems" (e.g., TRB, 1999, pp. 28-29). One of the PIs has previously used remote sensing to measure emissions from school and transit busses (e.g,. Frey and Eichenberger, 1997). However, remote sensing suffers from constraints on site selection and inability to obtain measurements for closely-spaced vehicles. Furthermore, because engine operating data are unobservable using remote sensing, there is substantial unexplainable variability in the measurements (e.g, Bishop *et al.*, 1996). Thus, although remote sensing may be useful for developing area-wide average emissions estimates (e.g., Singer and Harley, 1996), it is less useful as a basis for evaluation of microscale driving events associated with alternative transportation control measures (TCMs).

To evaluate the efficacy of pollution prevention strategies, it is critically important to obtain *on-road* data that are *representative of actual driving conditions*. The only proven approach for doing this is on-board instrumentation. In selecting a traffic management strategy to evaluate in this project, the team used criteria of: breadth of applicability; ability to conduct before-and-after tests; indicated level of cooperation and interest of the responsible transportation agency; and cost-effectiveness of data collection. Of the potential strategies, traffic system signalization is the strongest candidate. Improved signal coordination has been shown to yield fewer stops, stopped delays, starts, and the attending changes in speed. It is hypothesized that good signal coordination will reduce overall emissions.

The purpose of this paper is to: (1) discuss the protocols developed for data collection; (2) present an example of a data set obtained from one trip of field survey work; and (3) discuss the findings from the preliminary analysis of the data.

PROJECT OBJECTIVES

The purpose of this project is to measure real-world on-road vehicle emissions with a focus on characterizing the effect of traffic signal timing on emissions. The project, titled "Emissions Reduction Through Better Traffic Management," is sponsored by the North Carolina Department of Transportation. The project was initiated in April of 1999 and will continue through June of 2001.

Specific benefits that will accrue from successful completion of this project include: (1) quantification of the relationship between instantaneous emissions (i.e. CO, HC, and NO_x) and explanatory variables such as traffic, roadway, vehicle, engine, and driver behavior characteristics; (2) an approach for evaluation of the pollution prevention effects of traffic signalization for selected roadway corridors, vehicle types, and traffic conditions, taking into account both the positive and adverse impacts (e.g., on cross streets); (3) generation of data that can be used to develop realistic city- and facility-specific driving subcycles, which may then be used to improve other (for example, dynamometer) emissions measurement methods; and (4) ability to isolate the effects of short-term events, such as "open-loop" or "fuel-rich" driving, that can dominate total emissions, and to assess whether these events can be prevented via a variety of traffic management strategies.

TECHNICAL APPROACH

This project features the deployment of a portable on-road vehicle emissions measurement device to collect data regarding the real world emissions of vehicles driven on selected corridors before and after traffic signal coordination and timing have been modified. The instrument used in this study is the OEM-2100 manufactured by Clean Air Technologies International, Inc. This project has included the development of protocols for deployment of the OEM-2100 for data collection in the field, and development of methods for analyzing the data obtained from the OEM-2100. The specific data collected include second-by-second data streams for vehicle operation and vehicle emissions. Vehicle operation data obtained include: (1) vehicle speed (mph); (2) engine rpm; (3) engine coolant temperature; (4) manifold absolute pressure (MAP); (5) percent of wide open throttle; (6) open loop/closed loop flag; and (7) others depending on the specific vehicle. The emissions data that are obtained include: (1) carbon monoxide (CO); (2) nitric oxide (NO); (3) hydrocarbons (HC); (4) carbon dioxide (CO_2); and (5) oxygen (O_2). The OEM has an integrated computer that synchronizes and combines the vehicle operation and vehicle emissions data streams into a report of second-by-second vehicle operation and emissions.

Based upon the discussions with North Carolina Department of Transportation regarding the traffic signalization timing, two sites were selected for data collection. During the winter of 1999 and spring of 2000, a field study was conducted to obtain simultaneous emissions and traffic data at these two sites in Research Triangle Park, North Carolina. These sites include a corridor on NC 54 and a corridor on Miami Boulevard. Data have been collected using both the OEM-2100 and a laptop computer over the course of 20 field days of data collection at these two sites. Significant activities have been devoted to developing data collection protocols and analysis of the resulting data.

The data collection efforts include warming up the instrument, zeroing the instrument, and conducting the measurements over a prescribed route. During data collection, a time stamp is recorded when the vehicle passes through the center of each key intersection in the study corridor. The data stream regarding vehicle position is synchronized with the vehicle operation and emissions file using a macro. A fourth data stream, regarding road grade, was obtained by taking measurements, using a digital level, of the road grade on the study corridors at one-tenth of a mile increments. The road grade information is synchronized with vehicle position data using a macro.

Each trip is saved as a different field data file. At start of each trip we also enter the information regarding the vehicle characteristics, such as type, model year, engine size, and odometer reading, to the field data file. We used a thermometer and a humidity reader to record the temperature and humidity at start of each trip. This information as well as information about the driver is also recorded in the field data file.

Software has been developed to clean up the data files (e.g., remove data streams during instrument zeroing) and to analyze the emissions data. Data analysis techniques include: (1) visualization of data using time traces (e.g., speed versus time, emissions versus time, etc.), empirical cumulative distribution functions, bar charts of average emissions, etc.; (2) analysis of the data to estimate modal emissions for acceleration, cruise, deceleration, and idle; (3) analysis of the data to estimate emissions for non-delay and delay events; and (4) analysis of trip average emissions versus summary statistics (e.g., number of stops during a trip), among others.

The study design includes selection of vehicles and drivers, and deployment of vehicle/driver combinations during different time periods on specific corridors. The recent work has comprised a pilot study whose main purpose is to demonstrate the data collection and data analysis procedures and to provide some insight into key factors influencing variability in on-road emissions. As part of these pilot studies, a small number of vehicles have been deployed on the two selected corridors. The vehicles for which measurements have been obtained include two different 1996 Oldsmobile Cutlass, two different 1999 Ford Taurus, one 1998 Plymouth Breeze, and one 1998 Ford Club Wagon (15 passenger van). As part of other studies conducted on other roadways, measurements have been obtained on a variety of other vehicles, including a 1998 Toyota Camry (manual 5 speed transmission), a 1996 Honda Civic 2-door hatchback, a 1999 Toyota Corolla, a 1996 Dodge Caravan, and other vehicles such as a Dodge Ram 15 passenger van. Thus, to date, the OEM-2100 has been used successfully with vehicles ranging in size from a small hatchback to a large van, with engine sizes from approximately 1.6 liters to 5.4 liters. The pilot studies have focused primarily on the use of two drivers and on the Oldsmobile Cutlass and Ford Taurus vehicles. As part of parametric studies, six other drivers have been involved in data collection efforts on the two corridors.

A total of 300 one-way trips have been made so far during these data collection efforts on the two selected corridors. Data collection has focused on three peak periods: morning (i.e., 7:30 AM – 9:00 AM); lunchtime (i.e., 12:00 – 1:30 PM); and evening (i.e., 4:30 PM – 6:00 PM). A total of 100 morning, 109 noon, and 91 evening runs have been completed on the two corridors at this time. These data correspond to a 55 hours of measurements, during which time data were recorded each second. A total of 1500 vehicle miles were traveled during these data collection efforts, based on an average of approximately five miles per trip.

The next section presents information on the deployment of the OEM-2100.

COLLECTING ON-ROAD EMISSIONS DATA

The OEM-2100 is a portable instrument that can be installed in approximately 15 minutes in a light duty gasoline vehicle. The OEM-2100 has three connections with the vehicle: (1) a power cable typically connected to the cigarette lighter or power port; (2) an engine data link connected to the On-Board Diagnostic (OBD) link; and (3) an emissions sampling probe inserted into the tailpipe. The connections are fully reversible and do not require any modification to the vehicle. The unit can be removed from a vehicle in typically approximately five to ten minutes.

Figure 1 illustrates the placement of the OEM-2100 instrument on a seat inside the vehicle. Figure 2 illustrates the emission sampling probe and hose, which are routed into the vehicle and to the instrument. Figure 3 illustrates the interface of the OEM-2100 with the on-board diagnostic port of the vehicle.

The on-board computer in the instrument calculates mass emission rates per the methodology developed by Vojtisek-Lom and Cobb (1997).

More detail regarding the installation of the instrument in a vehicle can be obtained from http://www4.ncsu.edu/~frey/emissions/.

PROCESSING OF DATA

Emissions and engine data from OEM-2100, and vehicle position data from a separate laptop, are downloaded to a PC in the laboratory. Time-of-day time stamps were matched in the emission and field files with the help of a program written in Microsoft Visual Basic. Road grade information is also added to the combined file using distance traveled from the start of the trip as matching field. The final data set obtained from post-processing includes time-synchronized emissions, traffic and grade data for each trip. The data fields in the data set include: Time Stamps; Traffic Events (e.g., the time at which the vehicle enters a queue at an intersection and the time at which the vehicle clears the center of the intersection); Vehicle Speed (mph); Distance Traveled (mi); Acceleration (mph/sec); Engine RPM; Coolant Temperature (^{0}C); Throttle Position (percent); Intake Air Flow (g/sec); Dry Exhaust Flow (g/sec); Fuel Flow (g/sec); Fuel Flow (g/mi); NO (ppm); HC (ppm); CO (volume percent); CO_2 (volume percent); O_2 (volume percent); NO (g/sec); HC (g/sec); CO (g/sec); CO_2 (g/sec); grade (percent).

Figure 1. OEM-2100 installed in a 1998 Toyota Camry.

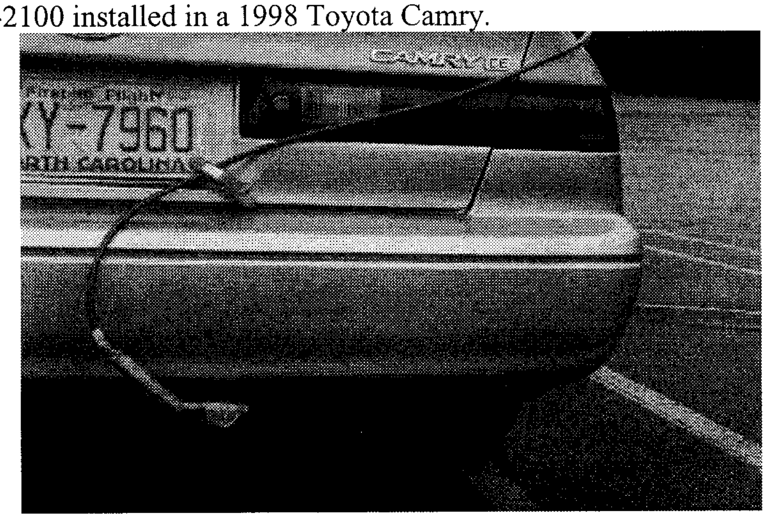

Figure 2. Sampling probe routed from vehicle tailpipe into vehicle, secured by clamps.

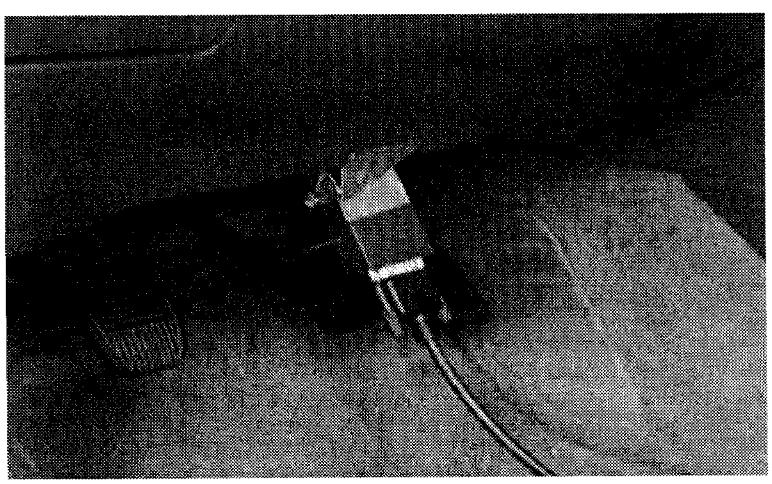

Figure 3. Data cable connected to On-Board Diagnostic (OBD) link.

EXAMPLE RESULTS

In this section, we present some illustrative results from recent data collection efforts. The examples include: (1) a speed versus time trace; (2) an emission versus time trace; (3) modal emissions estimates for two vehicles; (4) and distribution of time, distance, fuel use, and emissions for an average trip. The examples here are based upon data collected on the Miami Boulevard corridor in Research Triangle Park.

Vehicle Activity: Speed versus Time

Figure 4 is an example speed versus time trace from an on-road emissions measurement trip taken on Miami Boulevard on October 8, 1999. The figure is labeled with the location of the vehicle at specific times. The trip begins just south of Emperor Boulevard and ends a short distance north of U.S. 70. The time at which the vehicle passes through the center of an intersection is noted. In some cases, the same intersection is indicated twice. In these latter cases, the first notation indicates the time at which the vehicle enters a queue at the intersection, while the second notation indicates the time at which the vehicle clears the center of the intersection. For example, the vehicle stopped at Alexander Drive at approximately 8:10 am and cleared the center of the intersection at approximately 8:11 am. This particular trip is illustrative of the major cross streets on Miami Boulevard. The longest waiting times in this particular trip occur at the signalized intersections associated with the I-40 interchange, Alexander Drive, and Angier Drive. There are a total of 15 signalized intersections on this corridor. The northbound trip on Miami Blvd. depicted in Figure 4 is approximately 5 miles in length.

The emissions trace for CO for the same trip is shown in Figure 5. Of particular note is that the emission rate of CO is shown to be highly variable over the course of the trip. The peak emissions generally occur in association with accelerations. For example, the two largest "spikes" or peaks in CO emissions occur during the acceleration from a full stop at both Alexander Drive and Angier Avenue. These peaks illustrate that short-term events during a trip can lead to comparatively high emission rates. In contrast, the emission rates during idling at those two intersections are shown to be very low. Similarly, NO and HC emissions exhibit a number of short-term peaks that have emission rates much larger than during most of the rest of the trip. These measurements illustrate that total emission during a trip are not so much a function of miles traveled as they are of the way that the trip is conducted.

MODAL EMISSIONS

The measurements represented in Figure 5 indicate that the emissions vary as a function of driving mode. Therefore, the second-by-second emissions data were divided into four modal categories and the average emission rate for each mode was calculated. The four modes are: (1) acceleration; (2) cruise; (3) deceleration; and (4) idle.

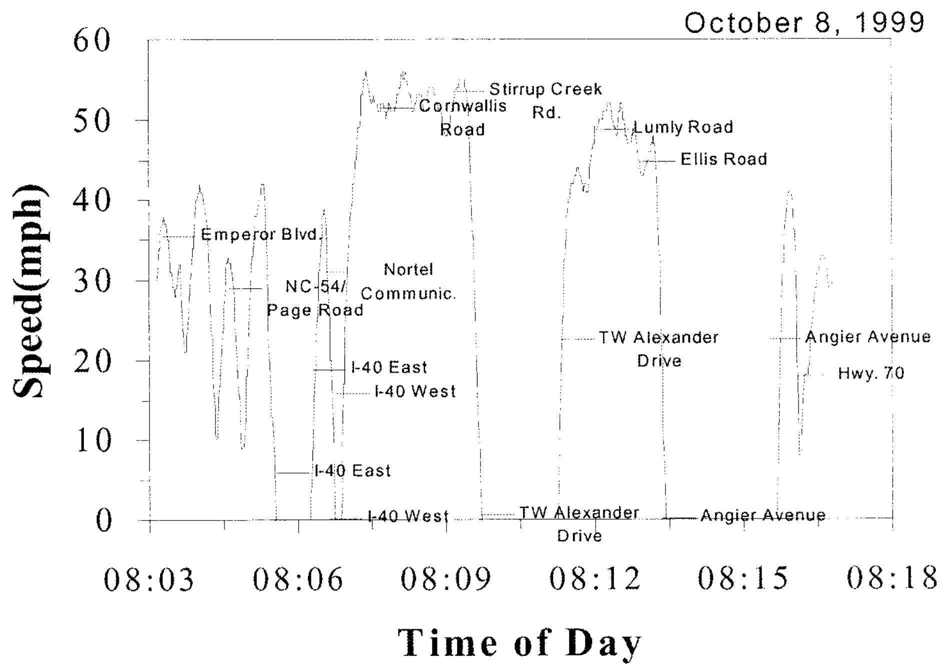

Figure 4. Example of a Speed versus Time Trace with Labels for major intersections

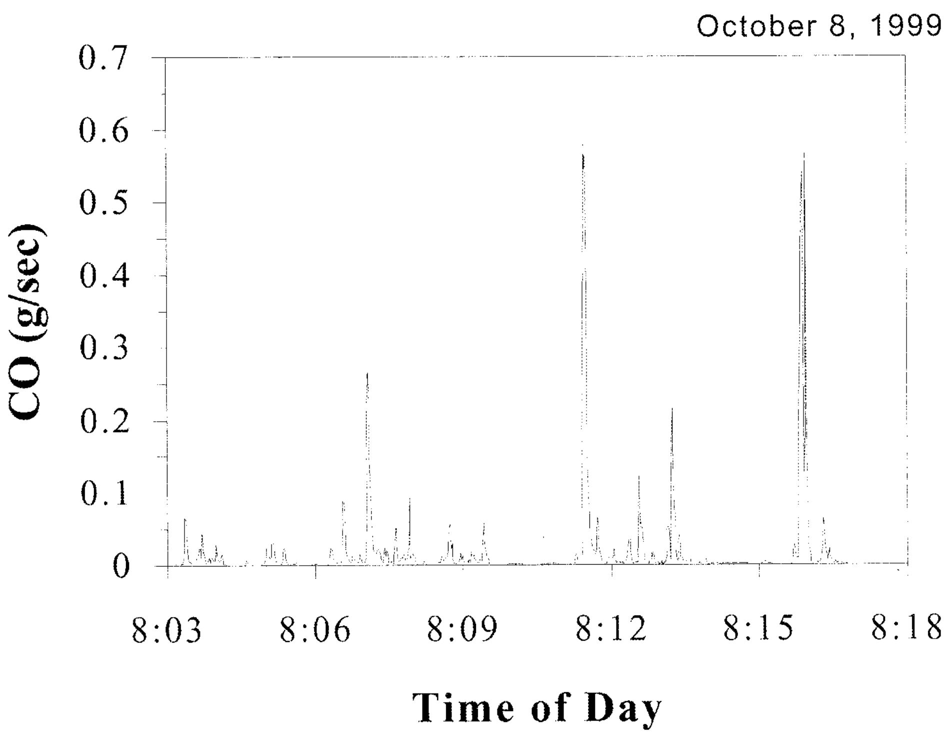

Figure 5. Example of an Emissions versus Time Trace for Carbon Monoxide.

The definitions of the modes used in this analysis are based upon the observed vehicle speed and acceleration. Idle is defined as having zero speed and zero acceleration. Acceleration is defined as having a speed greater than zero and an acceleration of greater than zero with some specific conditions imposed. If the acceleration is greater than or equal to 2 mph/s then the vehicle is defined to be in acceleration mode. If the acceleration has averaged to be 1 mph/s for at least three seconds, then the vehicle is also defined to be in acceleration mode. Deceleration is defined in a similar manner, except that the accelerations have negative values. All other situations are defined as cruising. Thus, cruising is approximately steady speed but some drifting of speed is allowed as part of the definition of cruise mode.

A program has been written in Microsoft Visual Basic that calculates the driving mode for second-by-second data and calculates an average value of emissions for each of the driving modes and for the total trip. To illustrate the types of results obtained from modal analysis of the emissions data, an example of results for CO emissions for a 1996 Oldsmobile Cutlass and a 1999 Ford Taurus is presented in Figure 6. These results are based upon averaging from 47 one-way trips driven with the Cutlass and from 29 one-way trips driven with the Taurus.

As shown in Figure 6, on average the acceleration driving mode has the highest CO emissions for both of the vehicles that were evaluated. For example, the 1999 Ford Taurus has an acceleration emission rate of 25 mg CO per second compared to a cruising emission rate of 10 mg CO per second. The average emission rate during deceleration is 3.8 mg CO per second, and during idling the emissions are only 1.1 mg CO per second. Thus, the emission rate during acceleration is more than an order of magnitude greater than the emission rate during idling. For the 1996 Oldsmobile Cutlass, the numerical values of the emission rates are different; however, the relative emissions are approximately similar. The average emission rate during acceleration is larger than the average emission rate during cruising, although the difference is less pronounced than for the 1999 Ford Taurus. The average acceleration emission rate of 16 mg CO per second is approximately two orders-of-magnitude greater than the average idling emission rate of only 0.2 mg CO per second.

Although not shown here, similar findings are obtained for NO and HC emissions. The average emissions are generally higher for acceleration than for any other mode, with cruising typically having the second highest emission rate followed by deceleration and idle.

A summary of the modal distribution of travel time, travel distance, fuel use, and emissions for an average trip on Miami Blvd is given in Figure 7. The summary is based upon a total of 60 one-way runs made with the Cutlass in Spring of 2000. Approximately 15 percent of the total travel time is associated with idling. Since the speed is zero during idling, no distance is traveled during this mode. The fuel use during idling is approximately five percent of the total fuel use compared to 15 percent of the total travel time. Less than five percent of the emissions of any of the pollutants occurs during idling. In particular, the emissions of CO during idling are so low that they are not visible in the graph. In contrast, although acceleration constitutes only approximately 15 percent of the trip in terms of total time or distance, The emissions during acceleration contribute approximately 30 to 40 percent of the total emissions of each of the pollutants measured and are comparable to the cruising emissions even though cruising

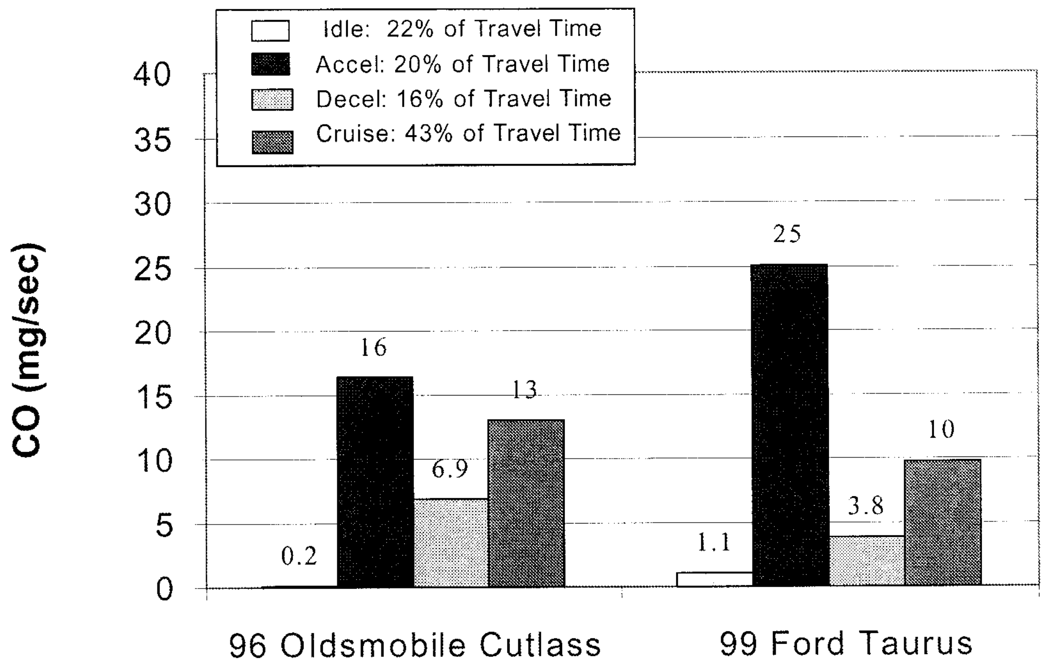

Figure 6. Analysis of Average Modal Emissions for a 1996 Oldsmobile Cutlass and a 1999 Ford Taurus.

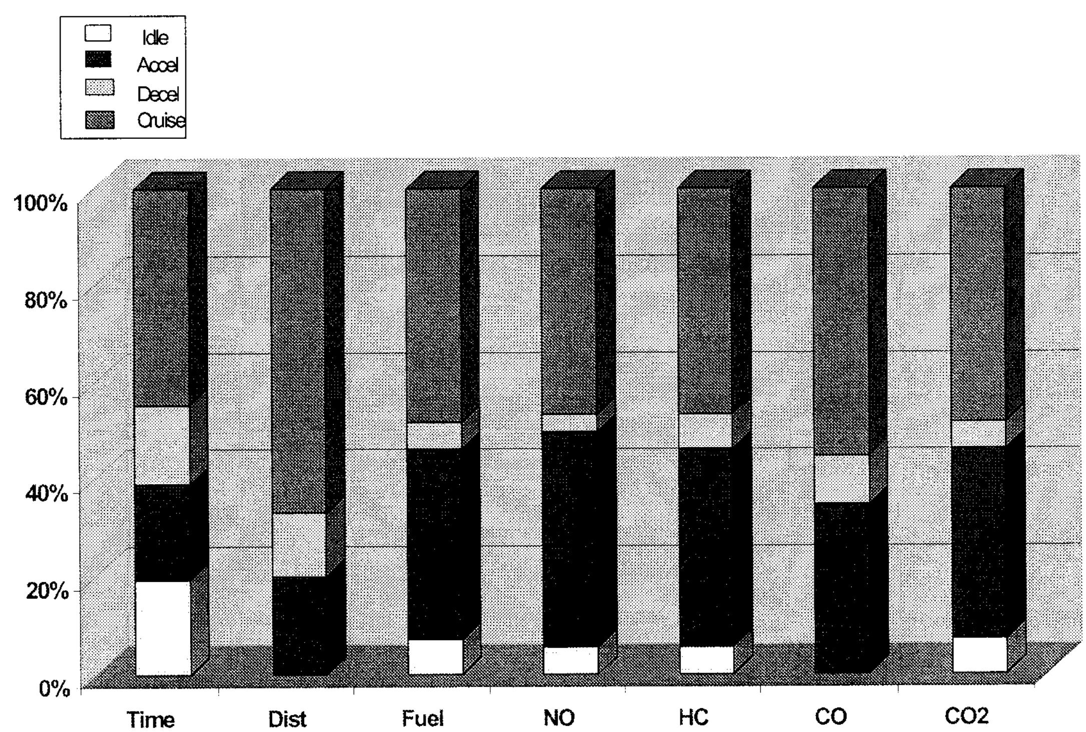

Figure 7. Distribution of Travel Time, Distance, Fuel Use, and Emissions by Driving Mode.

comprises approximately 50 percent of the total time and 70 percent of the total distance. The distributions in Figure 7 indicate that if emissions associated with accelerations could be reduced, such as by reducing the number of accelerations and, in particular, the small number of accelerations that have the highest emission rates (e.g., at Alexander Drive or Angier Avenue), then the overall trip emissions could be substantially reduced without requiring any change in the total miles traveled.

CONCLUSIONS AND FUTURE WORK

This project focuses on measurement of on-road vehicle emissions under real-world driving conditions for the purpose of evaluating the effect of traffic signal timing and coordination on emissions. At this time, a number of pilot studies have been conducted which have successfully demonstrated the use of a new portable on-board emissions measurement system. As part of this work, protocols have been developed regarding field deployment of the instrument and regarding data analysis. A substantial amount of activity has been focused on developing methods to analyze and interpret the data. It is critical to be able to analyze the data in a timely manner because of the large amount of data obtained and the need to obtain feedback regarding measurement results in order to identify potential hotspots or situations requiring special attention in terms of study design or instrument calibration and zeroing.

The data collected in this project are consistent with the hypothesis of this work that traffic signalization can have a significant impact on emissions. Based upon the vehicles tested to date in this project, a general finding is that the average emission rate during acceleration is substantially higher than the average emission rate during other driving modes of cruise, deceleration, and idle. In particular, the average emission rate during acceleration is typically an order-of-magnitude or more greater than the emission rate during idling. This finding is contrary to conventional wisdom of many transportation and air quality planners and policy makers, who for years have been operating under the assumption that idling emissions are very high compared to emissions during vehicle movement. The conventional wisdom has been based upon extrapolation of the Mobile5 emission factor model, which is based upon driving cycle data and not upon idling emissions data. It should be noted that the vehicles tested in this project tend to be newer vehicles and all vehicles tested in this project have an on-board computer and OBD data port.

A key benefit of the portable on-board emissions measurement device is that data are obtained simultaneously regarding vehicle activity and emissions. It is clear from the speed versus time and emissions versus time traces that peaks in emissions are strongly associated with accelerations. Accelerations are strongly influenced by signalization or other traffic control measures at intersections. In particular, accelerations from zero speed to cruising speeds typical of a primary arterial (e.g., 45 mph) can lead to substantial contributions to total trip emissions. The data obtained in this project provide important insight into the micro-scale effect of traffic control measures on real world, on-road emissions.

Although not reported here, other activities in this project have included: (a) evaluating the effect of different drivers on emissions; (b) comparing different vehicles of the same year, make and model; and (c) comparing vehicle activity and emissions before and after signal coordination changes on one corridor.

The empirical approach employed in this project to evaluating the real world effect of traffic control measures on emissions can be extended beyond evaluation of traffic signalization. For example, empirical "before and after" studies can be conducted for any type of facility improvement or control measure, whether it be modification of roadway geometry or replacing signalized intersections with roundabouts, just to name two examples out of many possibilities. Policy makers and decision makers are likely to find empirical approaches to development of real world on-road emission factors and evaluation of real world changes in emissions associated with various transportation improvement and management strategies to be increasingly attractive and critical to accurate assessment of air quality impacts.

As part of ongoing work we will be continuing data collection on the two pilot corridors and will also be designing and implementing a more extensive "evaluation study" involving a larger number of vehicles.

For those interested in following the progress of this project, information is available on our project web site at http://www4.ncsu.edu/~frey/emissions/.

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