Implications of Measured In-Use Light Duty Gasoline Vehicle Emissions for Emission Inventory Development at High Spatial and Temporal Resolution

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ABSTRACT

The objective here is to evaluate the intra-and inter-vehicle variability in real-world light-duty gasoline vehicle emissions and assess implications for development of onroad vehicle emission inventories. A field study was conducted to characterize variability for selected vehicles for both total emissions and emission rates by routes, time of day, road grade, and among vehicles. Real-world data were collected using a portable emission measurement system (PEMS). The study area included two origin/destination pairs, each with three alternative routes. On an average trip basis, the total NO emissions differed by 24% when comparing alternative routes and increased by 19% when comparing congested versus less congested travel time periods. Positive road grades were associated with approximately a 20 percent increase in localized emissions rates, while negative road grades were associated with a similar relative decrease. The average NO vehicle-specific power based modal emission rates differed by more than 2 orders of magnitude when comparing different vehicles. The results demonstrate that alternative routing can significantly impact trip emissions. Road grade should be taken into account for localized emissions estimation. Furthermore, there are locations on the roadway network where one or more vehicles may have high proportions of its total trip emissions. The magnitude and location of these emissions hotspots can vary by vehicle, pollutant, and time of day. Micro-scale modeling may be needed to capture episodic emissions such as for near-road short-term human exposure assessment. Implications for emission inventory development are discussed.

INTRODUCTION

Highway vehicle emissions contributed significantly to the overall air pollution in the US. For example, gasoline-fueled highway vehicles contributed 55%, 36%, and 28% to the estimated U.S. national emissions of CO, NO_x, and HC, respectively.[1] An accurate estimation of highway vehicle emissions is critical for effective air quality management.[2, 3]

Real-world vehicle fuel use and emissions are episodic in nature. Substantial portions of total trip fuel use and emissions can often be attributed to a small proportion of trip time, such as the portions associated with accelerations.[4] For example, for a particular light duty gasoline vehicle driven on a specific commuting route, more than 90% of NO emissions occur over less than 30% of the time of the trip. Furthermore, because of traffic flow patterns influenced by traffic control measures and roadway geometry, there may be specific locations on the roadway network that are conducive to localized high emissions. Such locations may be "hot spots" for high fuel use and emissions that could be the focus of traffic control strategies in order to reduce both local and total trip emissions.

Fleet-average emission factor models (EMFs) such as MOBILE6 can be used for estimation of emissions at the macro (e.g., urban) or meso (e.g., trip or corridor) scale. However, these meso-scale models cannot capture the localized effect of episodic events such as high acceleration,[3] which typically lead to a hotspot in emission. Thus, there are situations in which different temporal and spatial resolution of data is needed. For example, for use as input to an air quality model, emissions estimated for grid squares on the order of kilometers and on a time scale of an hour may not enable detailed insights into hotspots at a link basis, but could be influenced by such hotspots. In contrast, near roadside human exposure for pedestrians, or children in playgrounds near the road, will vary temporally and spatially. Human exposure is subject to the temporal and spatial distribution of vehicle emissions. Thus, emissions estimates at high temporal resolution (e.g., several seconds to half a minute) along the roadway are needed.

The objectives here are to identify the key emissions influencing factors at high temporal resolution, characterize the intra-/inter-vehicle variability in emissions, and assess the implications of development of highly temporally and spatially resolved vehicle emission inventories.

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METHODOLOGY

The methodology used here includes experimental design for real-world vehicle in-use data collection, field data measurements, quality assurance, and analysis of data. The methods used for data analysis include empirical comparisons, Vehicle-Specific Power (VSP)-based modal model, and temporal and spatial analysis.

Vehicle activity, fuel use, and emissions data for 10 vehicles operated by each of three drivers were collected on one or more of three alternative routes for each of two Origin/Destination (O/D) pairs, for both travel directions on each route and for morning and afternoon peak travel periods. The details regarding the experimental deign for data collection are given elsewhere.[5] A total of 230 hours of second-by-second data for more than 9000 vehicle miles traveled were collected using a portable emission measurement system (PEMS).

The field data collected for this study underwent a quality assurance process. Known errors associated with on-road data collection such as "auto-zeroing" were screened out and corrected if possible before being used for further data analysis.[5] The "auto-zeroing" refers to time periods of approximately 30 seconds during which the gas analyzer automatically measures the ambient air every ten minutes in order to prevent instrument drift. The quality assured data were combined with road grade estimates to develop a final database. Road grade was estimated using a Light Detection And Ranging (LIDAR) data-based method.[6]

In order to characterize the intra-vehicle variability in emissions, emissions were compared on a route basis for a given time of day, vehicle, and driver. Actual measurements of onroad emissions were used for these purposes.

VSP accounts for power demand, rolling resistance, road grade and aerodynamic drag and can be estimated based upon speed, acceleration and road grade.[9] VSP explains a substantial portion of variability in the rate of fuel use and tailpipe emissions.[9-11] VSP may be estimated generically for a typical light duty vehicle based on representative coefficient values:[10]

$$VSP = 0.278v\left[0.305a + 9.81\left(\sin\left(a\tan\left(\frac{r}{100}\right)\right)\right) + 0.132\right] + 0.0000065v^3 \tag{1}$$

where:

v = speed (km/h)
a = acceleration (km/h/s)
r = road grade (%)
VSP = Vehicle Specific Power (kw/ton)

In order to assess the effect of road grade on fuel use and emissions rates and inter-vehicle variability in emissions, a VSP-based modal model was used.[11] The VSP-based modal model defines 14 VSP modes based corresponding VSP values, as shown Table 1. Average modal fuel use and emissions rates were estimated for each of the 14 modes for a given vehicle.

To evaluate the effect of road grade on fuel use and emission rates, three cases were analyze, referred to as Cases *a*, *b* and *c*. The purpose of Case *a* is to evaluate the effect of only negative road grade on fuel use and emissions; the purpose of Case *b* is to evaluate the effect of only positive road grade on fuel use and emissions; and the purpose of Case *c* is to evaluate the overall effect of both negative and positive road grades on fuel use and emissions For each case, fuel use and emissions were estimated using the VSP-based modal emission models. Fuel use and emissions were then compared with and without consideration of road grade when calculating VSP, i.e., by substituting the *r* in Eq (1) with actual or zero values. For Case *a*, fuel use and emissions were estimated assuming that road grade was zero, and compared to estimates based on actual road grade, only for segments that have negative road grade. For Case *b*, fuel use and emissions were estimated assuming that road grade was zero, and compared to estimates based on actual road grade, only for segments that have positive road grade. For Case *c*, fuel use and emissions were estimated assuming that road grade was zero, and compared to estimates based on actual road grade, for the entire route. Three routes in the study area were chosen for this study, including Route 1, Route 2, and Route 3. These routes have the same O/D pair, i.e., North Raleigh to Research Triangle Park in North Carolina.

For characterization of inter-vehicle variability in emissions, modal emission rates among vehicles for the same mode were compared.

The spatial and temporal distributions of emissions and fuel use were evaluated using both time- and distance-based analyses.

For time-based analysis, mass emission rates were recorded from field data on a second-by-second basis for each point in time of a single run. There is autocorrelation in the second-by-second emission rates because of the response time of the measurement sensors in responding to changes in exhaust gas concentration and dependence of vehicle activities and emissions in a given second on vehicle activity and emissions in previous seconds. In order to reduce the influence of autocorrelation on emissions estimates, [5] emission rates were averaged based on consecutive (not rolling) averages. The averaging time was 12 seconds for CO, HC, and CO_2 emission rates (and fuel use rate) and 18 seconds for NO emission rates. These averaging times were selected so as to be larger than approximately three multiples of the time constant for instrument response to changes in concentrations.

For distance-based analysis, a mass emission per distance was obtained for individual segments for a single run. A roadway segment is defined to be 0.1 mile long. A run is a single trip on a given route. Hotspots in emissions and fuel use were identified for given routes. An emissions "hot-spot" is defined as a location where the peak emission rate is statistically greater by a factor of 2 than the average emissions over the entire trip, either using a unit of mass per time or mass per distance.[4]

In order to characterize average distance-based emission rates at various locations on a route, the mass emissions per distance for the same roadway segment were averaged over multiple runs. The number of data points that coincide with a roadway segment depends on the vehicle speed and varies from one run to another. On average, for a given vehicle in a 0.1 mile road segment for the selected route, there are 7 seconds of data, but for 22 percent of the segments, the travel time per segment is 12 seconds or more, and for 15 percent of the segments, the travel time is 18 seconds or more. Thus, the per-segment travel times are approximately comparable to the desired averaging time, in some cases.

For illustrative purposes, three vehicles were used as the basis of case studies. These include a 2005 Chevrolet Cavalier with a 2.2 liter engine, a 2005 Dodge Caravan with a 3.3 liter engine, and a 2005 Chevrolet Tahoe with a 5.3 liter engine. Example results are presented for NO emissions. NO is a precursor of tropospheric O_3 formation.

RESULTS AND DISCUSSION

This section describes the results of empirical comparisons of emissions by routes and time of day, comparisons of the effect of road grade on emissions, characterization of inter-vehicle variability in emissions, and spatial and temporal analysis of vehicle fuel use and emissions, including both time- and distance-based data analyses.

Empirical Comparisons

For a given O/D pair, on average, a different choice of route caused 14 to 46% difference in rates, and 14 to 41% difference in totals for fuel use and emissions based upon empirical data as shown in Table 2. The difference in fuel use and emission rates is mainly attributed to the average trip speed. For example, Figure 1 shows the average fuel use and NO emission rates for individual runs as a function of the average vehicle speed for each run.

Travel at a particular time of day and for a particular direction is usually associated with varying traffic flow conditions from one run to another. In general, for a given O/D pair, the average travel time in the afternoon appears to be longer than that in the morning, and for a given time of day, one travel direction appears to have longer travel time than the other direction for a given O/D pair. The latter is partly because the distance for different travel directions for a given O/D pair is different. The peak travel direction is the one that has slower average speed, which is calculated by the distance divided by the travel time. As shown in Table 2, the empirical average fuel use and emission differed by time of day (difference of peak travel direction relative to off-peak travel direction) by approximately 7 to 32% in rates and 9 to 33% in totals depending on pollutant and fuel use, with fuel use having the least variation.

Compared to the slowest average speed (longest average travel time), the difference in average travel time for alternative routes connecting the same O/D pair varied from 3% to 38%, and for average speeds varied by 4% to 45%, depending on the O/D pair and time of day. This indicates that the choice of route for a given O/D pair and time of day will make a difference in total travel time, which will affect the total fuel use and emissions. On average, the average speed and the total travel time for a given route and time of day vary by 10% when comparing different runs for the same travel direction.

Road Grade

Road grade plays a key role in calculating VSP, and thus the VSP-based modal emissions, as shown in Eq (1). Ignoring negative road grade overestimates VSP and emissions rates, while ignoring positive road grade underestimates VSP and emissions rates. The results of the evaluation of the effect of road grade on fuel use and emissions are presented in Table 3.

For the segments with negative road grades (Case *a* in Table 3), ignoring negative road grade overestimates total fuel use and emissions by 14 to 24% depending on the pollutant and route.

For the segments with positive road grades (Case *b* in Table 3), ignoring positive road grade underestimates total fuel use and emissions by 11 to 20%, also depending on the pollutant and route.

For the entire route, ignoring road grades does not significantly affect the estimates of total emissions. The difference in total emissions between with and without consideration of road grade is within 3%. This is because the effect of positive road grades is compensated by that of negative road grades for the case considered.

Vehicle

Each of the 10 vehicles tested in this study were characterized by a fuel use and emissions "fingerprint" based on average rates for each of 14 VSP modes. Table 4 summarizes the inter-vehicle variability based on the ratio of the highest to lowest observed rate among the ten vehicles for a given mode and quantity (either fuel use or emission rate). These ratios varied from 2.0 to 730 depending on VSP mode and quantity, indicating the existence of significant inter-vehicle variability. NO exhibits the highest variation and fuel use the least. In general, the magnitude of fuel use rates increases as the size of engine and the weight of vehicle increase.

For a given VSP mode, the inter-vehicle variability in fuel use is mainly due to the inter-vehicle variability in vehicle weight. For example, the ratio of the highest to the lowest fuel use rate for each mode is of similar magnitude as the ratio of highest to lowest vehicle weight except for Mode 3, as shown in Table 4. Larger vehicles are associated with more fuel consumption. The ratio for fuel use for Mode 3 is more than twice as high as that for vehicle weight. Fuel use is not sensitive to non-positive VSP.[11] Mode 3 includes vehicle idling. Fuel use at this mode was influenced by factors such as engine size (Typically, the engine size is proportional to the vehicle weight). Thus, the inter-vehicle ratio for fuel use at Mode 3 appeared to be larger than other modes.

For the exhaust gases, vehicle weight is only one influencing factor. Vehicle mileage, engine combustion efficiency, catalyst efficiency, fuel enrichment under high engine power demand, ambient conditions and others also influence the emissions. Thus, a larger ratio of the highest to the lowest mass emission rate was observed compared to fuel use rate. Moreover, the ratio of any pair vehicles differs by pollutant for a given mode, and may differ by VSP mode for a given pollutant. For example, for Mode 1, the vehicle pair with the largest NO ratio is the 1997 Dodge Caravan and the 2005 Dodge Caravan 2005; whereas the vehicle pair with the largest HC ratio is the 1997 Dodge Caravan and the 2005 Chevrolet Cavalier. For CO and for Modes 4 to 7, the vehicle pair with the largest ratio is the 1998 Plymouth Breeze and the 2005 Chevrolet Tahoe, whereas for Modes 11 and 12 it is the 1998 Plymouth Breeze and the 2000 Ford Crown Victoria. The higher ratio for CO between vehicle pair for Modes 11 to 14 compared to other modes is because the 1998 Plymouth tends to operate under fuel enrichment conditions at high engine load. Among all vehicles, the 1998 Plymouth is the highest CO emitter. For multiple modes for which the vehicle pairing and the associated weight ratio is constant, the ratio of the modes varies substantially. For example, the ratios of Modes 1 to 7 for NO vary from 72 to 731, even though they are based on the same pair of vehicles. This illustrates inter-vehicle variations on a modal basis.

Time-Based Analysis

In order to evaluate the temporal variation of vehicle emissions, time-based analysis of vehicle emissions were done by analyzing time series data for vehicle speed and emissions rates on a run basis for a given route.

Figure 2(a) presents the speed profile for a selected run on Route 1 from North Raleigh (NR) to Research Triangle Park (RTP). This trip starts from a residential area in NR on arterial roadways, continues onto an interstate freeway (I-540), and finishes on arterials and local roads in a business district in RTP. The speed profile has relatively low speeds at the beginning and end of the trip, (e.g., at elapsed times of 1 to 300 seconds, and 1050 to 1200 seconds), and relatively high speeds on the interstate (at elapsed times of 400 to 1000 seconds).

The hotspots in emissions and fuel use rates were associated with episodic events in vehicle operating conditions. For example, Figures 2(b) and 2(c) present the 18-second consecutive average NO emission rate and 12-second consecutive fuel use rate from NR to RTP, respectively. An acceleration event at elapsed times of 300 to 400 seconds is associated with an emissions hotspot for that time period. Emissions hotspots account for 17% of the trip time and 52% of the total NO emissions.

However, fuel use was not as sensitive to episodic events as NO emissions. The NO emission hotspots were associated with 22% of the total fuel consumed. One can also estimate fuel consumption hotspots, rather than emissions hotspots. Over the entire trip, there were fewer fuel use hotspots than emissions hotspots. For example, only 1%

of the trip time and 3% of the fuel use were associated with a fuel hotspot (at elapsed times of approximately 680 seconds).

Distance-Based Analysis

A distance-based analysis focused on the evaluation of the spatial variation in vehicle emissions.

As shown in Figures 3(a) and 3(b), emissions and fuel use varied by time of day. At some locations, emissions and fuel use hotspots occurred in both the morning and afternoon. However, for some locations, a hotspot that occurred at one time of day did not occur at the other. For example, at locations approximately three miles from NR to RTP, hotspots in NO emissions occurred both in the morning and afternoon because this is a ramp and vehicles are accelerating to merge onto the interstate. Approximately eight miles from NR, a hotspot was observed in the afternoon but did not occur in the morning. Conversely, a hotspot occurred in the morning but was not observed in the afternoon at 12 miles. This is due to the different traffic conditions at specific locations in different time periods. For example, there is an exit from an interstate at 12 miles. In the morning, vehicles heading for RTP exit here during peak directional congested traffic. In the afternoon, the peak traffic flow is in the reverse direction and thus this ramp is not congested. Similar to NO, average fuel use per mile also differed by time of day; however, the relative difference was smaller.

Comparing different vehicles driving on the same route for the same time of day, emissions and fuel use varied by vehicle, as shown in Figures 4(a) and 4(b) for NO emissions and fuel use, respectively. The average emissions vary among vehicles as a result of differences in vehicle weights, engine size, and other vehicle design factors. For example, the Tahoe generally has higher NO emissions than the Caravan and the Cavalier.

For a given vehicle, average emissions varied by location (roadway segments). At some locations, all vehicles produce emission and fuel use hotspots. There is variation regarding the location and importance of hotspots when assessed per vehicle. For example, when averaged over multiple runs, the Cavalier had hotspots that contributed to 31 percent of total emissions, while for the Caravan hotspots contributed to 62 percent of total emissions and for the Tahoe hotspots contributed to 48 percent of total emissions. All three vehicles produced simultaneous hotspots at approximately one percent of all road segments, leading to 5 to 7 percent of total emissions (depending on the vehicle). These common hotspots had average emissions of approximately a factor of 4.7 more than the trip average. These locations are usually associated with acceleration either on a ramp to an interstate or when leaving a signalized intersection at changes from red to green signal phase, e.g., at locations of 1.8 and 3 miles.

There were seven percent of locations where any pair of the three vehicles had hotspots in common. These contributed 10 to 30 percent of emissions, depending on the vehicle, with an average emission rate a factor of 4.3 more than the trip average. Finally, there were hotspots that were unique to a vehicle that occurred at 18 percent of all segments (for all vehicles, combined) and comprised 16 to 27 percent of trip emissions depending on the vehicle. These vehicle-specific hotspots had average emission rates a factor of 3.5 greater than the trip average.

Thus, at the few locations where there are hotspots common to all vehicles, the relative increase in emissions was higher than for hotspots that affected pair-wise combinations of vehicles or only an individual vehicle. However, the latter situations contributed more to total hotspot emissions than the former. Thus, both types of situations are likely to be important when conducting an overall assessment of hotspot emissions for fleets of vehicles operating on a route.

The ratios of the highest average NO emissions to that of the lowest average when comparing segments for a given vehicle are 1400, 5200, and 400 for the Cavalier, Caravan, and Tahoe, respectively. These ratios are 20, 5, and 12 for fuel use. Thus, there is substantial spatial variability in emissions and fuel use rates.

SUMMARY

For a given O/D pair, differences in the choice of routes for a given travel time period result in different total fuel use and emissions. Fuel use and emissions could be influenced by traffic management strategies that are based on real-time monitoring of traffic flow and delivery of travel advisories to encourage environmentally-friendly route selection.

Temporal variations in traffic conditions have significant effects on fuel use and emissions. Although an increase in average trip speed slightly increases the emission rates, the travel time is reduced by a larger proportion and the total emissions tend to be reduced. Therefore, traffic management strategies that increase average travel speeds for a given route under real world conditions tend to be preferred. However, these results are based on a specific study area and require further assessment under a wider range of driving conditions.

Road grade was shown to have significant effect on “micro-scale” fuel use and emissions and less or even insignificant effect on “meso-scale” fuel use and emissions. However, because these effects were evaluated based upon the data collected in the study area, assessment of the effect of road grade should be extended to other locations for more generalized conclusions.

Both intra- and inter-vehicle variability are significant sources of overall variation in emission rates at the micro-scale, especially at high temporal (and spatial) resolution. For example, if one must estimate short term near-roadside human exposures to support a risk assessment, there may be a need to simulate the effect of both intra- and inter-vehicle and its effect on fluctuations in local ambient concentration at specific locations and for short time periods.

For an individual vehicle, fuel use and emissions vary with location as a result of variations in vehicle operations such as acceleration and deceleration. The hotspots mainly occurred at places where high acceleration events were observed. Some hotspots are common to all vehicles, while others occur only for a subset of vehicles. Emissions hot-spots may vary by time of day. Further work is needed to compare hotspots for more pollutants.

Key implications are: (1) the spatial and temporal variations in mass per distance should be taken into account in quantification of the effect of episodic events on emissions; (2) identification of emissions hotspots can improve the accuracy of near roadside exposure and risk assessment; and (3) transportation improvement measures such as signal timing and coordination should be prioritized to reduce or eliminate hot spots in fuel use and emissions.

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KEY WORDS
Vehicle Emissions, Road Grade, ANOVA, Portable Emissions Measurement System (PEMS).

Table 1. Definition of vehicle specific power (vsp) modes.

VSP mode	Definition
1	VSP < -2
2	-2 <= VSP < 0
3	0 <= VSP < 1
4	1 <= VSP < 4
5	4 <= VSP < 7
6	7 <= VSP < 10
7	10 <= VSP < 13
8	13 <= VSP < 16
9	16 <= VSP < 19
10	19 <= VSP < 23
11	23 <= VSP < 28
12	28 <= VSP < 33
13	33 <= VSP < 39
14	39 <= VSP

Table 2. Relative difference between the highest and lowest average empirical fuel use and emissions (rates and totals) for all routes connecting the same o/d pair and time of day [a] (%)

Category	NO		HC		CO		Fuel	
	μ[b]	Σ[c]	μ[b]	Σ[c]	μ[b]	Σ[c]	μ[b]	Σ[c]
Route	18	24	18	15	46	41	14	14
Time of day	18	19	16	23	32	33	7	9

Note:

[a] For category "Route," relative difference is calculated based upon the highest to the lowest rates or totals in emissions and fuel use on a route basis;

For category "Time of day," the relative difference refers to Peak to Off-Peak consistently. The peak direction is defined as the travel direction that has a longer travel time (slower average speed) than other direction for a route. Similarly, the off-peak direction is defined as the travel direction that has a shorter travel time (faster average speed) than the other direction for a route.

[b] rate of mass per time (e.g., g/sec).

[c] total mass over the entire route (e.g., g).

Table 3. The percentage difference in estimated total fuel use and emissions between scenarios in which road grade is considered versus not considered (%).

Route	Case [a]	Segments	NO	HC	CO	Fuel
1	a	with "-" road grades	17	15	15	14
	b	with "+" road grades	-16	-12	-12	-11
	c	entire route	-0.6	0.4	0.6	0.7
2	a	with "-" road grades	21	19	19	17
	b	with "+" road grades	-15	-14	-13	-12
	c	entire route	-0.5	-0.5	-0.7	-0.9
3	a	with "-" road grades	24	24	23	22
	b	with "+" road grades	-20	-17	-16	-16
	c	entire route	-3	0.6	0.7	0.2

[a] Case *a*: For segments with negative road grades, road grade was assumed to be zero. Fuel use and emissions were estimated assuming that road grade was zero and compared to estimates based on actual road grade only for segments that have negative road grade. The estimates were done using VSP-based modal emissions models. The number in the table is the average from the three primary vehicles.

Case *b*: For segments with positive road grades, road grade was assumed to be zero. Fuel use and emissions considering road grade were compared to those not considering road grade only for segments that have positive road grade. The estimates were done using VSP-based model emissions models. The number in the table is the average from the three primary vehicles.

Case *c*: Road grade was set to zero for the entire route. Fuel use and emissions considering road grade were compared to those not considering road grade over the entire route. The estimates were done using VSP-based model emissions models. The number in the table is the average from the three primary vehicles.

Table 4. Ratio of highest to lowest average VSP modal emission and fuel use rates from the tested vehicles, and corresponding ratio of vehicle weight for the pair of vehicles with the highest and lowest indicated rates, by VSP mode[a]

VSP Mode	NO			HC			CO			Fuel		
	Rate	Wt.	VP	Rate	Wt.	VP	Rate	Wt.	VP	Rate	Wt.	VP
1	72	0.92	V7-V2	6.9	1.34	V7-V1	16.6	0.59	V5-V3	2.4	1.87	V3-V1
2	112	0.92	V7-V2	8.5	1.34	V7-V1	18.1	0.76	V5-V2	2.6	1.87	V3-V1
3	731	0.92	V7-V2	19.8	1.34	V7-V1	15.9	1.10	V5-V1	4.8	1.87	V3-V1
4	92	0.92	V7-V2	9.6	1.34	V7-V1	23.3	0.59	V5-V3	2.4	1.87	V7-V1
5	94	0.92	V7-V2	9.0	1.34	V7-V1	22.6	0.59	V5-V3	2.3	1.87	V7-V1
6	102	0.92	V7-V2	7.5	1.34	V7-V8	31.2	0.59	V5-V3	2.2	1.87	V7-V1
7	81	0.92	V7-V2	6.4	1.34	V7-V1	30.5	0.59	V5-V3	2.0	1.87	V3-V1
8	80	1.34	V7-V2	6.2	1.34	V7-V1	48.0	0.74	V5-V10	2.0	1.87	V3-V1
9	78	1.34	V7-V1	6.2	1.34	V7-V1	34.5	0.59	V5-V3	2.0	1.64	V3-V4
10	74	1.34	V7-V1	5.8	1.34	V7-V1	38.2	0.59	V5-V3	2.0	1.64	V3-V4
11	58	1.34	V7-V1	5.3	1.10	V7-V5	53.4	0.74	V5-V10	2.2	1.64	V3-V4
12	65	1.34	V7-V1	5.4	1.10	V7-V5	81.7	0.74	V5-V10	2.1	1.87	V3-V1
13	57	1.34	V7-V1	5.7	1.10	V7-V5	48.4	0.59	V5-V3	2.2	1.87	V3-V1
14	50	1.34	V7-V1	9.1	1.10	V7-V5	67.8	1.10	V5-V1	2.3	1.64	V4-V1

[a] For example, for VSP Mode 1 and NO emission rate, the ratio of the vehicle with the highest emission rate to that with the lowest is 72, and the ratio of the weight of these same two vehicles is 0.92.

Wt.- refer to weight; VP – vehicle pair (highest to lowest).

V1 – 2005 Chevrolet Cavalier with 2.2 L engine;
V2 – 2005 Dodge Caravan with 3.3 L engine;
V3 – 2005 Chevrolet Tahoe with 5.3 L engine;
V4 – 1997 Honda Accord with 2.2 L engine;
V5 – 1998 Plymouth Breeze with 2.4 L engine;
V6 – 2004 Dodge Stratus with 2.7 L engine;
V7 – 1997 Dodge Caravan with 3.3 L engine;
V8 – 2000 Dodge Caravan with 3.3 L engine;
V9 – 2002 Dodge Caravan with 3.3 L engine;
V10 – 2000 Ford Crown Victoria with 4.6 L engine.

Figure 1. Average NO emission and fuel use rates vs. average speed for individual runs of selected vehicles

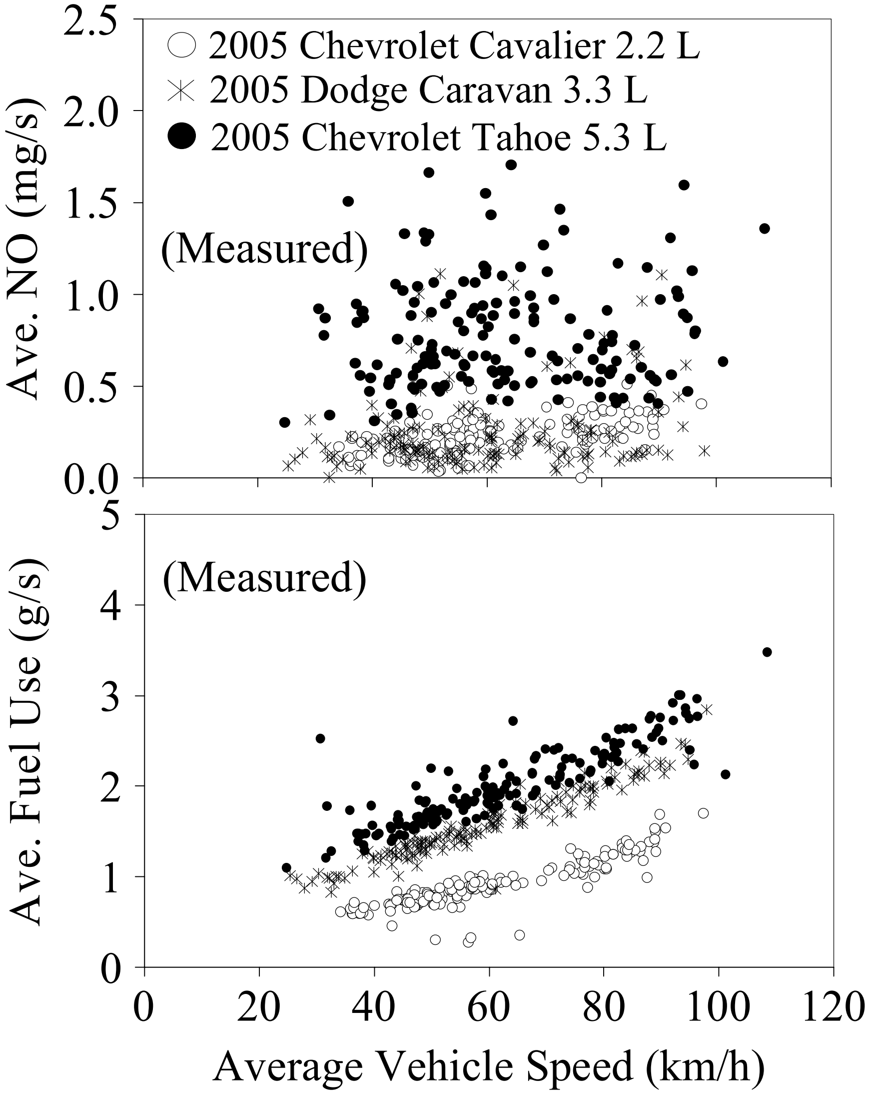
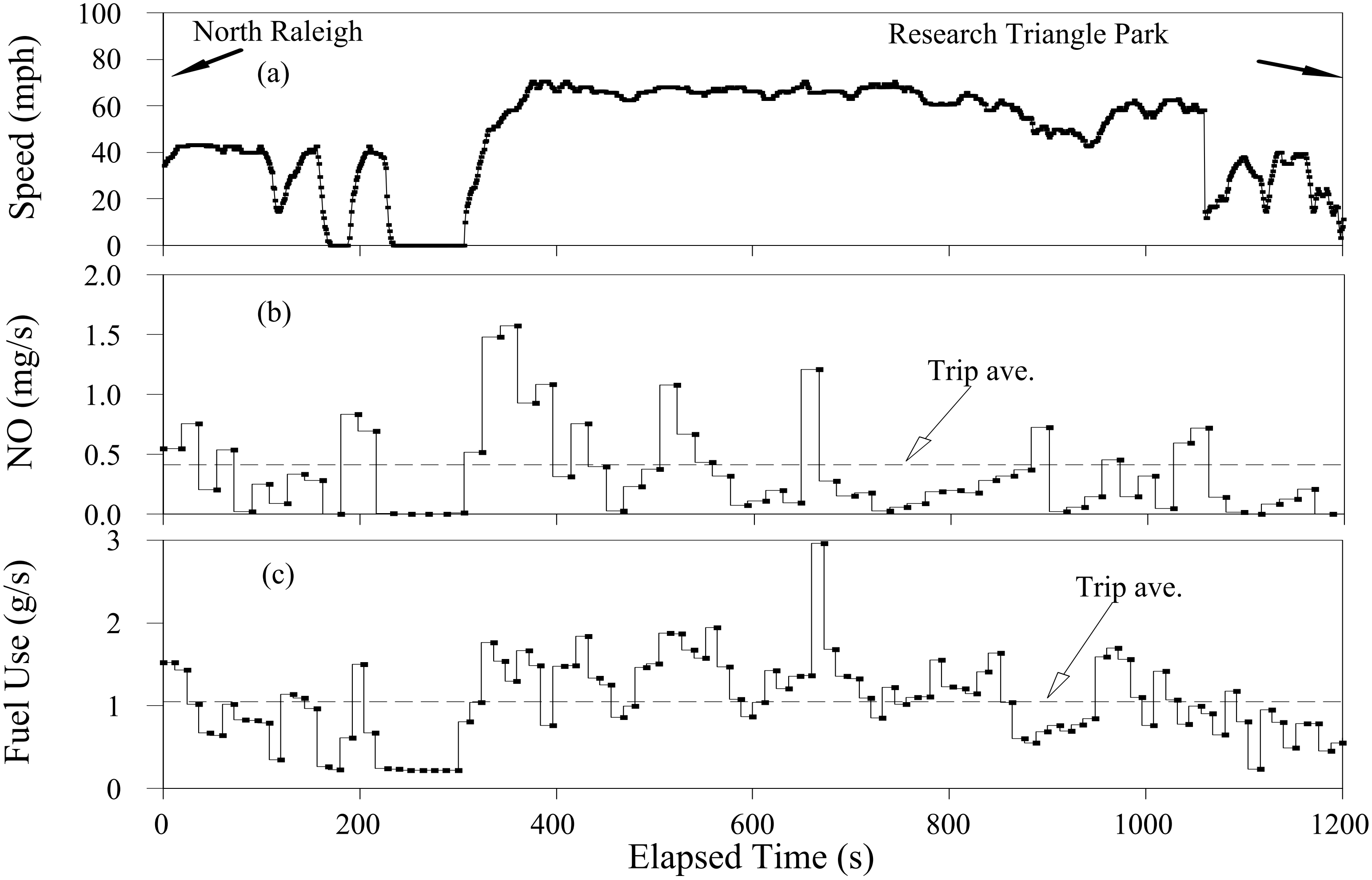
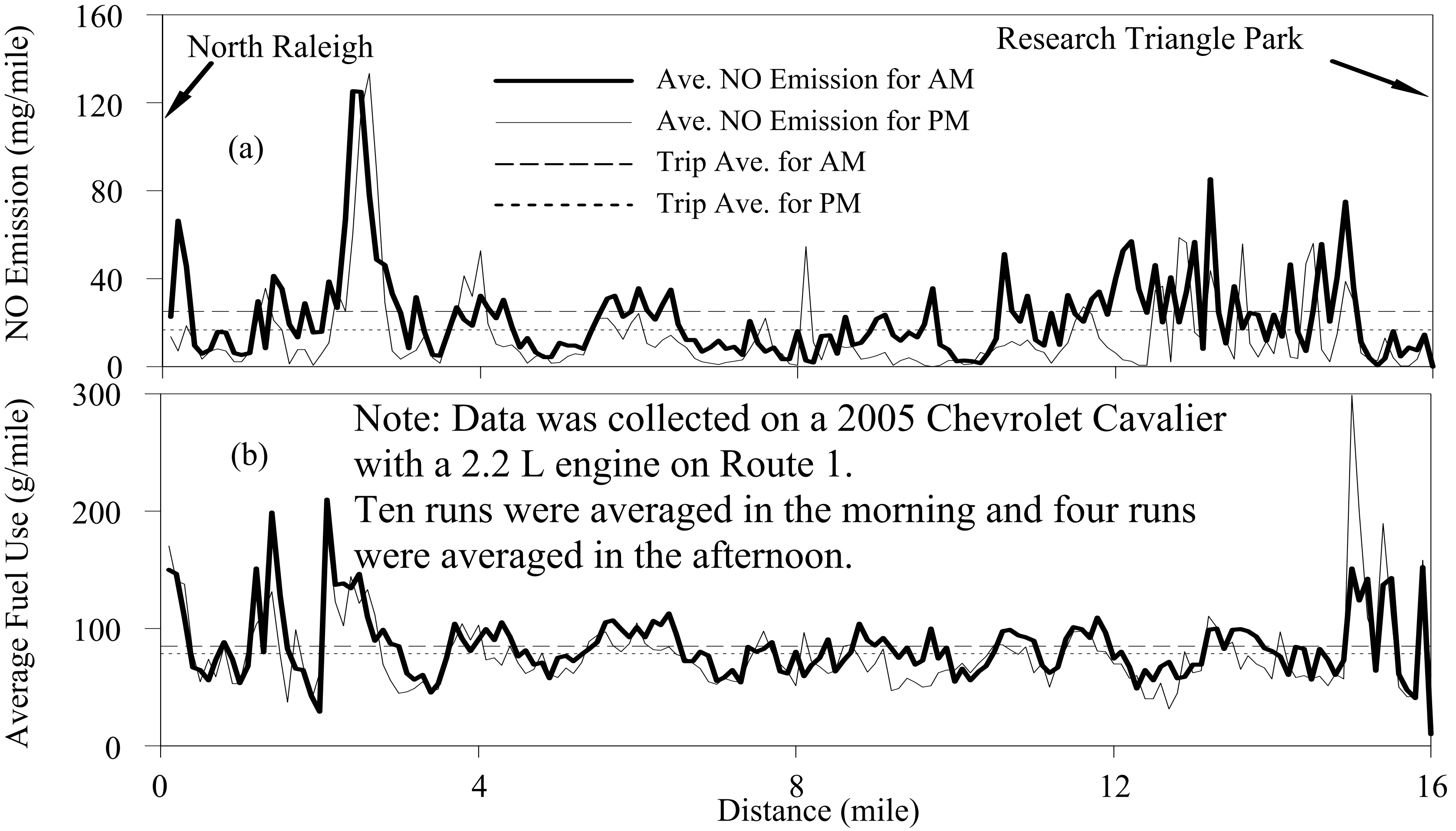


Figure 2. Speed profile and the time-averaged measured fuel use and emission rate



Note: Data were collected on a 2005 Chevrolet with a 2.2 L engine for a selected run on Route 1 in the morning. NO emissions are estimated for 18-second consecutive averages and fuel use is estimated for 12-second consecutive averages.

Figure 3. Average NO emission and fuel use rates on a distance basis for a selected vehicle and route and for morning and afternoon peak travel times



Note: Data was collected on a 2005 Chevrolet Cavalier with a 2.2 L engine on Route 1.
Ten runs were averaged in the morning and four runs were averaged in the afternoon.

Figure 4. Average NO emission and fuel use on Route 1 versus distance for different vehicles