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Emissions Reduction Through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements

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16. Abstract

The objectives of this study were to: (1) evaluate a new low-cost approach for measuring on-road tailpipe emissions of highway vehicles; (2) investigate factors that affect the amount and variability of on-road emissions, using statistical methods; and (3) devise and demonstrate methods for designing and conducting observational experiments that realistically evaluate pollution prevention strategies for on-road vehicles. Portable instruments were used for measuring carbon monoxide (CO), nitric oxide (NO), and hydrocarbon (HC) emissions and vehicle activity (e.g., vehicle speed, engine parameters) on a second-by-second basis. Data collection, quality assurance, reduction, and analysis protocols were developed. Field data collection occurred in a pilot and an evaluation phase. In total, over 1,200 one-way trips were made with more than 20 vehicles, 4,000 vehicle-miles traveled, 160 hours of data, and 10 drivers. The pilot study was used to identify key factors influencing on-road emissions and as input to the design of the evaluation study. In the evaluation study, data were collected intensively with a small number of vehicles on two corridors before and after signal timing and coordination changes were implemented. For the first corridor, changes in signal timing and coordination did not result in a significant change in traffic flow or emissions. However, substantial reductions in emissions were estimated for uncongested versus congested traffic flow when comparing travel in the same direction at different times of day. For the second corridor, there were significant improvements in traffic flow and some reduction in emissions for three of the four time period and travel direction combinations evaluated. The impact of signal timing and coordination changes with respect to non-priority movements involving cross-streets was evaluated. For the first corridor, there was no statistically significant observed change in emissions for non-priority movements. For the second corridor, there typically was a decrease in average speed and an increase in emissions for non-priority movements; however, many of the observed changes were not statistically significant. The study also demonstrated other analysis methods, including: (a) macro-scale analysis of trip average emissions and traffic parameters; (b) micro-scale analysis of second-by-second emissions and vehicle operation; (c) meso-scale analysis of modal emission rates; and (d) spatial analysis of emissions at specific locations along the corridors. Both statistical and theoretical-based approaches were evaluated. The implications of the study results for pollution prevention strategies are discussed. Conclusions are presented regarding instrumentation, protocols, analysis techniques, and case study-specific findings. Recommendations are given regarding future applications of on-board measurements.

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EXECUTIVE SUMMARY

In this study novel methods have been used for evaluating strategies aimed at preventing motor vehicle air pollutant emissions through better traffic management. Actual on-road emissions measurements were utilized in contrast to the laboratory-based dynamometer tests employed in many current projects. The primary objectives of this research were to:

1. Assemble, evaluate, and validate a new low-cost on-board emissions measurement (OEM-2100^{TM}) system;
2. Investigate factors that affect the level and variability of on-road emissions using rigorous statistical methods;
3. Devise methods for designing and conducting experiments that realistically evaluate vehicle-based pollution prevention strategies.

Objective (1) was satisfied via the procurement of two OEM-2100^{TM} portable on-road tailpipe emissions measurement systems. Objective (2) was satisfied by developing a data collection protocol, collecting on-road emissions data, and analyzing the data using graphical, statistical, and theoretical approaches. Objective (3) was satisfied by designing and conducting a real-world emissions measurement study before and after the implementation of changes to signal timing and coordination on two separate study corridors.

The project proceeded in two major phases. The first, or pilot, phase, involved preliminary deployment of the OEM-2100^{TM} with specific vehicle, driver, route, and scheduling combinations for purposes of developing data collection and reduction protocols and to develop a preliminary database for use in identifying potentially important factors influencing emissions. Based upon the lessons learned in the pilot phase, an experimental design was developed for the second, or evaluation, phase of the project. The evaluation phase focused on detailed evaluation of the change in vehicle movement and emissions associated with a change in signal timing and coordination on two corridors, each approximately two miles long.

Instrumentation. The OEM-2100^{TM} has three interfaces with a vehicle: (1) tailpipe exhaust gas is sampled; (2) engine data are downloaded via a diagnostic link; and

(3) power is obtained via the cigarette lighter, power port, or via direct connection to the vehicle's battery. The OEM provides a data stream of second-by-second engine and exhaust gas data, including vehicle speed and estimated mass emission rates of carbon monoxide (CO), nitric oxide (NO), hydrocarbons (HC), and carbon dioxide (CO_2). The device can be installed in approximately 15 minutes on vehicles with an engine diagnostic link. The OEM has been compared by others with laboratory measurements and its precision and accuracy are good. The two OEM units used in this study were compared with each other and found to provide similar results.

Data Collection. Field data collection activities include use of the OEM as well as supplemental equipment. Road grade was measured on the study corridors at one-tenth mile increments. The data were encoded into a database and synchronized with the engine and emissions data obtained from the OEM. Data regarding traffic signal timing and coordination before and after changes were made were obtained from NCDOT. Key characteristics of the study corridors, such as roadway geometry (e.g., number of lanes), speed limits, traffic control device locations (e.g., traffic signals) were recorded. A laptop computer was used for each evaluation study run to record temperature and humidity, and information regarding each vehicle tested. Events during trips were also recorded using a laptop computer, including the time at which the vehicle crossed the centerline of key intersections or entered queues.

Study Design. This was a before-and-after study without control groups. A series of multiple runs with each of two primary vehicles was conducted before new signal timing and coordination plans were implemented, followed by a similar series of multiple runs afterwards. A variety of potential "threats to validity" of this type of study were identified and evaluated. Some factors could be controlled in the before and after studies, such as selection of the same vehicle and driver. Other factors are not controllable, such as ambient weather conditions or systematic changes in traffic volumes. Changes in traffic volume were judged to be sufficiently small over the course of the study as to be negligible. In contrast, weather conditions, although not controllable, are observable and data were collected for these.

The pilot study involved vehicle selection, time of day selection, route selection, and driver selection. The pilot study included approximately 400 one-way vehicle runs involving 2,060 vehicle miles traveled, 68 hours of data collection, 10 different drivers, and over a dozen different vehicles. A key lesson learned from the pilot study is that there is a substantial amount of inter-run variability in measurements take with the same vehicle on the same corridor, direction of travel, time of day, and driver. The pilot study highlighted the need for obtaining a sufficient number of repeated runs so that mean emissions can be estimated with a reasonable degree of precision.

Similar to the pilot study, the evaluation study involved selection of sites, routes, vehicles, drivers, fuels, and time of day. The evaluation study focused on intensive data collection with two primary vehicles on each of two corridors, supplemented with some data from secondary vehicles. A total of 824 one-way runs representing 100 hours and 2,020 vehicle miles of travel were conducted involving two primary drivers, two secondary drivers, and six vehicles on one corridor and four vehicles on the other. In addition, some data were collected for "non-priority" runs on each of the two evaluation corridors. A non-priority run involves entry onto the corridor via a side street and exiting to another side street. The purpose of the non-priority runs was to evaluate what impact changes in through movement might have with respect to cross-traffic.

Data Reduction and Screening. A substantial effort was devoted during the study to the development of data reduction and screening protocols. Data collected from the OEM, from the laptop computer used in the field, and from other sources (e.g., measurement of road grade) were integrated into a single combined vehicle emissions and traffic data file. The data were screened for errors that would impact the quality of the data. Errors for which the data were screened include: (a) abnormal traffic conditions unrelated to the study objectives (e.g., occurrence of an accident that slowed traffic); (b) field condition errors (e.g., "zeroing" of the instrument in an area with high ambient levels of pollutants); (c) laptop computer errors, such as loss of battery power; (d) engine scanner errors, such as loss of data communication with engine diagnostic link in the vehicle; (e) gas analyzer errors, such as failure of the gas analyzer control head to update reported measured values; (f) negative emission values, such as might occur with unacceptable instrument drift or improper zeroing of the instrument; and/or (g) synchronization errors, such as occurred when there was a blockage in the gas sampling line leading to a delayed gas analyzer response compared to the engine scanner response.

The run-average emission estimates reported by the OEM device are reasonably robust to some error in synchronization of the engine scanner and gas analyzer files, and synchronization problems were corrected without loss of data. The most common problems that resulted in loss of data were, in descending order, engine scanner problems, gas analyzer problems, and laptop computer problems. For the evaluation study, 89 percent of the attempted field measurement runs resulted in a valid data file.

Methods for data reduction were developed to enable estimation of vehicle position along the corridor at any time during the run. Road grade was estimated corresponding to the vehicle position. A procedure was developed for calculating emissions for four driving modes: idle; acceleration, deceleration, and cruise. A procedure was developed for calculating control delay and the number of stops. To support micro-scale assessments, procedures were developed for calculating the equivalence ratio, which is a non-dimensional measure of the fuel-to-air ratio in the engine, and engine power demand.

Exploratory Analysis of Data. After collecting, screening, and reducing data from field measurements, an exploratory analysis was conducted to understand variability in vehicle emissions and to identify key potential explanatory variables. The first step was to visualize data in the form of time traces for vehicle speed, emissions of CO, NO, and HC, and other data collected or reported by the OEM on a second-by-second basis. By inspection of the time traces, it was possible to identify qualitatively situations that tend to produce high emissions, such as accelerations. Statistical methods, including Analysis of Variance (ANOVA) were employed. Based upon ANOVA, it was determined that the time and direction of vehicle travel, average speed, and in some cases other variables may have an important relationship with emissions. Some variables that were identified by ANOVA as significant in some cases, such as the use of air conditioning, driver, and date, were evaluated more thoroughly using the Kolmogorov-Smirnov test and were typically found by that test to be insignificant. Key potential explanatory variables were reviewed in detail for each of NO, HC, and CO emissions.

Multicomparison tests were done to confirm the importance of direction and time of travel as important explanatory variables. Non-parametric regression analysis was done to identify trends of individual vehicle emissions with respect to average speed, average temperature, and average humidity where appropriate. In one case, average NO emissions were shown to decrease with an increase in average humidity, which is consistent with expectations regarding how NO emissions should be sensitivity to humidity. Average HC emissions were typically found to decrease with an increase in average speed, to increase with an increase in average temperature, and to decrease with an increase in average relative humidity. Average CO emissions were found to decrease with an increase in average speed. However, there is also a large amount of variability in the trends. These results are specific to the conditions under which the data were collected, and may not extend to ranges of the explanatory variables that were not observed (e.g., to average speeds higher or lower than those observed in this study).

There can be substantial inter-vehicle variability in emissions even for vehicles of the same model year, make, and model. For example, a total of six different 1999 Ford Tauruses and four 1996 Oldsmobile Cutlasses were tested, primarily during the pilot study. There were cases with at least one pollutant for each of these two types of vehicles where at least one of the measured vehicles was significantly different than the others with respect to trip average emission rates. Variation in emissions between vehicle makes and models were also assessed. There is typically more variability in emissions when comparing vehicles of different make and model than when comparing vehicles of the same year, make, and model. For a given vehicle, CO emissions typically had the largest run-to-run variability compared to NO and HC.

Average emissions for any given vehicle vary with different driving modes. Typically, emissions on a mass per time basis are highest during acceleration and tend to decrease, in descending order, for cruise, deceleration, and idle. Depending on the vehicle and pollutant, there can be an order-of-magnitude difference in the average emissions during acceleration versus idle.

Vehicle emissions are influenced by traffic flow characteristics. However, some vehicles are influenced differently than others. For example, some vehicles displayed an increase in average NO emissions as average speed increased, while others displayed the opposite trend. For average HC and CO emissions, the trends were qualitatively similar among different groups of vehicles although there were some quantitative differences.

Average HC emissions generally decreased as average speed increased, as did average CO emissions.

Road grade was investigated as a potential explanatory variable using a statistical multicomparison method. Road grade varied within approximately plus or minus five percent on the two evaluation corridors. For one vehicle, the Chevrolet Venture, there was a clear trend of an increase in average NO emissions with an increase in positive road grade. However, in all other cases evaluated, there was no clear significant relationship between emissions and road grade. The effect of road grade may have been relatively small because the road grades may not have been steep or long enough to produce high emissions events for most vehicles.

Overall, average speed, time and direction of travel, control delay, and number of stops were found to be important factors in explaining vehicle emissions. Other factors, such as average ambient temperature, average relative humidity, and air conditioning usage, were not generally important across all datasets, but may be useful as explanatory variables in specific cases. The results are based upon a specific range of variation in data collected during this study, and should not be extrapolated to conditions not observed in this study.

Emissions Modeling Approaches. An example study was done to illustrate how macroscopic traffic parameters, such as average speed, control delay, and number of stops, are related to corridor average emissions. Vehicles were grouped based upon similarity in emissions, and statistical analysis was applied to infer relationships between emissions and each of these traffic parameters. Average HC emissions tend to decrease as average speed increases. While similar results were obtained for CO emissions, three different groups of vehicles revealed three different trends of average NO emissions versus average speed. A key factor influencing CO emissions is the occurrence of fuel enrichment. An analysis of average corridor emissions versus maximum equivalence ratio revealed the important influence that even isolated enrichment events can have with respect to total emissions.

The relationship between emissions and road grade was evaluated for a Chevrolet Venture operated on the Chapel Hill Road corridor and for a Ford Taurus operated on the Walnut Street corridor. In most cases, there was no clearly discernable relationship between road grade and emissions of either HC, NO, or CO. The lack of a clear trend is likely because the road grades were not particularly large and because other factors had more substantial influence on emissions in these cases.

Based upon the results of the exploratory analysis, a macro-scale traffic flow-based approach to estimating emissions was explored in which control delay and stops were taken into account. Typically, an increase in the number of stops and/or in the control delay was found to lead to an increase in corridor emissions.

A micro-scale approach to estimating emissions was also explored, focusing on evaluation of the explanatory power of equivalence ratio, fuel flow, and engine power demand. The results clearly indicate that CO emissions are a function of equivalence ratio, with the highest emission rates occurring only during fuel enrichment and with a linear relationship between emissions and fuel-rich equivalence ratios. NO and HC emissions tend to increase as fuel flow rate increases, although there was also a substantial amount of variability in the data. There was not a strong relationship between emissions and power demand. However, it was found that there is a positive correlation between emissions of any pair-wise combination of NO, HC, and CO. Thus, if emissions are high for one of the three, they will tend to be high, on average, for the other two. However, there is also a substantial amount of variability in emissions of any individual pollutant that cannot be explained based upon knowledge of the emission rate of either of the other two pollutants.

Effect of Traffic Signal Timing and Coordination on Traffic Flow and Emissions. The culminating point of this study was a detailed evaluation of the effects of changes in signal timing and coordination with respect to vehicle movement and emissions for the two evaluation corridors: Chapel Hill Road and Walnut Street. For both corridors, a detailed assessment was done regarding the modal emission rates of the two primary vehicles tested on each corridor.

For Chapel Hill Road, there was very good agreement between the modal emission rates of each vehicle tested during the "before" study period versus the modal emission rates measured during the "after" study. The consistency in average modal emission rates suggests that there was not a large change in uncontrollable conditions. However, when modal emissions were evaluated at a more disaggregated level, such as by time of day and direction of travel, more pronounced differences in emission rates were observed when comparing the before and after cases. The larger differences are in part because of the smaller sample sizes involved and the inherent variability in the data. In addition, there could be some influence of changes in ambient conditions or in the condition of the vehicle. Although the before and after studies were performed as quickly as possible, typically several weeks were required for each of the before study and the after study, and an interval of typically a few weeks was required to allow for NCDOT to implement the changes in signal timing and coordination. The differences in the trip duration and fraction of total trip time spent in each of the four driving modes were also characterized for the before and after measurements.

A detailed assessment was performed of the sensitivity of total emissions for a typical run for the before and after cases. The sensitivity analyses enabled prediction of expected changes in total emissions for the corridor if the modal emission rates remained constant in both the before and after studies. Furthermore, the sensitivity analyses provided insight into the relative importance of changes in observed emission rates, changes in observed trip duration, and changes in observed fraction of total trip time spent in each driving mode, with respect to the overall change in emissions. Changes in observed modal emission rates were substantial in some cases. If modal emission rates had not changed, then changes in trip duration would be the most important factor influencing changes in trip emissions. Changes in the fraction of time spent in each driving mode for a given trip duration had only a modest effect on total trip emissions in most cases.

The Chapel Hill Road corridor that was evaluated was highly congested during the rush hour peak time and direction. Changes in signal timing and coordination resulted in relatively little improvement in traffic flow. Therefore, there was relatively little change either observed or predicted in emissions in most cases. A summary of the results is given in Table ES-1. For the Ford Taurus, very small changes were observed with regard to trip duration, average speed, control delay, or number of stops, and none of the observed changes were statistically significant. Therefore, there was no substantial improvement in traffic flow. Typically, there was less than a plus or minus 20 percent change in emissions. However, even though the change in traffic flow in the afternoon

Table ES-1. Summary of Key Findings for Chapel Hill Road Before and After Comparisons: Percentage Change in Traffic Flow Parameters and Overall Change in Emissions[a]

	Ford Taurus				Chevrolet Venture			
Time Period	Morning		Afternoon		Morning		Afternoon	
Direction	North	South	North	South	North	South	North	South
Trip Duration[b]	+10	-5.9	+7.8	-13	+40	-5.7	-3.5	-3.6
Average Speed[b]	-5	+9	-5	+19	**-30**	+6	+2	+3
Control Delay[b]	+2	-17	+33	-30	**+54**	-25	-17	-21
Total Stops[b]	+9	-37	-4	-28	**+68**	-43	+1	-8
HC Emissions[c]	Inc	Dec	Dec	Dec	S. Inc.	Insig	Insig	Dec
NO Emissions[c]	Inc	Dec	Insig	S. Dec.	S. Inc.	Insig	Insig	Insig
CO Emissions[c]	Inc	Dec	Insig	S. Dec.	S. Inc.	Dec	Insig	Dec

[a]Comparisons of traffic flow are based upon observed data. Comparisons of emissions are based upon predicted comparisons of total emissions in which emission factors are held constant in the before and after case but in which the time distribution of driving modes and the trip durations varies as observed..

[b]Percentage average change for the after case with respect to the before case. Statistically significant changes are shown in boldface type for average speed, control delay, and total stops.

[c]Qualitative change in average emissions for the after case compared to the before case. Insig. = insignificant change (less than plus or minus 5 percent); Dec = decrease; S.Dec = Substantial decrease (e.g., more than minus 20 percent); Inc = Increase; S.Inc. = Substantial Increase (e.g., more than plus 20 percent).

time period and southbound direction was not statistically significant, there was an indication that traffic flow improved somewhat, because it appeared that average speed increased, control delay decreased, and the number of stops decreased. For this case, a decrease in NO and CO emissions of more than 20 percent each was estimated.

For the Chevrolet Venture deployed on Chapel Hill Road, there was one time period and direction combination in which there was a statistically significant degradation in traffic flow accompanied by a substantial increase in emissions of all three pollutants. However, for the other three time/direction combinations, there was relatively little change in either traffic flow and emissions.

Spatial Analysis and Emissions Hotspots. Even though average emissions may not change over the entire length of the corridor, it is possible that there can be specific locations on the corridor that experience substantial changes in emissions. A spatial analysis of average speed and average emissions for each one-tenth of a mile increment along the corridor was performed. In several cases for each of HC, NO, and CO emissions, there were specific locations along the corridor at which there were statistically significant increases or decreases, even though the trip average emissions did not change substantially. Thus, it is possible to identify emissions hotspots and to identify specific locations where roadway geometry or traffic control measures may be influencing emissions. Emissions hotspots were typically associated with local increases in average speed, such as at an intersection as vehicles accelerate from a stop or delay. For example, there was a bottleneck on the Chapel Hill corridor at Aviation Parkway that produces an emissions hotspot as vehicles accelerate leaving the intersection in the peak direction of travel.

Trade-Offs with Non-Priority Movements. A limited amount of data were collected for vehicle movement along non-priority runs on Chapel Hill Road, involving entry to and exit from the corridor along side streets. However, a relatively small number of measurements were made for nonpriority movements and there was substantial variability in the measurements. Overall, it does not appear that there was a substantial change in emissions for nonpriority runs for Chapel Hill Road.

Effect of Traffic Congestion on Emissions. Because traffic flow on Chapel Hill Road is primarily in one direction during each peak travel period, it is possible to compare emissions for the same direction of travel under congested and uncongested conditions simply by comparing morning and afternoon data, as indicated in Table ES-2. Most vehicles travel northbound during the morning and southbound during the

Table ES-2. Summary of Key Findings for Chapel Hill Road Uncongested and Congested Comparisons: Percentage Change in Traffic Flow Parameters and Overall Change in Emissions[a]

	Ford Taurus		Chevrolet Venture	
Direction	North	South	North	South
Trip Duration[b]	-56	-60	-43	-44
Average Speed[b]	**+118**	**+61**	**+137**	**+64**
Control Delay[b]	**-77**	**-78**	**-80**	**-61**
Total Stops[b]	**-83**	**-75**	**-84**	**-80**
HC Emissions[c]	S. Dec.	S. Dec.	S. Dec.	S. Dec.
NO Emissions[c]	S. Dec.	S. Dec.	S. Dec.	S. Dec.
CO Emissions[c]	S. Dec.	S. Dec.	S. Dec.	S. Dec.

[a]Comparisons of traffic flow are based upon observed data. Comparisons of emissions are based upon predicted comparisons of total emissions in which emission factors are held constant in the uncongested and congested case but in which the time distribution of driving modes and the trip durations varies as observed..

[b]Percentage average change for the congested case with respect to the uncongested case. Statistically significant changes are shown in boldface type for average speed, control delay, and total stops.

[c]Qualitative change in average emissions for the uncongested case compared to the congested case. Insig. = insignificant change (less than plus or minus 5 percent); Dec = decrease; S.Dec = Substantial decrease (e.g., more than minus 20 percent); Inc = Increase; S.Inc. = Substantial Increase (e.g., more than plus 20 percent).

afternoon. Thus, for northbound travel, the morning period represents congested conditions, and the afternoon period represents uncongested conditions. Conversely, for southbound travel, the afternoon period represents congested travel and the morning period represents uncongested travel. This comparison controls for roadway geometry. The findings from the results summarized in Table ES-2 are very clear. There is a substantial and statistically significant improvement in traffic flow for the uncongested case compared to the congested case for both travel directions and for both primary vehicles. Moreover, there is a substantial decrease in emissions for all three pollutants for the uncongested cases of approximately 50 percent. Thus, there would be a clear benefit to reducing congestion on Chapel Hill Road if that were possible. However, because traffic flow is essentially already at capacity for this corridor, changes in signal timing and coordination by themselves are not effective at improving either traffic flow or emissions.

Signal Timing and Coordination Improves Traffic Flow and Emissions on Walnut Street. For the Walnut Street corridor, the results of the comparison showed an improvement in traffic flow and emissions in most cases as the result of the change in signal timing and coordination, unlike the results for Chapel Hill Road. However, the analysis for Walnut Street was complicated by larger differences between the observed before and after average modal emission rates. While the average modal emission rates for each of the two primary vehicles were mostly similar between the before and after cases, when modal emission rates were disaggregated by time of day and direction of travel, larger differences were observed. Total emissions for the corridor were estimated for a variety of scenarios, including holding emission rates constant in the before and after cases. In a series of sensitivity analyses, it was found that the trip emissions were most sensitive to changes in trip duration, rather than to the time distribution of the trip in each driving mode or to the modal emission rates. Relative comparisons of before and after trip emissions were found to be essentially the same regardless of whether the observed average modal emission rates from only the before case versus those for only the after case were used to estimate total trip emissions for both the before and after cases. This suggests that relative comparisons can be very robust even if the absolute value of emissions may differ because of uncontrollable environmental factors.

As shown in Table ES-3, there was a statistically significant improvement in traffic flow in both travel directions in the morning, and in the northbound direction in the afternoon, observed with both primary vehicles. Emissions were estimated to decrease for some or all of the three pollutants in each case where traffic flow improved significantly. In cases where there was no significant change in traffic flow, there was also no significant change in emissions.

Similar to Chapel Hill Road, a spatial analysis of speed and emissions along the Walnut Street corridor revealed that there are specific locations at which emissions change more substantially than for the trip average. Observed data suggest that there is an increase in emissions for the nonpriority runs that were evaluated, although in many cases the sample sizes are sufficiently small and the variability in measurements between runs is sufficiently large that the results are not statistically significant.

Overall, the Walnut Street corridor illustrates the successful application of a transportation control measure leading to a reduction in vehicle emissions. Specifically, the changes in signal timing and coordination generally had a beneficial effect in reducing average vehicle emissions on the corridor. The improvement in average

Table ES-3. Summary of Key Findings for Walnut Street Before and After Comparisons: Percentage Change in Traffic Flow Parameters and Overall Change in Emissions[a]

	Ford Taurus				Oldsmobile Cutlass			
Time Period	Morning		Afternoon		Morning		Afternoon	
Direction	North	South	North	South	North	South	North	South
Trip Duration[b]	-14	-24	-23	+0.3	-16%	-17%	-21%	-0.9%
Ave. Speed[b]	**+14**	**+32**	**+29**	-1.8	**+18**	**+20**	**+29**	-1.8
Control Delay[b]	**-40**	**-63**	**-55**	-4.6	**-38**	**-50**	**-56**	+8.5
Total Stops[b]	**-30**	**-60**	**-29**	-2.3	**-29**	**-46**	**-29**	-11
HC Emissions[c]	Dec	Dec	Dec	Insig	Dec	Dec	Dec	Insig
NO Emissions[c]	Dec	Dec	Insig	Insig	Dec	Dec	Dec	Insig
CO Emissions[c]	Dec	Dec	Insig	Insig	Insig	Dec	Insig	Insig

[a]Comparisons of traffic flow are based upon observed data. Comparisons of emissions are based upon predicted comparisons of total emissions in which emission factors are held constant in the before and after case but in which the time distribution of driving modes and the trip durations varies as observed..

[b]Percentage average change for the after case with respect to the before case. Statistically significant changes are shown in boldface type for average speed, control delay, and total stops.

[c]Qualitative change in average emissions for the after case compared to the before case. Insig. = insignificant change (less than plus or minus 5 percent); Dec = decrease; S.Dec = Substantial decrease (e.g., more than minus 20 percent); Inc = Increase; S.Inc. = Substantial Increase (e.g., more than plus 20 percent).

emissions was associated with measurable improvements in traffic flow, as quantified based upon increases in average speed and reductions in average control delay and in the average number of stops per mile.

Pollution Prevention. The implications of this study with respect to pollution prevention strategies were discussed. Factors such as vehicle characteristics, traffic flow, corridor characteristics, and driver behavior can substantially influence emissions and be controlled either by a driver, by a facility designer, or by improved operation of the facility. It is possible to design, deploy, and empirically evaluate transportation control measures with respect to improvements in air pollutant emission rates.

Conclusions. A brief summary of key conclusions is given in Table ES-4. The more detailed findings are as follows:

- The instrumentation used is capable of providing precise and accurate measurements of emissions compared to laboratory methods, and it provides detailed traffic flow data.
- Field studies can be designed to serve specific study objectives. In this case, the study objective was a before and after comparison.
- A successful protocol for field data collection, data reduction, data screening, and data analysis was developed and implemented.

Table ES-4. Summary of the Key Findings of this Project.

• This study has established the feasibility of using on-board emissions measurements to collect real-world on-road tailpipe emissions data for CO, NO, and HC. • Modal (acceleration, deceleration, idle, cruise) emission rates are for the most part stable for the same vehicle/driver combination. • Measured emission rates (on a gram per second basis) are highest during the acceleration driving mode. • Measured emissions tend to increase with traffic congestion since there are more acceleration events, as observed on Chapel Hill Road. • Signal improvements such as coordination and retiming have resulted in lower emissions on Walnut Street.

- Key elements of experimental design were identified. Some aspects can be controlled. Some aspects are uncontrollable but observable.
- Key lessons learned from the pilot study substantially improved the quality of the evaluation study, such as the importance of obtaining multiple runs with the same vehicle to support before and after comparisons.
- There are substantial differences in real world on-road modal emission rates on a mass per time basis. These differences suggest that acceleration produces the highest emission rate and idle produces the lowest emission rate. Therefore, efforts aimed solely at reducing idling time may not always be successful in achieving overall reductions in air pollution emissions.
- Both micro and macro scale approaches to emissions estimation were explored.
- Average modal emission rates can be compared in the before and after studies as an indication of whether there are large systematic changes in emissions. For both of the evaluation study corridors, there was largely agreement between the average modal emission rates for the before and after cases.
- Modal emission rates were found to vary more substantially for specific time of day and direction of travel combinations when comparing before and after results, which necessitated development of simplified models and sensitivity analyses to help clarify before and after comparisons of total emissions.
- Traffic flow did not change substantially and in one case appeared to worsen for Chapel Hill Road, which was already at capacity before the signal timing and coordination change was implemented. In contrast, traffic flow improved in most cases for Walnut Street.
- If modal emission rates were the same in the before and after cases, the results suggest relatively little change in emissions for Chapel Hill Road and reductions in emissions for Walnut Street.
- There is a substantial decrease in estimated emissions for the same direction of travel on Chapel Hill Road when comparing uncongested to congested conditions. Emissions of NO, CO, and especially HC were higher in the congested case compared to the uncongested case.

- Spatial analysis of traffic flow and emissions data can reveal emissions hotspots or specific locations at which emissions change more substantially than do the corridor average emissions. There can be significant local changes in emissions even though the average emissions over the corridor may not change significantly.
- Changes in emissions were associated with changes in quantitative measures of traffic flow such as average speed, average control delay, and average number of stops per mile.
- This project demonstrated that a study can be designed and successfully executed to collect, analyze, and interpret real world on-road tailpipe emissions data regarding before and after comparisons associated with a change in traffic control.

Recommendations. Key recommendations are summarized in Table ES-5. More detail regarding the recommendations is as follows:

- On-board emissions measurement studies need a careful experimental design that is specific to a particular study objective. Key considerations in study design that should be considered in future studies are vehicle selection, driver selection, routing, deployment of instrumentation, and scheduling of on-road data collection by travel direction and time period.
- On-board emissions measurement is a viable method for measuring representative real world tailpipe emissions data. The methods developed in this study should be applied to other study objectives, such as evaluation of other transportation control measures, transportation improvement projects or plans, alternative routing, emissions hotspots, driver behavior, and other important factors that may substantially influence real world emissions. On-road data from an appropriate study design can also be used to verify or validate previously developed emission factor models.
- A variety of techniques should be used to analyze the large data streams obtained from on-board emissions measurement, including visual/graphical,

Table ES-5. Summary of the Key Recommendations of this Project.

• On-board emissions measurement methods should be used in future studies to improve knowledge of real-world on-road tailpipe emissions. • On-road measurement studies should be carefully designed taking into account well-defined study objectives. • Objectives for future studies should include but not be limited to empirical evaluation of Transportation Control Measures (TCMs) and Transportation Improvement Projects (TIPs) and plans; assessment of emissions hotspots; evaluation of driver behavior; validation of emission factor models; and development of public education tools to educate drivers about their role in pollution prevention. • Appropriate and thorough data screening, reduction, and analysis protocols should be used. • Variability and uncertainty should be accounted for in the study design and when making inferences based upon measured data. • NCDOT and others should use on-road emissions data to aid in the design and evaluation of TCMs and TIPs.

statistical, and theoretical-based approaches. The data screening, reduction, and analysis protocols developed in this project should be considered for use in other studies as appropriate.

- There is substantial variability in vehicle emissions from one run to another even for the same vehicle, route, driver, time of day, and travel direction. Therefore, for some study objectives, but not necessarily all, it will be necessary to repeat the data collection activities in order to obtain a statistically reliable estimate of the mean emissions for a given vehicle. For studies aimed at before and after comparisons with the same set of vehicles, this is an especially important consideration. For studies aimed at characterizing average emissions for a fleet, it is less important to have a large number of replications of measurements with individual vehicles, but it is important to have a sufficiently representative sample of different vehicles.

- On-board emissions measurement can be used to support the development of emission factors and should be considered by EPA and others in the development of future emission factor models.
- Transportation control measures and transportation improvement projects that modify traffic flow can also modify real world on-road tailpipe emissions from vehicles. This study demonstrated a comparison of uncongested versus congested traffic flow on Chapel Hill road and the effect of a change in signal timing and coordination on Walnut Street that are associated with statistically significant improvements in average speed, control delay, and number of stops per mile and with significant decreases in emission rates of CO, NO, and HC. These examples demonstrate that TCMs and TIPs can be designed and implemented to reduce real-world on-road emissions. In particular, measures that reduce the amount of time that vehicles spend in the acceleration driving mode should be considered.
- The information obtained from on-road studies should be used to develop public education messages aimed at the driving public, so as to inform them about how their driving behavior relates to air pollutant emissions from their vehicles.
- The air quality benefits of TCMs or TIPs should not be assumed without empirical validation. For example, "conventional wisdom" has been that reducing idling time will lead to reductions in overall emissions. However, the measurements in this study show that the average emission rate during acceleration, on a time basis, is typically a factor of five to ten larger than the average acceleration rate during idling among the variety of vehicles tested. While very long periods of idling can lead to substantial emissions, for a typical commuting type of trip accelerations are likely to produce a disproportionate share of the total trip emissions. Some TCMs, such as traffic calming devices designed to promote a reduction in average driving speed, may lead to an increase in emissions associated with more frequent

accelerations. Hypotheses such as this, as well as those based upon conventional wisdom, can and should be tested by real-world empirical studies.

NCDOT should be encouraged to carry out projects that reduce congestion on signalized arterials and/or improve coordination and signal timing as those strategies have been shown in this work to have a demonstrable effect on emission rate reduction.

1.0 INTRODUCTION

In this study novel methods have been used for evaluating the impacts of strategies aimed at preventing motor vehicle air pollutant emissions through better traffic management. This study features the deployment of a portable, on-board vehicle data measurement device to collect vehicle emissions and engine data as the vehicle is driven under real-world conditions. This research is among the first studies featuring deployment of an on-board emissions measurement system to multiple vehicles.

This project began in April 1999 and ended in July 2001, for a total duration of 28 months. The project was sponsored by the North Carolina Department of Transportation (NCDOT) via the Center for Transportation and the Environment (CTE) and was conducted by North Carolina State University (NCSU).

1.1 Objectives of the Project

The primary objectives of this research were as follows:

1. Assemble, evaluate, and validate a new low-cost on-board emissions measurement system;
2. Investigate factors that affect the level and variability of on-road emissions using rigorous statistical methods;
3. Devise methods for designing and conducting experiments that realistically evaluate vehicle-based pollution prevention strategies.

The specific pollution prevention strategy evaluated in this project was modification of signal timing and coordination as a means to improve traffic flow. The pollutants studied include carbon monoxide (CO), nitric oxide (NO), and hydrocarbons (HC). A hypothesis that motivated this project is that vehicle emissions are sensitive to micro-scale events that occur during a trip or along a specific corridor. Such events, such as accelerations at intersections, may cause relatively high emission rates. Therefore, efforts to smooth traffic flow by improving signal timing and coordination may lead to a reduction in the number of accelerations and, hence, lead to reductions in emissions.

1.2 Overview of Project Approach

The method chosen to evaluate the pollution prevention benefits of traffic signal timing and coordination featured measurement of actual on-road tailpipe emissions using a portable emissions measurement system. This approach was selected over other possible approaches, such as laboratory dynamometer testing or remote sensing, because it is possible to measure actual emissions during real-world driving for an entire trip or route.   In contrast, dynamometer testing may not be representative of real world driving, and remote sensing can only be conducted at specific sites. The on-board emissions measurement approach used in this study also features the collection of vehicle activity data, including vehicle speed and specific engine parameters. The benefits of on-board emissions measurement compared to other approaches are detailed in Chapter 2.

The project featured five major components to support the three primary objectives. These five components include: (1) acquisition of equipment; (2) identification of study corridors and experimental design for on-road data collection; (3) development of data collection, screening, reduction, and analysis protocols; and (5) development of findings and recommendations.

NCSU obtained a prototype on-board emissions measurement system, the OEM-2100™, from Clean Air Technologies International, Inc. (CATI). The OEM-2100™ is described in detail in Chapter 3. After obtaining the prototype unit, NCSU made recommendations to CATI for improvements, and subsequently acquired a second unit incorporating several design changes. However, the fundamental equipment within both units is the same, and the data collected with both units are comparable, as described in Section 3.3. During the early phase of the project, preliminary efforts were made to deploy the instruments, collect data, and analyze the data. The main purpose of the preliminary efforts was to verify instrument operation and to develop appropriate protocols.

Simultaneously with the acquisition of equipment, the study team collaborated with the Traffic Engineering Branch of NCDOT to identify corridors for use in a pilot study. The main task of the pilot study, which took place during the first year of the project, was to deploy a number of vehicles on two specific corridors, both before and after signal timing and coordination was modified on each corridor. The purpose of the pilot study was manifold, including: (1) development of a data collection methodology; (2) development and demonstration of key aspects of experimental design for on-board emissions data collection; (3) development of protocols and methods for data reduction, screening, and analysis; and (4) exploratory analysis of data to learn lessons helpful to the design of data collection in the second major phase of the project. These four key aspects are detailed in Chapters 4, 5, 6, and 7, respectively. Based upon the lessons learned in the pilot study, a more focused data collection effort was developed in the second year of the project for two additional corridors as part of an evaluation study.

The development of data collection, reduction, screening, and analysis protocols represents a generalizable contribution of this study. Although on-board emissions measurement offers an opportunity for development of data sets important to the analysis of real world transportation and air quality problems, instrumentation by itself is merely a necessary but not sufficient condition for gaining accurate insights. It is critically important that data be collected taking into account not only the vehicle engine and emissions data measured by the on-board emissions measurement system, but also taking into account other important data pertaining to vehicle activity and conditions. For example, information regarding vehicle position, key events during a trip, road grade, ambient temperature, humidity, and other variables should be included in the field data collection protocol. Procedures were developed to combine data from multiple sources into a single database as part of data reduction. Data screening involved development of methods for quality assurance and quality control of the data, and elimination of any data sets that contained specific types of errors. Data analysis involves standard approaches for developing summary results from each individual vehicle run. Examples of summary results include trip average total mass emissions for each pollutant, emission rate in mass per time units, emission rates in mass per distance units, and emission rates for each of four driving modes (idle, acceleration, deceleration, and cruise). Moreover, estimates of traffic flow characteristics, such as control delay, number of stops, and vehicle speed, were also developed.

The design of a data collection effort must take into account the deployment of vehicles, drivers, and instrumentation. The timing of data collection and the specific locations of data collection runs must also be considered. The pilot study enabled the study team to identify key real-world considerations for study design that were taken into account when developing the evaluation study.

Based upon the data collected during this project, several methods for making inferences were explored. One general set of methods is based upon a macroscopic approach to estimating emissions for a study corridor or route based upon average traffic flow characteristics (e.g., average control delay, average number of stops per mile, average speed). Alternatively, another set of methods were explored based upon micro-scale analysis of second-by-second vehicle emissions and engine data. For example, the relationship between CO emissions and the fuel-to-air ratio in the engine was explored. These two general categories of approaches are detailed in Chapters 8 and 9, respectively.

Inferences regarding the effectiveness of signal timing and coordination changes on two corridors were developed based upon statistical analysis of data collected before and after the changes were made. The two corridors chosen for the evaluation study were a section of Chapel Hill Road (NC 54) and a section of Walnut Street in Cary, NC. These corridors are the focus of Chapters 10 and 11, respectively. Four vehicles were deployed on each corridor, with the most intensive data collection efforts focused on two primary vehicles on each corridor. Among the key results of the comparison are evaluations of the changes in average speed, control delay, number of stops, and emissions of three pollutants associated with changes in signal timing and coordination.

Overall, a total of 17 vehicles were used for data collection, involving 10 drivers, 1,532 one-way vehicle trips, 4,330 miles of vehicle travel, and 180 hours of on-road data collection. Thus, the project has developed a large database that includes second-by-second data for each data collection run, as well as summary data and the results of specific analyses.

The implications of the data analysis are interpreted in Chapter 12 with respect to the development of pollution prevention strategies for on-road vehicle emissions. Key conclusions are developed in Chapter 13 for the methods of data collection, data reduction, data screening, data analysis, experimental design, modeling approaches, effects of the specific transportation control measure evaluated in this study, and pollution prevention strategies. Specific recommendations for future work are offered in Chapter 14.

2.0 BACKGROUND ON VEHICLE EMISSIONS

A literature review was performed of the relevant research related to vehicle emissions. Background information on vehicle emissions formation is given. Brief information on regulations related to vehicle emissions are presented. General approaches used in vehicle emissions measurement and modeling are described. A review of the relationship between traffic models and emissions models is given. Finally, factors influencing vehicle emissions are summarized as cited in the literature.

2.1 Background

Most vehicle emissions area product of the engine combustion process. Most passenger cars and light-duty trucks use a gasoline fueled four-stroke, spark-ignited (SI) internal combustion engine. The main pollutants of concern in the case of SI engines are nitrogen oxides (NO_X), carbon monoxide (CO), hydrocarbons (HC), and organic toxics (i.e., benzene, acetaldehyde, formaldehyde, and 1,3-butadiene). Particulate Matter (PM), a very important pollutant in the case of compression-ignition engines, is produced in very small amounts in SI engines (Degobert, 1995).

Nitrogen Oxides and carbon monoxide are formed during the combustion process and are emitted only from the tailpipe. Hydrocarbons and air toxics may originate both from the tailpipe in the form of unburned or partially burned fuel, as well as in the form of evaporative emissions from the fuel tank, fuel lines, and losses during the refueling process. Evaporative losses of HC are estimated to be about the same order of magnitude as the contribution from the exhaust (Sher, 1998; Degobert, 1995).

2.2 Vehicle Emissions Regulations

The harmful effects of air pollution on public health were formally recognized by the requirements of the Clean Air Act Amendments (CAAA) of 1970, which mandated establishment of National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: carbon monoxide; lead; nitrogen oxides; ozone; particulate matter; and sulfur dioxide (Curran *et al*., 1994). The NAAQS sets a primary standard for ambient concentrations of criteria pollutants to protect public health with “an adequate margin of safety”, and a secondary standard to protect public welfare against environmental and property damage. The CAA has been amended three times, in 1970, 1977, and 1990.

The CAAA contains stringent requirements for further reductions in emissions from highway vehicles by having strict monitoring and sanctions for non-performance, and to bring non-attainment areas into compliance (TRB, 1995). Areas for which the ambient concentration of a criteria pollutant exceeds the NAAQS are said to be in non-attainment for that pollutant. Such areas are subject to severe restrictions on permitting of any new emission sources, and are required to develop plans to reduce emissions to acceptable levels.

One of the most important air pollution regulations that affects mobile sources is the “conformity” rule. Conformity is a determination made by Metropolitan Planning Organizations (MPOs) and Departments of Transportation (DOT) that transportation plans, programs, and projects in non-attainment areas are in compliance with the standards contained in State Implementation Plans (SIPs) (i.e., plans that codify a state’s CAAA compliance actions) (FHWA, 1992). To demonstrate conformity, a transportation plan or project must improve air quality with respect to one or more of the following: (1) the motor vehicle emission budget in the SIP; (2) emissions that would be realized if the proposed plan or program is not implemented; and/or (3) emissions levels in 1990 (TRB, 1995). Conformity requirements have made air quality a key consideration in transportation planning (Sargeant, 1994).

The Congestion Management and Air Quality Improvement (CMAQ) program is another important piece of legislation that integrates air quality and transportation. The CMAQ program was introduced under the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991 and continued later under the Transportation Efficiency Act for the 21st Century (TEA-21) in 1998. Only non-attainment and maintenance areas are eligible for CMAQ funding. The first priority for CMAQ funding are programs and projects in the SIP. Regardless of whether a project is in the SIP, the project must be in a state’s Transportation Improvement Plan (TIP) to be eligible for CMAQ funding. Various project types are allowed for CMAQ funding, such as transit projects, pedestrian/bicycle projects, traffic signal coordination projects, travel demand management programs, and emissions inspection and maintenance (I/M) programs.

In spite of efforts to controlling emissions, about 134 million people lived in counties that violated one or more of the NAAQS in the year 1998 (EPA, 1998a). On-road vehicles are estimated, based upon emission inventories prepared by the U.S. Environmental Protection Agency, to contribute 30 percent of HC emissions, 32 percent of NO_x emissions, 56 percent of CO emissions, and 9 percent of PM emissions in 1998 (EPA, 1998a). The contribution of motor vehicle emissions to local emission inventories, such as in urban areas, may be higher than the national average values. It should be noted that vehicle emissions are obtained by using MOBILE model and are subject to uncertainties inherent in this model (NRC, 2000).

Mobile sources also contribute to greenhouse gas emissions. Approximately one third of the total U.S. anthropogenic emissions of CO_2 come from the transportation sector (EIA, 2000).

2.3 Approaches to Estimating Motor Vehicle Emissions

An effective air-quality improvement program requires identification of , inventory of, and control of emission sources. An emission inventory is a listing and description of air pollutant emitting sources, including a quantitative estimate of pollutant emissions (Stern, 1976). In developing inventories, emission factors and emissions producing activity data are used. An emission factor is the amount of pollutant produced per unit activity. For highway vehicles, emission factors are typically expressed on grams of pollutant emitted per vehicle-mile of travel, grams of pollutant emitted per gram of fuel consumed, or grams of pollutant emitted per unit time (NRC, 2000). Thus, the activity data required for emission inventory development would typically be an estimate of total vehicle miles traveled, total fuel consumed, or time spent for emissions process respectively.

At present, four different methods are used or proposed to calculate motor vehicle emission factors. These methods are: driving cycle-based emission factor models; modal emissions-based models; fuel-based approaches; and on-road emissions data-based models. Driving cycle-based approaches underlie the current practice for vehicle emissions estimates in the U.S.

2.3.1 Driving Cycle-Based Models

The two highway vehicle emission factor models used for regulatory purposes in the U.S. are EMFAC7 in California and MOBILE5b elsewhere. EPA is currently developing a new version of MOBILE, MOBILE6, which will be available soon. These models are based upon emissions data for selected driving cycles. A driving cycle is composed of a unique profile of stops, starts, constant speed cruises, accelerations and decelerations and is typically characterized by an overall time-weighted average speed (TRB, 1995; NRC, 2000). Different driving cycles are used to represent driving under different conditions.

Driving cycle test data are used as the basis for estimating emission factors in these models. For example, in MOBILE5b, base emission rates (BER) are derived by driving new and in-use light-duty motor vehicles through the Federal Test Procedure (FTP). As explained by TRB (1995), the FTP is an emission test composed of a defined cycle of starts, stops, accelerations, and constant-speed cruises conducted on a laboratory dynamometer under standard conditions. These conditions include the use of a specific fuel, control of test cell temperature, and replication of a predetermined speed profile by a test driver (EPA, 1993).

The MOBILE and EMFAC driving cycle-based models are used for regulatory purposes by EPA and California Air Resources Board (CARB), respectively. However, both of these models have some disadvantages and weaknesses. The emissions estimates of both models are based on a limited set of driving cycles. Historically, these driving cycles have been limited at representing real driving conditions, which affect the emission factors (Kelly and Groblicki, 1993; Denis *et al.*, 1994; Barth *et al.*, 1996; NRC, 2000; EPA, 1993).

Driving cycle-based models do not consider the differences in engine load while calculating the emission factor. When the load on the engine is high, the temperature of the engine increases significantly. Thus, to prevent over-temperature damage to the engine and catalyst, vehicles are often designed to operate in fuel rich mode under high engine loads. As stated by EPA (1993), it was found that HC and CO emissions increased by almost 20 to 100 times during this type of fuel rich operation. The high engine load may be due to high accelerations, high speeds, positive road grades, air conditioning operation, or any combination of any of these items. Driver behavior can also affect the duration of both cold starts and of events leading to high-emissions enrichment operation, which in turn have substantial effects on emissions regardless of the total number of vehicle miles traveled.

EPA has recently developed MOBILE6. This version is a substantial improvement over the current Mobile5b model. For the first time, it will be possible to develop regional emissions estimates based upon a weighted averaging of different facility-specific, link based driving cycles that can represent different level of service. With the addition of Supplemental FTP (SFTP) cycles, off-cycle emissions will be incorporated in the model. While the Mobile6 model is likely to enable more accurate area-wide average emissions estimation than its predecessor, the use of standardized driving cycles make the Mobile6 model inapplicable for evaluation of the micro scale impact of TCMs.

2.3.2 Modal Emissions-Based Models

Driving cycle-based models were developed for calculating regional emission inventories using aggregated vehicle emissions and activity data. Because of averaging of vehicle emissions and vehicle activity data these models are not suitable for evaluating traffic operational improvements that affect traffic and driving dynamics. For example, improvements in traffic flow (e.g., signal coordination and timing) cannot be evaluated with driving cycle-based models (NRC, 2000). In order to estimate effects associated with driving dynamics the modal operation of a vehicle and related emissions need to be analyzed. Modal emissions-based models relate emissions directly to the operating mode of vehicles. The operating modes include cruise, acceleration, deceleration, and idle (NRC, 2000; Barth and Norbeck, 1997; Frey *et al.*, 2001; Tong *et al.*, 2000).

Several research studies have been performed using dynamometers and instrumented vehicles producing second-by-second emissions data to investigate vehicle emissions associated with modal events (Cicero-Fernandez and Long, 1994). By testing a small set of newer technology vehicles, these studies found that CO and HC emissions are greatly affected by various acceleration modes.

Several researchers have developed modal-emissions models. One way of developing a modal-emissions model is to set up a speed-acceleration matrix in order to characterize vehicle operating modes of idle, cruise, and different levels of acceleration/deceleration and determining corresponding emissions (West and McGill, 1997). According to Barth *et al.* (1996), the problem with such an approach is that it does not properly handle other variables that can affect emissions, such as road grade or use of accessories. Another disadvantage is that the vehicle history is not properly considered, as the vehicle emissions in a given second might be a function of the previous second's speed and acceleration (NRC, 2000).

Another type of modal-emissions based model is based on mapping. This approach has been employed since the 1970s for some fuel economy models. The conceptual approach is to translate real-time speed and route information into instantaneous vehicle rpm and load parameters then use an engine map to look-up the instantaneous emission rates for the specific rpm and load conditions, and continuously integrate the instantaneous emission rates to estimate the total emissions from a given set of vehicle activities. In developing engine maps vehicle mileage accumulation is not taken into consideration. Another weakness is that emissions occurring under transient conditions may not be adequately represented by the emissions map that is derived under steady-state conditions. Mapping type of models have been developed by LeBlanc *et al*., (1994); Shih and Sawyer, (1996); and Shih *et al*., (1997).

The aggregate modal modeling approach used by Georgia Institute of Technology for the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) model is similar to emission mapping, in which the relationship between emissions and modal activities are developed. The term "aggregate" is used because the relationship rely on 'bag' data to derive their modal activities (Washington, 1997). The model estimation data consisted of more than 13,000 laboratory tests conducted by the EPA and CARB using standardized test cycle conditions and alternative cycles (Bachman, 1999). Hierarchical tree-based regression analysis was applied to the database using several vehicle technologies and operating characteristics as variables to explain variability in emissions. Vehicle activity variables include average speeds, acceleration rates, deceleration rates, idle time, and surrogates for power demand. Variables are defined as percentage of cycle time spent in specified operating condition.

A regression tree is formed from the analysis, with the nodes of the tree providing datasets for the specific vehicle technology groups and operating characteristic combinations. At each node of the regression tree ordinary least squares regression (OLS) is fitted to the data to find the relation between emissions and exploratory variables (Bachman, 1999). FTP Bag2 emission rates were analyzed for vehicles in each technology group and emission rates greater than a group's average rate plus two standard deviations were labeled as high emitters. The remaining vehicles were labeled as normal emitters (Washington, 1997). FTP Bag2 emissions are used as baseline, relationships developed through this study are used as correction factors. Therefore, all limitations and weaknesses related to the FTP test are also true for this model.

The Center for Environmental Research and Technology at University of California Riverside (UCR-CERT) is currently developing a modal emissions model that will reflect Light-Duty Vehicle (LDV) emissions produced as a function of the vehicle's operating mode. The final model is expected to predict second-by-second tailpipe (and engine-out) emissions and fuel consumption for different vehicle categories in different states of condition (e.g., properly functioning, deteriorated, and malfunctioning) (Barth *et al.*, 1997).

In developing the model 315 vehicles from 24 different vehicle/technology groups were tested on FTP (Federal Test Procedure) test, EPA's high-speed driving cycle (US06), and the newly developed modal driving cycle (MEC) (Barth *et al.*, 1997).

In the UCR-CERT model second-by-second tailpipe emissions are modeled as the product of three components: fuel rate (FR), engine-out emission indices ($g_{emission}/g_{fuel}$), and time-dependent catalyst pass fraction (CPF). The model is composed of six modules: (1) engine power demand; (2) engine speed; (3) fuel/air ratio; (4) fuel-rate; (5) engine-out emissions; and (6) catalyst pass fraction. Power demand is estimated using environmental parameters (wind resistance, road grade, air density, and temperature), and vehicle parameters (velocity, acceleration, vehicle mass, cross-sectional area, aerodynamics, vehicle accessory load, transmission efficiency, and drive-train efficiency). Power demand is combined with other engine parameters (gear selection, air/fuel ratio, and emission control equipment) to develop dynamic vehicle or technology group emission rates (Barth *et al.*, 1996).

The model uses a total of 47 parameters to estimate vehicle tailpipe emissions. The researchers identify 16 of them as readily available, which can be either obtained from public sources such as specific and generic vehicle parameters or specified by users, such as operating parameters. These parameters include both easily obtainable parameters, such as vehicle mass, engine displacement, number of cylinders, and others, such as maximum torque, catalyst indicated efficiency, maximum drivetrain efficiency, and accessory power usage. The 31 remaining parameters are identified as “calibrated parameters”, which need to be calibrated against measurements. Eighteen of these parameters are reported to be sensitive for the model’s output (Barth *et al.*, 1996). The researchers used three different methods for calibrating the parameters: (1) regression equations; (2) optimization process; and (3) direct measurements.

It is clear that with so many parameters needing calibration that the model is potentially very difficult to use. For that reason researchers are planning to add a feature to generate random vehicles with the vehicle/technology categories by randomly selecting from the distribution of values across vehicles for each parameter. They identified statistical distributions for each parameter in the model (Barth *et al.*, 1997).

The researchers at UCR-CERT are planning to integrate their model to TRANSIMS model. TRANSIMS is a transportation model that allows the detailed simulation of the transportation system of an urban area. TRANSIMS predicts trips for individual households, residents and vehicles (Williams *et al.*, 1999). TRANSIMS has an environment module to estimate the effect of transportation on air quality. For this purpose TRANSIMS will use three different emission models. For light duty vehicles UCR-CERT’s modal emissions model will be used. For heavy-duty vehicle emissions a model developed by University of West Virginia will be used. The evaporative emissions modal model will use the models being developed for Mobile6 (Williams *et al.*, 1999).

2.3.3 Fuel-Based Models

In the fuel-based method, emission factors are normalized to fuel consumption and expressed as grams of pollutant emitted per gallon of gasoline burned instead of grams of pollutant per mile. In order to obtain an overall fleet-average emission factor, average emission factors for subgroups of vehicles are weighted by the fraction of total fuel used by each vehicle subgroup. The fleet-average emission factor is multiplied by regional fuel sales to compute pollutant emissions (Singer and Harley, 1996).

The fuel based approach is amenable to the use of emissions data collected for on-road vehicles using either remote sensing or tunnel studies, as opposed to relying on laboratory tests in the driving cycle approach. Therefore, this approach may yield a key benefit of being more representative of on-road emissions. Emissions can be calculated by vehicle class by applying the multiplication separately for each class.

The accuracy of a fuel-based model depends on how well the vehicles and driving modes from which emission factors were measured represent the entire area under study. The accuracy of the age distribution used to weight emissions data from each vehicle model year is another important consideration.

2.3.4 On-Road Data-Based Measurements

On-road emissions data can be obtained by using Remote Sensing Device (RSD) or on-board instrumentation. Remote sensing devices uses infrared (IR) and, in some cases, ultraviolet (UV) spectroscopy to measure the concentrations of pollutants in exhaust emissions as the vehicle passes a sensor on the roadway. Some applications of RSD include: monitoring of emissions to evaluate the overall effectiveness of inspection and maintenance programs; identification of high emitting vehicles for inspection or enforcement purposes; and development of emission factors (Frey and Eichenberger, 1997; Rouphail *et al.*, 2000). The major advantage of remote sensing is that it is possible to measure a large number of on-road vehicles (e.g., thousands per day). The major disadvantages of remote sensing are that it only gives an instantaneous estimate of emissions at a specific location, and cannot be used across multiple lanes of heavy traffic. Furthermore, remote sensing is more or less a fair weather technology (Frey and Eichenberger, 1997; Rouphail *et al.*, 2000).

On-board emissions measurement is widely recognized as a desirable approach for quantifying emissions from vehicles since data are collected under real-world conditions at any location traveled by the vehicle. On-board emissions measurement has not been widely used because it has been prohibitively expensive. Therefore, instrumented vehicle emissions studies have typically focused on a very small number of vehicles (Kelly and Groblicki, 1993; Cicero-Fernandez and Long, 1997; Gierczak *et al.*, 1994; Tong *et al.*, 2000). In other studies, researchers have measured engine parameters only (Denis *et al.*, 1994; LeBlanc *et al.*, 1994; Guensler *et al.*, 1998; West *et al.*, 1997). However, in the last few years, efforts have been underway to develop lower-cost instruments capable of measuring both vehicle activity and emissions. For example, the U.S. Environmental Protection Agency (EPA) is developing an on-board measurement system for both light and heavy duty vehicles (Scarbro, 2000). Vojtisek-Lom and Cobb at the University of Pittsburgh developed a relatively low cost, portable, and non-invasive method for measuring gasoline and natural gas-fueled vehicle emissions, and demonstrated the use of the equipment in a study aimed at characterizing shuttle bus emissions at the university (Vojtisek-Lom and Cobb, 1997). More recently, the concepts employed by Vojtisek-Lom and Cobb have been commercialized by Clean Air Technologies International, Inc., which markets the OEM-2100™ portable emissions measurement system.

Variability in vehicle emissions as a result of variation in facility (roadway) characteristics, vehicle location, vehicle operation, driver, or other factors can be represented and analyzed more reliably with on-board emissions measurement than with the other methods. This is because measurements are obtained during real world driving, eliminating the concern about non-representativeness that is often an issue with dynamometer testing, and, at any location, eliminating the siting restrictions inherent in remote sensing.

The National Research Council (2000) reviewed the structure and performance of the Mobile model, investigated ways to improve the model, and made recommendations for the New Generation Model (NGM). One of the recommendations of the NRC study is to develop the capability to estimate emissions at different scales such as microscale, mesoscale, and macroscale. It is suggested by the EPA that data from on-board measurement devices should be used for NGM (EPA, 2001).

2.4 Transportation Models and Vehicle Emissions

It is important to understand what causes the variations in vehicle emissions, especially which factors are responsible for episodes of high vehicle emissions. However, it is also important to understand the relationship, if any, between vehicle emissions and traffic parameters commonly used by traffic analysts so they can make informed choices of how roadway design and traffic control measures affect vehicle emissions. For this purpose, a literature review was performed of commonly used traffic models and their integration with vehicle emissions models. The traffic models can be separated into three general groups as described below.

2.4.1 Travel Demand Models

Travel demand models are typically used for estimating roadway needs in the long-term future, such as a 20-year horizon. As a result of the inherent uncertainty in long-range forecasts, travel demand models usually focus on predicting roadway characteristics at the link-level (section of roadway between intersections), rather than at the intersection level where turning volumes during the peak hours are critical. Travel demand models are macroscopic in nature. A macroscopic model uses variables that represent averages for a specified duration of time to predict results. Link-level macroscopic parameters that are predicted from travel demand models include: daily and occasionally peak hour traffic volume, vehicle capacity of the link, and average vehicle speed. Commonly used travel demand models include TRANPLAN (The Urban Analysis Group, 1995), EMME/2 (INRO Consultants, 2000), and TMODEL2 (Tmodel Corporation, 1997). Except for EMME/2, which has developed a set of additional macros and utilities to compute MOBILE5 emissions, travel demand models do not typically have the capability to predict MOBILE5 emissions.

2.4.2 Macroscopic Traffic Operations Models

Traffic operations models are typically macroscopic and are primarily used for determining roadway geometrics and signal timing design. A more detailed view of traffic conditions, such as peak hour intersection turning volumes and traffic signal phasing plans, are needed for traffic operations models. Commonly used traffic operations models include Synchro (Husch, 1998), SIGNAL97 (Strong Concepts, 1995), HCS (McTrans Center, 1998), Transyt-7F (UF TRC, 1991), and Passer II-90 (UF TRC, 1991b). Synchro contains a simplified emissions model that was calibrated by the University of Florida Transportation Research Center (UF TRC) using studies involving measurement of fuel consumption in a variety of dynamometer cruise and stop-and-go cycles. The vehicle emissions are assumed to be a constant multiple of fuel consumption (UF TRC, 1991). However, past research has shown that emissions are not directly correlated with fuel consumption due to enrichment events (Denis, *et al*., 1994; Kelly and Groblicki, 1993; LeBlanc, *et al*., 1994).

Other traffic models, such as Transyt-7F, HCS, and Passer II-90, do not have the capability to estimate vehicle emissions. SIGNAL97 can estimate CO emissions but is based upon a Illinois DOT project in the early 1980s. A study by Dion *et al.* (2000) presents a mesoscopic model (a combination of microscopic and macroscopic parameters) that estimates fuel consumption and emissions based on average travel speed and number of stops per kilometer. A study by Barth *et al.* (1996) presents a methodology for relating macroscopic freeway traffic parameters to microscopic speed data. Three separate statistical variations of second-by-second speed were tested as surrogates to the macroscopic measure of traffic density: positive kinetic energy, total absolute second-by-second speed difference (TAD), and coefficient of variation of second-by-second speed (CV). Of these three, CV related best to traffic density, with an r-squared value between 0.66 and 0.68. Matzoros and Van Vliet (1992) used a modal emissions model to estimate emissions at unsignalized, signalized, and roundabout-controlled intersections. Emission rates were used for cruise, idle, creeping, deceleration, and acceleration modes based on two dynamometer studies completed in the United Kingdom. In summary, there is a lack of vehicle emissions models in commonly used macroscopic traffic operations models. The few macroscopic traffic models that do incorporate emissions estimates (i.e. Synchro and SIGNAL97) are based on out-of-date fleet mixes tested on laboratory dynamometers.

2.4.3 Microscopic Traffic Simulation Models

Microscopic traffic models use computer simulation to model individual vehicles on a transportation network using traffic flow theory concepts such as car following and gap acceptance. Microscopic traffic models directly measure traffic characteristics on a second-by-second basis, rather than relying on models to relate traffic volumes and roadway geometry to measures of effectiveness. Commonly used microscopic traffic models include CORSIM (FHWA, 1997), INTEGRATION (Van Aerde, *et al*., 1995), and PARAMICS (Paramics, 1998). CORSIM uses a speed-acceleration lookup table to predict vehicle emissions every second. The emissions rates used by CORSIM are based on unpublished dynamometer testing at Oak Ridge National Labs (FHWA, 1997). CORSIM vehicle activity output can also be used by states or others with their own emissions estimation approaches when applying CORSIM for a specific purpose.

INTEGRATION computes the fuel consumption for each vehicle on a second-by-second basis as a function of speed and acceleration. It then estimates vehicle emissions as a function of the fuel consumption, ambient air temperature, and the extent to which a particular vehicle's catalytic converter has already been warmed up during an earlier portion of the trip. PARAMICS calculates emissions on a second-by-second basis in a similar fashion to the other microscopic models. Based on research conducted at the Transport Research Laboratory in England, a speed-acceleration lookup table is used for each vehicle.

Another microscopic model, TRANSIMS, is currently being developed at the Los Alamos National Laboratory. TRANSIMS will be primarily a travel demand model for long-range transportation planning, with the capability of microscopic second-by second modeling (NRC, *et al.*, 2000). As stated previously, TRANSIMS will incorporate three different models to enable vehicle emission estimation.

2.5 Factors Influencing Vehicle Emissions

In this section, factors influencing vehicle emissions are summarized as cited in the literature. There are mainly four groups of parameters that affect vehicle emissions as indicated by Guensler (1993). These groups are: (i) vehicle parameters; (ii) fuel parameters; (iii) vehicle operating conditions; and (iv) vehicle operating environment.

2.5.1 Vehicle Parameters

Vehicle parameters are related to vehicle technology and include vehicle class (i.e., weight, engine size, horse power), model year, vehicle mileage, fuel delivery system, emission control system, and on-board computer control system. Studies have shown that vehicle make and model year are significantly related to vehicle emissions. For example, vehicle emissions are generally higher for older vehicles (Pollack *et al.*, 1992; Rouphail, 2000; Calvert, 1993; Barth *et al.*, 1997; Stedman and Bishop, 1999). The effect of other vehicle parameters are investigated in several other research projects (Bart *et al.*, 1997; Bachman, 1999).

2.5.2 Fuel Parameters

Fuel parameters include fuel type, oxygen content, fuel volatility, hydrocarbons content as indicated by Guensler (1993). Contents of the fuel, physical and chemical properties have significant effects on vehicle emissions (Calvert et al., 1993; Guensler, 1993).

2.5.3 Vehicle Operating Conditions

The starting mode of the vehicle (cold or hot), average vehicle speed, modal activities that cause enrichment, load (i.e., air condition, heavy load), and driver behavior are examples of vehicle operating conditions (Guensler, 1993). Cold-start emissions are significantly higher than hot-start emissions (Singer *et al.*, 1999; An *et al.*, 1996). The magnitude of emissions is a function of commanded air/fuel ratios, catalyst temperature, and engine temperature (Heywood, 1988; Joy, 1992; Pozniak, 1980). In most vehicles on-board computer control systems initially demand an enriched fuel mixture to prevent the engine from stalling (Bachman, 1999).

The equivalence ratio is defined as the ratio of the actual fuel-to-air mass ratio in the engine divided by the stoichiometric (sometimes referred to as "theoretical") fuel-to-air mass ratio. If the engine is operating at stoichiometric fuel-to-air ratio, the equivalence ratio is one. If the engine is operating with an excess of fuel compared to the air intake, then the engine is running "fuel-rich" and the equivalence ratio will be greater than one. Conversely, if the engine is running "fuel lean", the equivalence ratio will be less than one (Degobert, 1995). Gasoline-fueled vehicles equipped with a three-way catalyst are computer-controlled to operate very close to an equivalence ratio of one during most driving. However, if higher vehicle performance is required, such as during hard acceleration, the engine will operate in a fuel-rich mode, referred to as "enrichment." It is well known that CO emissions increase during enrichment. NO emissions on the other hand are highest when equivalence ratio is approximately one (Degobert, 1995).

Catalytic converters must reach “light-off” temperatures of roughly 300 ^{0}C to work efficiently (Bachman, 1999). Until the catalyst reaches this temperature, the tailpipe emissions are the same as the engine-out emissions. Once the catalyst warms up, it is effective at substantially reducing emissions of CO, HC, and NO. In order to protect the catalyst from overheating during periods of high engine power demand, the on-board computer of the vehicle commands the engine to operate fuel-rich. This results in insufficient oxygen in the exhaust to allow for CO and HC to be oxidized. Thus, under fuel rich conditions, the catalyst effectiveness is substantially reduced, and emissions are potentially much higher than during normal vehicle operation.

One of the events that causes enrichment is use of the air conditioner. Air conditioners place an additional load on the engine. This load increases the fuel consumption and can increase the emissions for a given vehicle speed and road load (EPA, 1993;NRC, 2000).

Driver behavior may also have a significant effect on vehicle emissions since it has an effect on the frequency and magnitude of enrichment events. Aggressive driving appears to cause significantly higher emissions (TRB, 1995; Shih *et al.*, 1997; Shih and Sawyer, 1996; and LeBlanc *et al.*, 1995).

Vehicle average speed is one of the parameters that has been used as the main explanatory variables in regulatory models such as the Mobile and EMFAC models. The relation between emissions and average speed are based upon dynamometer tests. Speed correction factors were developed based upon a series of test cycles with different mean speeds. The FTP emissions (at the mean FTP speed of 19.6 mph) are multiplied by the speed correction factor for a desired speed to give the emissions at the desired speed. Speed correction factors are function of vehicle, model year, and pollutant species (NRC, 2000).

2.5.4 Vehicle Operating Conditions

Vehicle operating conditions include the environmental conditions under which the vehicle is operated, such as humidity, ambient temperature, and road grade.

Ambient temperature is known to affect vehicle emissions. Studies have been conducted to determine this effect and include them in vehicle emissions models (NRC, 2000). FTP tests are conducted at 75°F, and in order to account for other temperatures MOBILE model includes temperature-correction factors. It has been found by EPA that CO and HC increase gradually (typically 10-30 percent) with decreasing temperatures from about 80°F to 50°F. Below 50°F, emissions increase non-linearly (NRC, 2000). Lax

(1994) found that there is 60 percent increase in HC from 55°F to 35°F (or 3 percent per °F), and 100 percent increase in CO from 55°F to 35°F (or 5 percent per °F). Humidity is another environmental parameter that might have an effect on vehicle emissions. Humidity is being used with ambient temperature to develop heat index parameter that will be used in Mobile 6 to model the effect of A/C (NRC,2000).

Another parameter that can have an effect on vehicle emissions is road grade. Road grade affects vehicle emissions by impacting the load on the engine. Gravity exerts a force on a vehicle that must be counteracted to maintain a constant speed (Bachman, 1999). In a study conducted by Cicero-Fernandez and Long (1997), it has been found that there is about 0.04 g/mile increase for HC for each 1 percent increase in road grade. For CO the increase is 3 g/mile for each 1 percent grade increment. Recent studies include the effect of road grade by estimating the effect of road grade on acceleration (Bachman, 1999).

2.5.5 Summary

In this section variables influencing vehicle emissions are summarized as cited in the literature. In this study variables that can explain variability in vehicle emissions and can be measured with the instruments available will be considered. These variables are: vehicle parameters such as vehicle make and model; parameters related to vehicle operating conditions such as equivalence ratio, air conditioner use, drivers, and average speed; and parameters related to the vehicle operating environment such as ambient temperature, humidity, and road grade.

3.0 EMISSIONS MEASUREMENT METHODOLOGY

This chapter describes the data collection methodology undertaken in this study. Specifically, this chapter discusses in detail the description, setup and validation of the OEM-2100™ equipment.

3.1 Description of OEM-2100™

3.1.1 Components of OEM-2100™

The OEM-2100™ is portable and can be installed in approximately 15 minutes in a light duty vehicle. The equipment has a width of 53 cm, a height of 41 cm and a depth of 31 cm. It weighs approximately 30 kg. The OEM-2100™ is typically placed on the front passenger seat, as shown in Figure 3-1. It has three connections with the vehicle: (1) a power cable typically connected to the cigarette lighter; (2) an engine data link connected to the On-Board Diagnostics (OBD) data port; and (3) an emissions sampling probe inserted into the tailpipe. Figure 3-2 shows the internal connections to the engine diagnostic link and the cigarette lighter. Figure 3-3 displays the connection to tailpipe. The emissions sampling hose is secured to the outer surfaces of the vehicle, such as license plates, antennae, rain gutters, etc., with clamps or duct tape. The emissions sampling hose is typically routed through a partially open back window into the vehicle and then to the instrument. A hose for obtaining reference air for zeroing purposes is routed outside, typically via the front passenger window.

The OEM-2100™ unit has a built-in computer with central processing unit (CPU), hard drive, 3.5” floppy disk drive, and a parallel port that allows connection of ZIP drive. In the current OEM-2100™ model, the hard drive has 2.0 gigabytes of memory and the CPU contains a Intel Pentium 233MHz processor. The OEM-2100™ has a screen display that shows the gas analyzer and engine scanner data, plus the mass emissions calculations in grams per second and grams per mile basis.

Overall, the device is fairly unobtrusive in that the connections are fully reversible and do not require any modification to the vehicle. Figure 3-4 shows a fully equipped vehicle that is ready for data collection.

3.1.2 Measurements by the OEM-2100™

There are two main functions of the OEM-2100™: (1) to measure tailpipe emissions; and (2) to collect engine diagnostics data. These measurements are made simultaneously second-by-second while the vehicle is driven.

To measure the tailpipe emissions, a five-gas analyzer is utilized. The analyzer can measure CO, CO_2, HC, NO, and O_2 emission rates. CO, CO_2 and O_2 are measured as volume percentages, while HC and NO are measured in volume parts per million (ppm). The instrument uses a non-dispersive infrared (NDIR) bench to measure HC (as hexane), CO, and CO_2 emissions. NO and O_2 emissions from the tailpipe are measured by an electrochemical cell method (Vojtisek-Lom and Cobb, 1997).

The engine scanner is connected to the OBD link of the vehicle, from which engine and vehicle data may be downloaded during vehicle operation. OBD was developed during the early 1980s to detect malfunctions and diagnose problems in the engine (EPA, 2000). Model year 1990 and later vehicles have OBD connections. In most cars, especially those manufactured since the 1996 model year, the OBD link is located under the dashboard of the vehicle.

Eight OBD parameters are stored by the OEM-2100™ in a data file. These parameters are: manifold absolute pressure; vehicle speed; engine speed (RPM); intake air temperature; coolant temperature; intake mass air flow (available only on some vehicles); percent of wide open throttle; and open/closed loop flag. The OEM-2100™ computer synchronizes the incoming emissions and engine data. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (1997).

Figure 3-1. OEM-2100^{TM} Installed in Passenger Seat

Figure 3-2. OEM-2100^{TM} Internal Connections

Figure 3-3. OEM-2100™ Tailpipe Connection

Figure 3-4. Toyota Camry Fully Equipped with OEM-2100™

Table 3-1. OEM-2100^{TM} Setup Procedure

Step	Description
1	Place OEM in passenger seat and secure it
2	Power OEM-2100^{TM} by connecting to cigarette lighter or other power source
3	Connect OEM to engine OBD link
4	Secure emissions sampling probe into exhaust tailpipe
5	Connect sampling probe to OEM through passenger seat window
6	Route air calibration tube outside passenger seat window
7	Turn on OEM computer and gas analyzer to let analyzer warm up
8	Set up engine scanner on OEM to get data from OBD link
9	Verify OEM is measuring engine and emissions data

3.1.3 Setup of OEM-2100^{TM}

The OEM-2100^{TM} can be setup in a light duty vehicle in approximately 15 minutes. Nine steps are needed to complete the setup and to be ready for data collection. These steps are summarized in Table 3-1.

The engine scanner of the OEM-2100^{TM} can be setup in two ways for most vehicles. The preferred setup is "vehicle-specific", in which the user selects the manufacturer of the vehicle and enters selected portions of the Vehicle Identification Number (VIN) that specify the year, model, and engine size of the vehicle. With the "vehicle-specific" setup, the engine scanner is able to sample data with a frequency of less than once per second. However, for some vehicles this type of setup is not fully implemented, and the alternative "generic OBD II" setup must be used. In the case of the generic setup, data obtained from the engine is sampled approximately only every three seconds. Thus, with the higher data sampling rate, the vehicle-specific setup is preferred if possible.

As soon as the power is connected to the instrument, it is good practice to turn on the gas analyzer and let it warm up. The gas analyzer goes through a procedure to warm up and stabilize, which initially involves a relatively high frequency of zeroing. Zeroing is a means of preventing drift in measurements and involves a period of measuring ambient air to establish baseline levels for each of the gases measured. More detail regarding zeroing is given in Section 3.2. When the gas analyzer is turned on, it will automatically zero, followed by five minutes of sampling. Zeroing takes between 45 seconds and approximately two minutes and 45 seconds, depending upon the design of the specific instrument and the stability of the instrument. During the warm up period, the analyzer will zero again after the first five minute interval, followed by a second five minute interval of sampling, followed by two fifteen minute sampling intervals, and then by thirty minute intervals from then on. Between each interval, the instrument automatically zeros. Thus, it is most convenient if data collection can be done within a thirty minute interval. The warm-up process takes approximately 54 minutes before the instrument is on a schedule of zeroing every 30 minutes.

The instrument warm up period can occur as the vehicle is being driven to a measurement location, or it can take place via vehicle battery power while the vehicle is cold. The instrument has its own internal battery which has enough capacity to maintain the instrument voltage during ignition of the vehicle's engine. Therefore, it is possible to maintain power to the equipment during a cold-start of the vehicle. The only major consideration in measuring cold starts is that there can be condensation in the tailpipe. If the condensation gets into the instrument, it can cause the internals of the instrument to become wet. It takes approximately a full day to dry out an instrument if it has become wet internally. Alternatively, the instrument could be modified to include additional water trapping capability in the sampling line.

3.2 Validation and Calibration of OEM-2100™

The precision and accuracy of the OEM-2100™ was tested by the New York Department of Environmental Conservation (DEC) and at the U.S. EPA's National Fuels and Vehicle Emissions Laboratory in Ann Arbor, Michigan (Clean Air Technologies, 2000). Three light-duty gasoline vehicles (1997 Oldsmobile sedan, 1998 Plymouth Breeze and 1997 Chevrolet Blazer) were tested by NYDEC using the I/M 240 and NYCC driving cycles. Two light-duty vehicles, a Mercury Grand Marquis and a Dodge full size pickup truck, were tested by EPA using the FTP, US06, NYCC, and FWY-HI driving cycles at Ann Arbor. The emissions were measured simultaneously by the dynamometer equipment and by the OEM-2100™.

The OEM-2100™ is calibrated on a routine basis using a calibration gas. For this purpose, a calibration gas that has a composition of 4.03 percent CO, 12 percent CO_2, 1,190 ppm HC (as C_3H_8), and 2,026 ppm NO was used. As a first step, calibration gas is measured by the OEM-2100™. If the measured values differ significantly from the known true values, then the OEM-2100™ is calibrated with respect to the calibration gas. The calibration process has been repeated approximately every 3 months. The difference between the actual and measured values for NO ranges between -5 percent and +4 percent. For CO, this range is -6 and +2 percent. The range is -7 and - 0.7 percent for HC, and the range is -3 and +7 percent for CO_2. Therefore, the instruments have been shown to be stable and hold calibration reasonably well. After calibrating the equipment, it was found that the difference between the actual value and the measured value ranged between: -1.5 percent and -0.2 percent for CO; -2.2 and 0.3 percent for HC; -0.8 and +0.2 percent for CO_2; -3 and +0.6 percent for NO. In general, there is very good agreement between the instrument's measurements and the true composition of the calibration gas.

Figure 3-5 displays CO, HC, and NO emission traces comparing the OEM-2100 and laboratory dynamometer results for one run on the I/M 240 driving cycle with a 1997 Oldsmobile 2.4-L Automatic. As shown in the traces, the two methods match well, with the OEM showing slightly higher CO and HC measurements during high emission spikes.

Overall, the results show high correlation between the OEM measurements and laboratory dynamometer tests for total emissions of each pollutant for each vehicle tested. As shown in Figure 3-6, there is a good correlation between OEM and dynamometer test results for total NO emissions. The R^2 value for the comparison is 0.987.The R^2 values for the comparisons were 0.946 for HC, and 0.999 for CO indicating that the individual OEM runs were correlated strongly with the laboratory data. The accuracy of the OEM measurements in comparison to the dynamometer measurements was reflected by the slope of the regression lines. If the slope of the regression line is 1.0, then the OEM measurements would be very accurate, assuming that the dynamometer measurements represented the true emissions. The slopes of the regression lines were 1.22 for HC, 1.01 for NO, and 0.90 for CO emissions. The standard error, a measure of precision, was less than ten percent of mean emissions for all of the pollutants except for the comparison of OEM-2100™ hydrocarbon measurements with Flame Ionization Detector (FID) measurements, which had a standard error of 24 percent of mean emissions.

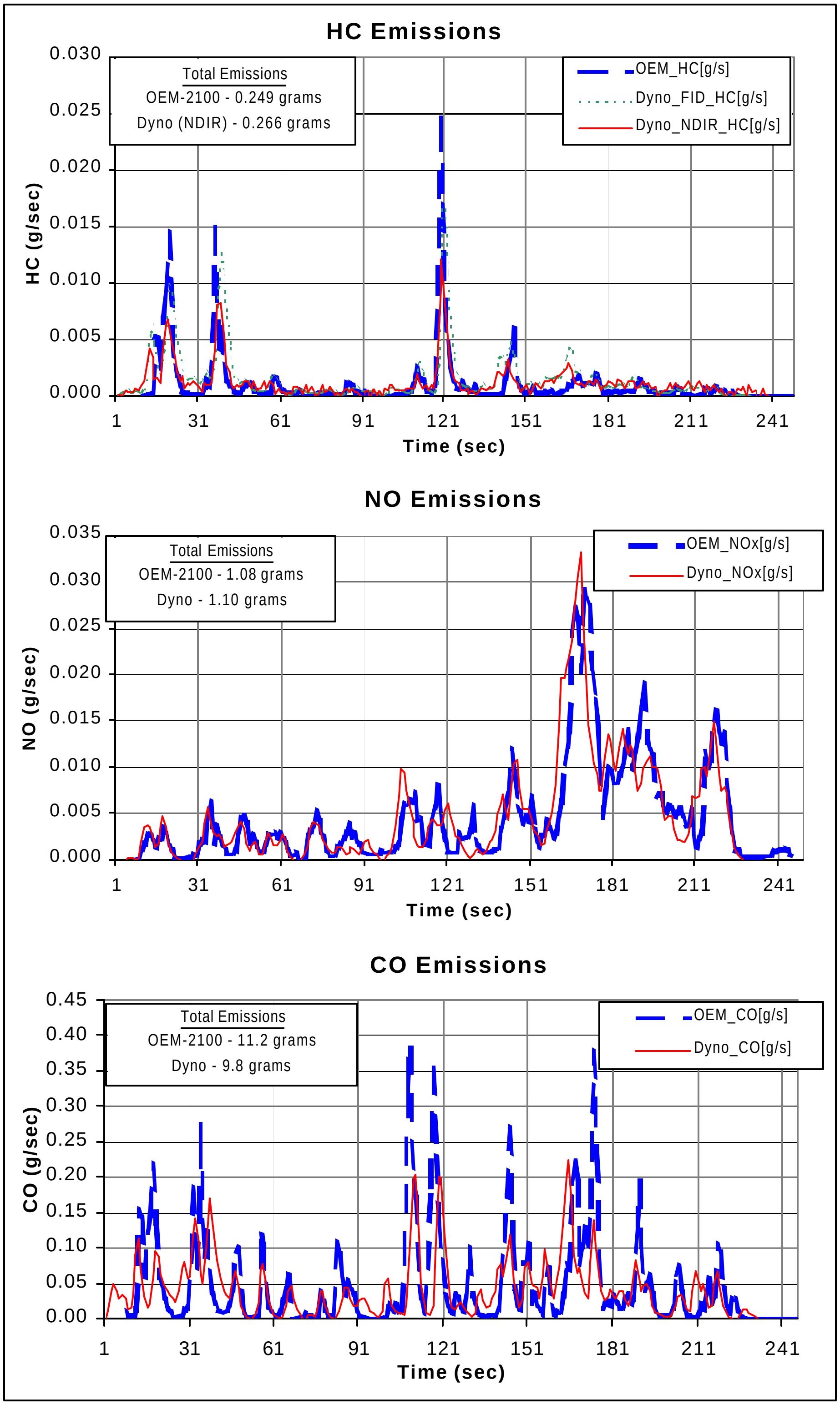

Figure 3-5. Comparison of OEM-2100^{TM} and Dynamometer Emissions on I/M 240 Cycle

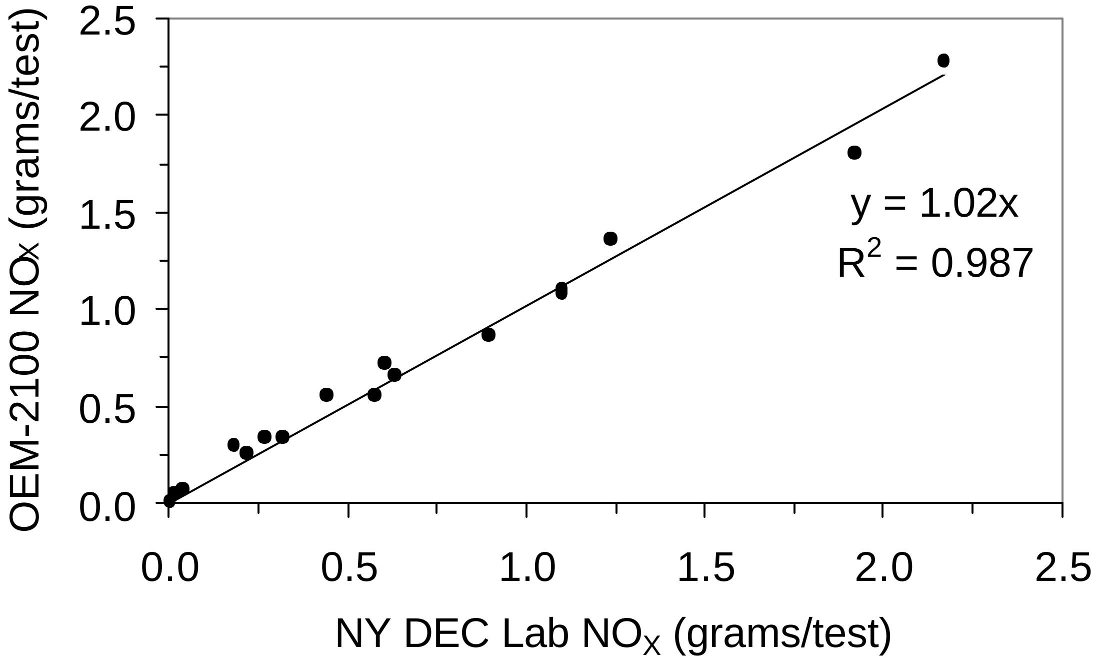

Figure 3-6. Correlation between OEM-2100[TM] and Dynamometer Test Results for Total NO Emissions

Based upon the validation tests, it was concluded that the OEM is both reasonably precise and reasonably accurate. Some of the apparent discrepancies in the comparison to the laboratory measurements may have been because of specific flow measurement problems in the laboratory. The lack of precision of the OEM HC measurements compared to the FID laboratory measurement is expected, because the OEM uses a different detection method (NDIR).

Routinely during data collection and operation of the instrument, the instrument automatically zeros itself on a periodic basis. Zeroing is done by making measurements on ambient air, which is taken to be a reference gas. The main challenge in zeroing is to sample ambient air that is believed to be free of significant levels of CO, HC, and NO. The O_2 and CO_2 levels are assumed to be at typical average ambient values of 21 volume percent and 0.03 volume percent respectively, while ambient levels of CO, HC, and NO were assumed to be zero. The CO_2 level in the exhaust is typically approximately 15 volume percent and it is not important for the instrument to be sensitive to ambient CO_2 levels.

Table 3-2. OEM-2100^{TM} Calibration Results Before Comparison Test

Gas	Unit 1	Unit 2	Calibration Gas
CO (%)	4.03	4.03	4.03
HC (ppm)	1188	1188	1190
NO (ppm)	2020	2068	2026
CO_2 (%)	12.0	12.0	12.0

3.3 Comparison of OEM-2100^{TM} units

In our study, two OEM-2100^{TM} units were used to collect data. In order to be able to compare results from these two equipments a procedure was developed that enabled data collection using both instruments simultaneously.

The key challenges in using two OEM-2100 units simultaneously are to obtain power, obtain an exhaust sample, and obtain an engine data sample for both units. One unit can be powered from the vehicle cigarette lighter connection while the other unit can be powered by connection with a battery, either on the vehicle or independent of the vehicle. Two exhaust gas sampling probes can be located in the tailpipe. However, unless there is a means for splitting the signal from the OBD link to the engine scanners in each of the two instruments, it is not possible to simultaneously measure engine data with both units. In order to deliver an engine data stream to both instruments, it would be necessary to rewire one of the instruments, which was considered to be undesirable. A simpler approach is to measure engine data with only one instrument. Thus, it is straightforward to obtain simultaneous data from the two gas analyzers in terms of emissions concentrations, but it is more difficult to obtain simultaneous engine data and to calculate mass emission rates from both instruments. However, for purposes of comparing the two instruments, the data from the gas analyzer is the most critical. Given the relative simplicity of comparing only the gas analyzers, this is the approach employed. Before setting up the experiment OEM-2100^{TM} units were calibrated. The measurements after calibration are very close to the true value as given in Table 3-2.

Two vehicles, a 1996 Honda Civic and 1999 Toyota Corolla were used for the comparison. The comparison was conducted on May 17, 2001 from 15:00 until 16:20 pm at North Carolina State University. The weather was cloudy with a temperature of 60^0F and 56 percent relative humidity. Since both instruments were subject to the same ambient conditions, no corrections are needed when making comparisons.

The procedure employed for the comparison required the simultaneous use of two cars in part so that two sources of power were available and in part to “fool” one instrument by feeding it an engine data stream. Specifically, one instrument was installed in the Honda Civic and the other instrument was installed in the Toyota Corolla. Each instrument received power from the vehicle in which it was installed: power was obtained from the cigarette lighter in the Corolla and from the vehicle’s battery via direct connection in the Civic. The latter was necessary because the Civic’s cigarette lighter was not operational. Each instrument was connected to the respective vehicle’s OBD link, so both instruments had an engine data stream. However, the sampling probes of both instruments were simultaneous placed in the tailpipe of only one of the two vehicles. To facilitate this, the two vehicles were parked closely enough together so that both sampling probes could be used with either vehicle. Thus, it was possible to obtain gas analyzer data from both instruments for a single tailpipe. The engine data from the vehicle that was not being tested was simply disregarded. However, the engine data stream was required in order for the instrument to record all data, including that from the gas analyzer, because the software in the OEM-2100 will record gas analyzer data only if there is also an input engine data stream.

The procedure used for collecting data is summarized in Table 3-3. The objective of the procedure was to establish a baseline idle emission rate and then cause large increases in CO emissions so that it would be easy to determine the relationship between an increase in engine RPM and an increase in emissions. By comparing the time traces of CO emissions from both gas analyzers, it would be possible to determine if both units are collecting gas analyzer data at the same time. The comparison test procedure has a duration of 780 seconds, or 13 minutes, per test.

When collecting data simultaneously from one tailpipe using two sampling probes, a potential concern was that there could be variability in the exhaust gas flowrate and/or pollutant concentrations at different points in the cross section of the tailpipe. If that were to be the case, then the two sampling probes might not measure a similar gas composition. Therefore, in order to identify and/or correct for potential effects of exhaust

Table 3-3. Procedure for OEM-2100^{TM} Comparison Test

Event	Time (seconds)
Idle	180
Engine at 2000 RPM	60
Idle	120
Throttle Snap	1-2
Idle	120
Throttle Snap	1-2
Idle	120
Throttle Snap	1-2
Idle	120
Sinusoidal	60

gas channeling or cross-sectional variability in exhaust gas composition, two different orientations of the two sampling probes were used. In the first test on a given vehicle, the sampling probe of the first instrument would be inserted so that it sampled the upper cross-section of the tailpipe, and the sampling probe of the second instrument would be inserted so that it sampled the lower cross-section of the tailpipe, referred to here as the "first" orientation. In a second test on the same vehicle, the position of the two sampling probes was reversed, referred to here as the "second" orientation. The same two tests were done on both vehicles, for a total of four tests. Thus, a total of 26 minutes of data were collected from each vehicle.

Figure 3-7 illustrates the results obtained for CO emissions from the comparison test using the exhaust gas stream from the Honda Civic. In the top panel, the "first" orientation of the two sampling probes was used, while in the bottom panel, the "second" orientation of the two sampling probes was used. Similar results for HC and NO are given in Appendix I, along with results for all three pollutants for the Toyota Corolla.

The emissions traces obtained simultaneously from both instruments in a given test appear to agree very well with each other, except for an apparent shift in the time at which a response is observed. It appears that OEM2 responds sooner to a change in concentration in the exhaust gas than does OEM1. For example, in the top panel of Figure 3-7, the first large spike in CO emissions is measured by OEM2 at approximately 363 seconds into the test, whereas the spike is not measured by OEM1 until approximately 372 seconds into the test. Thus, there appears to be a nine second difference in the response of the two instruments. However, aside from the difference in

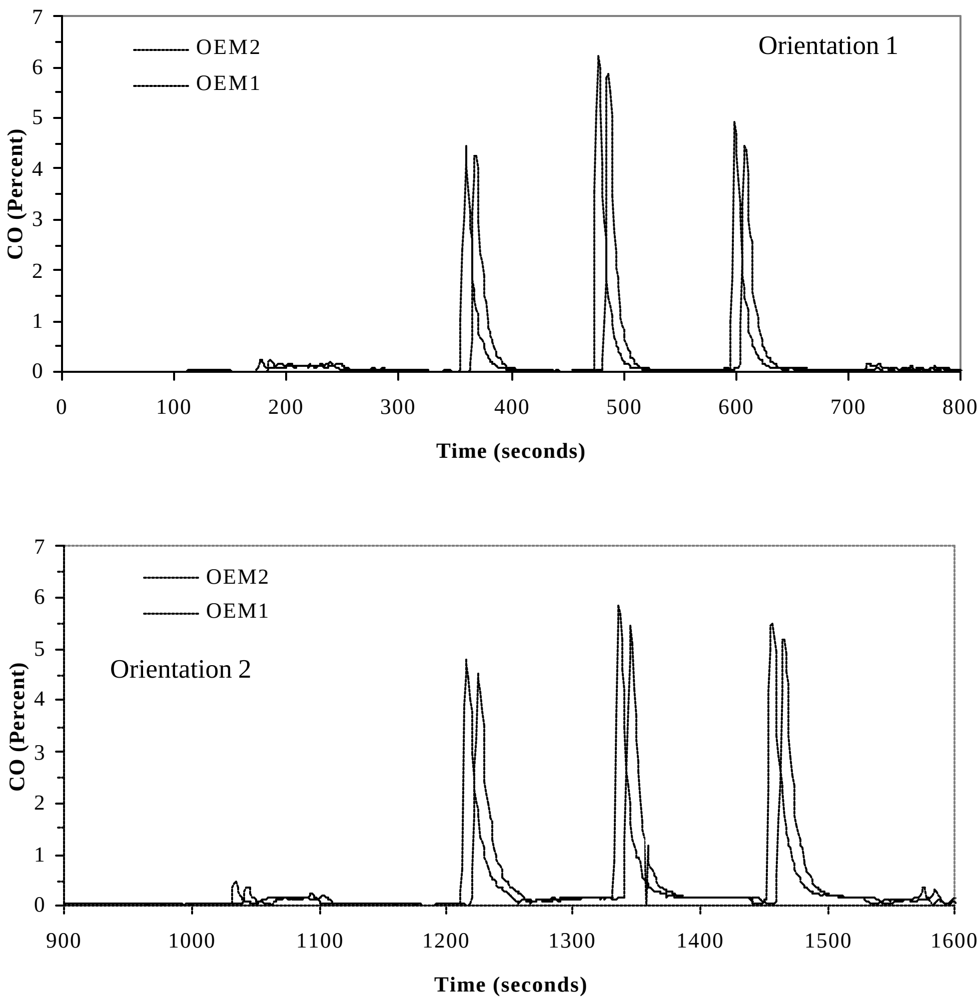

Figure 3-7. OEM-2100™ Comparison Test Results for 1996 Honda Civic

the time of the response, the two instruments respond similarly to the exhaust gas. For example, the height and width of each peak is similar during a given test.

The two tests of a given vehicle are not exactly the same because of slight differences in how the driver executed the test procedure. Thus, in comparing the top and bottom panels of Figure 3-7, it is apparently that there are small differences in the typical height and width of specific peaks. However, the two instruments compare similarly regardless of the orientation of the sampling probes. Thus, it does not appear that there was any cross-sectional variability in exhaust gas composition that would affect the representativeness of the measurements.

The results of the tests imply that there is a significant difference in the time at which the instruments respond, but that otherwise there is not a substantial difference in how the instruments respond. To verify this hypothesis, the gas analyzer data streams from both OEM units were adjusted to eliminate the time difference between them simply by shifting the time series of one instrument by nine seconds, and then overlaying with the time series of the other instrument. An example of this type of comparison is shown in Figure 3-8 in the case of CO, HC, and NO concentrations measured for the Toyota Corolla for the first orientation.

The comparison shows that the two time traces are nearly indistinguishable when they are superimposed with correction for differences in time delay. Thus, both instruments appear to have similar response times when the difference in time delay is corrected. Furthermore, the difference in total emissions are less than five percent for all of the pollutants.

Based upon the results of this comparison, a quality assurance effort was undertaken to correct the time lag of the gas analyzer data for the OEM1. As part of a diagnostic effort after the comparison test was done, it was determined that a blockage was causing the nine-second time delay. More detail is provided in Section 6.1 as part of the discussion of data post processing.

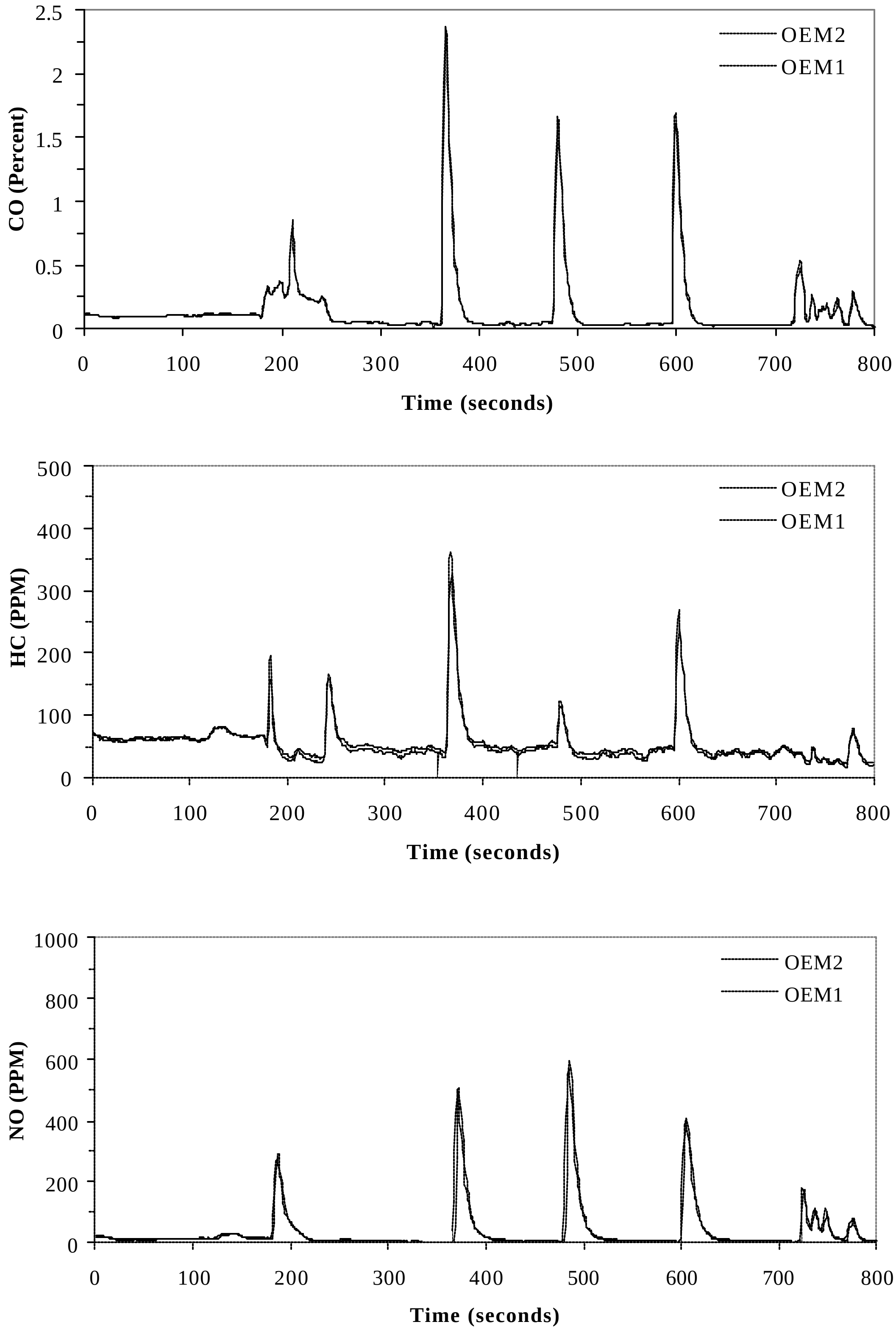

Figure 3-8. OEM-2100™ Comparison Test Results for 1998 Toyota Corolla After Correction for Time Delay

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4.0 DATA COLLECTION METHODOLOGY

The previous chapter described the measurements of emissions and engine data. This section describes the methodology undertaken for collecting data regarding other potentially useful explanatory variables. Specifically, this section discusses the description of instruments used and the types of data collected employed for variables that may help explain emissions, such as vehicle characteristics, corridor characteristics, traffic flow, ambient conditions, and operating characteristics.

4.1 Instrumentation and Software

Vehicle emissions and engine-related parameters were collected using the OEM-2100™. Other explanatory variables were measured using different equipment. For example, road grades were measured at one-tenth of mile increments with a digital level. The road grade information was encoded into a database and was synchronized with other data collected using a program written in Microsoft Visual Basic.

Temperature, humidity, and other information regarding vehicle activity were also recorded. Ambient temperature and relative humidity measurements were taken using a portable weather gauge attached to the outside of the test vehicles and recorded for each run. The following sections will explain the purpose and methodology used for collection of data for potential explanatory variables.

4.2 Vehicle Characteristics

4.2.1 Purpose

Data regarding the vehicle characteristics were collected to determine their effects on vehicle emissions and help explain the variability in vehicle emissions. Parameters related to vehicle characteristics include vehicle class (i.e., weight, engine size), model year, and vehicle mileage. Several research studies indicate that vehicle model, type, and mileage significantly affect vehicle emissions (Pollack *et al.*, 1992; Rouphail, 2000; Calvert, 1993; Barth *et al.*, 1997; Stedman and Bishop, 1999; Bachman, 1999).

4.2.2 Methodology

In order to record parameters related to vehicle characteristics as well as other characteristics such as ambient temperature and humidity, a Visual Basic program was developed. Before every data collection trip, data regarding vehicle characteristics were entered. These parameters include: vehicle model year (e.g., 1999); vehicle model (e.g., Ford); vehicle model (e.g., Taurus); vehicle body type (e.g., Four door); vehicle trim line (e.g., Sedan); curb weight (e.g., 3353 lb); vehicle identification number (VIN); engine size (e.g., 3.0 L); transmission (e.g., Automatic); fuel type (e.g., Gasoline); fuel delivery system (e.g., Fuel Injection); odometer reading; presence of cruise control; and presence of trailer. A screen capture of the software is given in Figure 4-1.

4.3 Corridor Characteristics

4.3.1 Purpose

Data specific to the physical characteristics of each test corridor were collected to allow for quantification of the effect of these characteristics on vehicle emissions and help potentially to explain the variability in vehicle emissions data. Specific corridor characteristics that were quantified include road grade, traffic signal settings, corridor geometry (i.e., number of lanes, horizontal curves, and intersection configurations), and corridor segment lengths. Road grade information was collected because past research has shown at grade has an effect on vehicle emissions (Cicero-Fernandez and Long, 1997; Bachman, 1999). Traffic signal settings, including the maximum green times, maximum cycle length, and intersection offsets, were collected because the presence and effectiveness of signal coordination are defined by these settings, and determining the effect of signal coordination on vehicle emissions is the primary task of this research.

The lengths of the corridor segments (defined as the distance between signalized intersections) were measured to provide the basis of the spatial analysis, which allows analysis of vehicle emissions and engine data spatially throughout the corridor. Without measuring the true distance of each segment, then it would be impossible to know precisely where a spike in vehicle emissions occurred on the corridor.

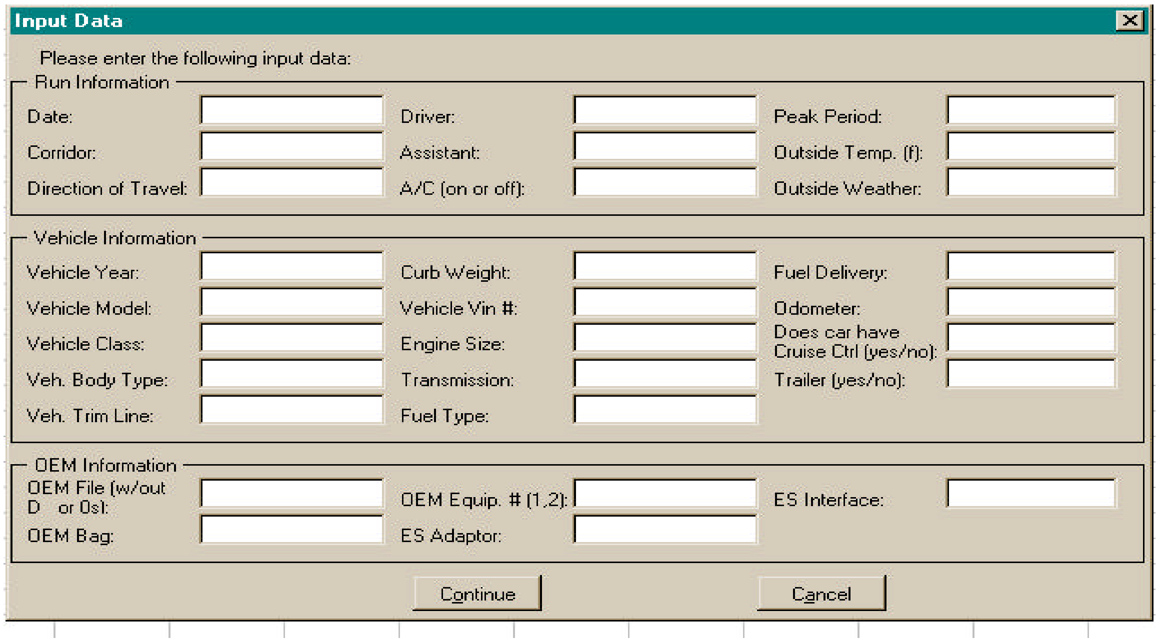


Figure 4-1. Screen Capture from Field Program

4.3.2 Road Grade Measurement

A digital level, which has an accuracy of 0.1 degrees, was mounted to the inside windowsill of a Chevrolet Venture minivan. Before measurement, the digital level was calibrated by leveling on the floor of a building with the help of a level indicator that is part of the instrument. The Chevrolet Venture minivan was driven along each test corridor and the grade was measured every 0.1 miles. Measurements were made as close to the center of the road as possible.

4.3.3 Traffic Signal Settings

The NCDOT provided current signal timing plans for the signalized intersections along each test corridor. Because all of the traffic signals had actuated control, the green times are not fixed. The maximum green times were used as an indication of the amount of green time given to each movement during the AM and PM peaks. This is a reasonable assumption because traffic volumes are typically highest during the peak hours, and high traffic volumes often cause the signal phases to receive the maximum green time allowed. The cycle lengths were estimated by summing the maximum green times and clearance interval for each phase.

After implementing signal coordination plans, the NCDOT provided updated signal timing plans with new maximum green times and the introduction of intersection offsets. Offsets represent the time offset in green times at consecutive intersections such that a vehicle can travel from one intersection to the next without stopping. Signal timing plans (green times, offsets) are often slightly adjusted when they are programmed into the controllers in the field to better optimize the signal timings based on field observations. Thus, the actual signal timing plan in the field may differ from that on the file at NCDOT. However, typically these adjustments are minor and thus the signal timing plans obtained from NCDOT are believed to be a good indication of actual conditions.

4.3.4 Corridor Specifications

The number of through and turn lanes along the corridor between intersections, as well as intersection lane configurations (i.e., number of through and turn lanes, presence of lane additions/drops) were recorded using field observations of the test corridors. Also, field observations noted the presence of horizontal curves along the test corridors. In addition, speed limits and other traffic control were noted for the test corridors.

4.3.5 Corridor Segment Lengths

The lengths of test corridors were measured using two different methods. The first method utilizes the second-by-second OEM measurements of speed, which yields a direct estimation of distance traveled each second. This method assumes that the OBD system accurately measures vehicle speed and that the vehicle begins recording OEM data (emissions and engine diagnostics information) at the same point each run. If runs are recorded starting at different points then the subsequent measurement of the length of the corridor segments are going to be different during each run.

The second method consisted of directly measuring the segment lengths using a vehicle odometer. Most odometers read in increments of only 0.1 miles. Numerous runs with various vehicles were compared to obtain the average length of each segment. This method assumes the odometer accurately measures distance. The measurements by different vehicles revealed very little variability in odometer measurements. Thus, this method was deemed more precise than the first method.

4.4 Traffic Flow Characteristics

4.4.1 Purpose

The traffic flow characteristics that were collected for each data run include average corridor speed, free flow speed, intersection control delay, intersection stopped delay, number of intersection stops, number of corridor stops. These parameters were collected to quantify the effectiveness of the signal coordination plans and to investigate relationships between traffic parameters and vehicle emissions.

4.4.2 Methodology

Measurements of traffic flow characteristics were based on recording timestamps using a laptop computer for each significant traffic event, including:

- stopping at a signalized intersection,
- passing through the center of a signalized intersection, and
- stopping or slowing significantly at a mid-block due to a turning vehicle or incident

These timestamps were used to develop estimates of the traffic characteristics discussed below. Figure 4-2 displays a sample run with the timestamps of traffic events recorded on the vehicle speed profile. The Data Reduction and Screening chapter details how the traffic characteristics were estimated based on recording traffic event timestamps.

4.5 Other Characteristics

4.5.1 Purpose

Several other characteristics were deemed necessary for data collection during the corridor runs because they have both been shown in past research to have an impact on vehicle emissions (NRC, 2000; EPA, 1998b; TRB, 1995; Shih *et al.*, 1997; Shih and Sawyer, 1996; LeBlanc *et al.*, 1994; and Lax, 1994). These parameters include: ambient temperature; ambient humidity; driver effect; and air condition usage.

4.5.2 Methodology

Ambient temperature and relative humidity measurements were taken from a portable weather gauge attached to the outside of the test vehicles and recorded for each

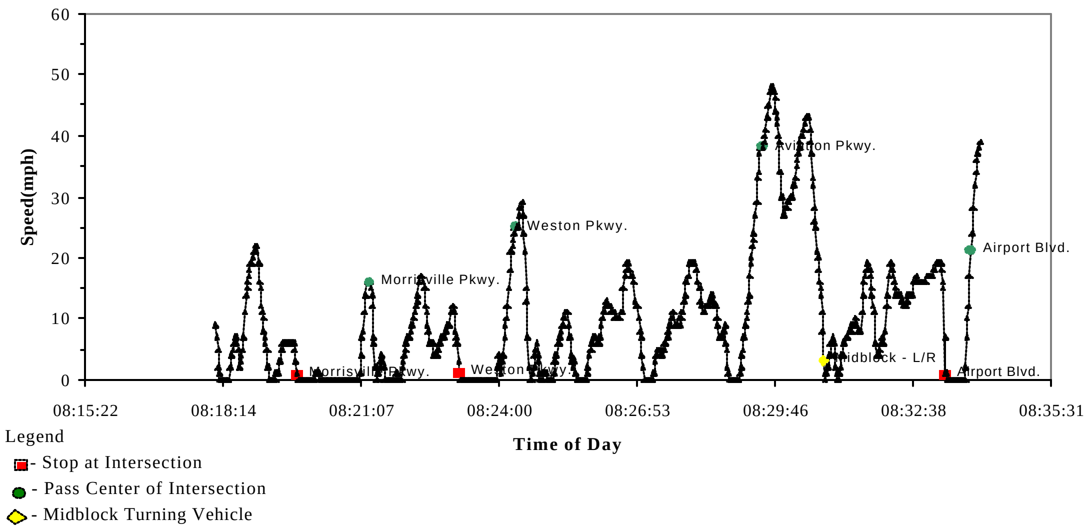


Figure 4-2. Sample Speed Profile with Traffic Event Time Stamps

run. Ambient temperature and humidity as well as air condition usage and drivers were recorded for each trip using the Visual Basic program. The input screen where these parameters are entered is given in Figure 4-1.

A number of different drivers were used during the corridor runs, with two primary drivers completing the majority of runs and a number of secondary drivers completing a small number of runs. The drivers were told to use their natural driving styles, so the runs were not designed specifically for a range of different driving styles and levels of aggressiveness. However, a number of traffic flow characteristics can help identify the level of aggressiveness of each driver and determine if a variety of driving styles were present. The relation between traffic flow characteristics and driver style is discussed in detail in the Section 7.0.

4.6 Summary of Data Collection

Table 4.1 summarizes the exploratory variables collected in this study. Description gives whether parameter is dynamic or static type. A dynamic parameter is one that is vehicle-specific. A static parameter is a constant feature of the corridor.

Table 4-1. Summary of Data Collected

Parameter	Description
Vehicle Model Year, Make, Model, and Vehicle Information Number (VIN)	Dynamic
Odometer Reading	Dynamic
Driver	Dynamic
Accessory Use (e.g., Air Condition)	Dynamic
Ambient Temperature	Dynamic
Relative Humidity	Dynamic
Road Grade	Static
Locations of Intersections	Static
Speed Limit	Static

5.0 EXPERIMENTAL DESIGN

5.1 Objective

A field experiment was conducted between Fall 1999 and Fall 2000 to obtain simultaneous emissions and traffic data on four major arterials in Research Triangle Park and Cary, North Carolina. This was an observational experiment of real-world data and not a controlled laboratory experiment. The primary objective of the experiment was to test the effectiveness of signal coordination in reducing vehicle emissions. Secondary objectives were to investigate factors that affect the level and variability of on-road vehicle emissions and to devise methods for designing and conducting experiments that realistically evaluate vehicle-based pollution prevention strategies.

The experiment was conducted in two phases, a pilot study and an evaluation study. The pilot study collected data on the first two test corridors, NC-54 and Miami Boulevard. The objective of the pilot study was to develop and improvement of a methodology for performing on-road emissions data collection and to better understand the factors that influence the collection of traffic parameter and emissions data. In short, the pilot study was an exploratory step before completing the data collection for the evaluation study. The primary objectives of the evaluation study were to evaluate the effectiveness of signal coordination on vehicle emissions and to identify methods for evaluating other pollution prevention strategies.

5.2 Experiment Type

The experiment type chosen was a before-and-after study without control groups. A series of runs were performed before the signal coordination plans were implemented. Approximately the same number of runs was then performed after the coordination plans were implemented.

Performing runs on a set of control arterials (adjacent arterials with similar geometric and congestion characteristics) was not included primarily because of budgetary and time limitations and the lack of availability of realistic control arterials. By not including a set of control arterials, the possibility of a number of “threats to the validity” of the experiment were introduced, including history, regression to the mean, and instability (Council, *et al.*, 1980). However, each possible threat to validity was identified and either are addressed in the study design or can be evaluated as part of data analysis.

Perhaps the potentially most important threat that could arise would be the 'history' effect, which would arise if other underlying changes may occur aside from signal coordination between the before and after cases, such as:

- ♦ differences in vehicle make and model tested,
- ♦ differences in fuel type,
- ♦ differences in driver aggressiveness,
- ♦ differences in use of air conditioner,
- ♦ differences in ambient weather conditions, and
- ♦ differences in traffic volumes.

Vehicle, fuel type, driver aggressiveness, and use of air conditioner are all variables that were controlled through the experimental design. However, the ambient weather conditions and traffic volumes could not be controlled. Ambient weather conditions were observed so that they could be considered in statistical analysis of the before and after data. If ambient conditions differed enough between the before and after runs to cause a difference in emissions, then a statistical analysis of the data would reveal that ambient conditions such as temperature and humidity have a statistically significant relationship with variability in emissions. Furthermore, in designing the study, an effort was made to keep the time frame for the "before" case as brief as possible, to keep the time frame for the "after" case as brief as possible, and to keep the interval between the before and after cases as short as possible. This was done to minimize the opportunity for seasonal changes in weather to play a role. Typically, the "before" data were selected over a period of two to three weeks. A period of a few weeks would be required after the before study to allow time for NCDOT to implement the signal timing and coordination change. Then, the "after" data would be collected over a period of two or three weeks.

Although it is theoretically possible that traffic volume might change over the course of a before-and-after study on a given corridor, it was the judgment of the project team that any such change over an approximately two month period on the specific corridors studied would be negligible.

The ‘regression to the mean’ effect occurs when the natural variations in a sample tend to regress to its mean value over time. This effect typically occurs especially when a sample is chosen for its high value (i.e. a highway safety study might choose only high accident locations for its sample). For this experiment, the test arterials were not chosen based on their high congestion or vehicle emission levels. Thus, the effect of regression to the mean was deemed to be negligible for this study.

The final threat to validity is instability, which occurs due to potentially large random variability in the sample data. This threat can be overcome through adequate sample sizes and appropriate statistical testing.

5.3 Pilot Study

5.3.1 Site Selection

The pilot study called for on-road emissions collection on two major arterials, whose characteristics are summarized in Table 5-1. The selection criteria included: located in suburban areas with low traffic signal density (1 to 5 signals per mile), fairly low roadside development, and speed limit around 45 mph. This type of arterial is

Table 5-1. Traffic Characteristics of Test Corridors for Pilot Study

Characteristic	NC 54 (Nortel Entrance to Barbee Rd.)	Miami Blvd. (Emperor Blvd. to Hwy. 70)
Speed Limit (mph)	Mainly 45, segments of 35 and 50	45
Number of Through Lanes	Mainly 4, Segments of 2	Mainly 4, Segments of 2
Center Turn Lane?	Yes, on 4-lane sections	Yes, on 4-lane sections
Number of Traffic Signals	8	13
Corridor Length (mi.)	3.8	5.9
Signal Density (signals/mi.)	2.1	2.2
Free Flow Speed (mph)[1]	40, 45[2]	45, 50[3]
Arterial Level of Service[4]	B – AM/Noon Peaks C – PM Peak	C – AM/PM Peaks B – Noon Peak

Notes: 1. See Section 3.3.2 for discussion of free flow speed estimation.
2. 45 mph from Nortel Entrance to Alexander Dr. and 40 mph from Alexander Dr. to Barbee Rd.
3. 45 mph from Emperor Blvd. to I-40 East, and 50 mph from I-40 East to Hwy. 70.
4. Based on HCM Table 11-1 (2).

classified as a Class I arterial according to the HCM (TRB, 1997). A major constraint in selecting test corridors was that only those arterials planned for signal coordination within the time frame of the experiment were chosen. Thus, only a handful of corridors were identified that met the standards of being a Class I arterial, of being updated with signal coordination within the experiment time frame, and of being located in the Triangle area to facilitate logistics of data collection.

5.3.2 Vehicle Selection

For each corridor, the main objective was to compare differences in emissions before and after a signal timing and coordination change. Thus, the focus was on understanding relative differences in emissions. As a result, it was considered appropriate to focus on intensive repeated measurements with a small number of vehicles. By conducting repeated runs with a vehicle, it is possible to develop high confidence regarding estimates of mean emissions of that vehicle on the corridor for both the before and after measurements. Furthermore, it is possible to statistically compare the mean emissions for both the before and after cases to determine if there is a statistically significant difference between the two. A statistically significant difference in mean emissions between the before and after cases would be an indication of a change in emissions potentially attributable to the modification of traffic signal timing and coordination.

One of the main purposes of the pilot study was to help ascertain how many runs are required with a single vehicle in order to estimate the mean emissions with a reasonably high degree of confidence. Furthermore, another purpose was to evaluate inter-vehicle variability in emissions. Therefore, measurements were taken repeatedly for a small set of primary vehicles, and additional measurements were made with a small set of secondary vehicles.

For both NC 54 and Miami Boulevard, the two primary vehicles were a 1996 Oldsmobile Cutlass sedan and 1999 Ford Taurus sedan. However, the vehicles were rented from the North Carolina state motor pool, and not the same exact Cutlass or Taurus was driven each time. For example, four different Ford Taurus and three different Oldsmobile Cutlass vehicles were driven on NC 54. On Miami Boulevard, two different

Ford Taurus and three different Oldsmobile Cutlass vehicles were driven. One of the Oldsmobile Cutlasses driven on NC 54 was also driven on Miami Boulevard. None of the Ford Tauruses was driven on both corridors.

A number of secondary vehicles were also driven on Miami Boulevard to help determine the variability in vehicle emissions by vehicle make and model and how different vehicles respond to improving traffic conditions. These secondary vehicles included a 1998 Plymouth Breeze sedan and 1998 Ford Club Wagon 15-passenger van. No secondary vehicles were driven on NC 54. Refer to Table 7-6 for a detailed summary of the vehicles driven on each test corridor.

5.3.3 Driver Selection

A driver's aggressiveness in accelerating and desired top speed can influence the magnitude of vehicle emissions on a given run. For the pilot study, three primary drivers were used for the majority of runs. In addition, a number of secondary drivers were used for a small number of runs. Using a variety of drivers in the pilot study was planned to help identify the impact of driver style on vehicle emissions, as this information would be taken in consideration for the evaluation study.

5.3.4 Fuel Selection

Regular unleaded gasoline was intended to be used for all runs. However, 1999 Ford Tauruses were obtained from the downtown Raleigh motor pool operated by the North Carolina State motor pool, where they fueled all Ford Taurus vehicles with an ethanol and gasoline blend using a mix of 85 percent ethanol and 15 percent regular unleaded gasoline. The use of ethanol was not known until after completing the pilot study, so all Ford Taurus runs on NC 54 and Miami Boulevard were completed with the ethanol and gasoline blend. All other vehicles were driven using regular unleaded gasoline.

5.3.5 Time of Day Selection

The time of day during which corridor runs were made was based on the periods that signal coordination plans were implemented. Typically, signal coordination plans are only implemented for the periods during the heaviest traffic congestion. For both NC

54 and Miami Boulevard, signal coordination plans were implemented for the AM (7-9 AM), noon (11 AM-1 PM), and PM (4-6 PM) periods. Thus, an approximately equal number of runs were collected for each of these periods.

5.3.6 Route Selection

The signal coordination plans for this experiment all attempted to ensure the smooth progression of vehicles through the corridor, and not for vehicles turning onto or off of the corridor. Thus, all runs for the pilot study were completed by driving through the test corridor without turning. A run is defined for this experiment as a one-way trip from one end of the test corridor to the other end.

5.3.7 Data Collection Summary

Table 5-2 displays a summary of the data collected for the pilot study. The table represents the total runs collected, of which some were not used in the data analysis for various reasons as discussed in Chapter 6 on Data Screening. To differentiate different vehicles, vehicles were numbered. Overall, data collection for the pilot study totaled approximately 408 one-way runs, 68 vehicle-hours, and 2,060 vehicle-miles of simultaneous vehicle emissions and engine diagnostic data.

5.3.8 Key Lessons from Pilot Study

A number of lessons were learned from the pilot study that were useful in designing the evaluation study. The main lesson learned was the high variability in emissions data for vehicles of the same make and model. Chapter 7 on exploratory analysis shows that two different vehicles of the same make and model can produce significantly different emission rates. Because it is important to control all emissions variability so that the only difference in the before and after runs is the presence of signal coordination, the pilot study highlighted the importance of driving the exact same vehicles in the before and after runs.

The pilot study also highlighted the importance of using the same fuel type in the before and after runs. Preliminary analysis chapter indicates that there is likely some difference in emission rates when using regular unleaded versus the ethanol and gasoline

Table 5-2. Field Data Collection Summary for Pilot Study

Test Arterial	Signal Coord.	Total Runs[1]	Peak - Runs	Driver[2] – Runs	Vehicle Make and Model –Runs
NC 54	Before	100	AM – 34 Noon – 32 PM – 34	AU – 46 JC – 34 NU – 20	1999 Ford Taurus (1) – 42 1999 Ford Taurus (2) – 18 1996 Oldsmobile Cutlass (1) – 40
	After	106	AM – 36 Noon – 38 PM – 32	AU – 49 JC – 45 LW – 6 MV – 6	1999 Ford Taurus (3) – 20 1999 Ford Taurus (4) – 22 1996 Oldsmobile Cutlass (2) – 33 1996 Oldsmobile Cutlass (3) – 31
Miami Blvd.	Before	100	AM – 28 Noon – 39 PM – 33	AU – 41 JC – 27 NU – 32	1999 Ford Taurus (5) – 29 1996 Oldsmobile Cutlass (2) – 13 1996 Oldsmobile Cutlass (4) – 34 1998 Ford 15 Pass. Van (1) – 10 1998 Ford 15 Pass. Van (2) – 14
	After	102	AM – 40 Noon – 32 PM – 30	AU – 35 JC – 40 CF – 6 NR – 6 GU – 6 AF – 6 AS – 3	1999 Ford Taurus (6) – 32 1996 Oldsmobile Cutlass (5) – 58 1998 Plymouth Breeze (1) –12

Notes: 1. A run is defined as a one-way trip from one end of the corridor to the other end.
2. Initials of driver's first and last name.
3. The Ford Taurus vehicles were fueled with an ethanol and gasoline blend.

blend. Thus, the Ford Taurus vehicles from the North Carolina State motor pool should be used only after the fuel tank of ethanol and gasoline blend is emptied and refilled with regular unleaded gasoline.

There is a less clear trend between driver style and emission rates; however, it is important to use the same drivers in the before and after runs to prevent any additional variability due to driver style. Because both vehicle make and model and driver style have an impact on vehicle emissions, it became clear that the evaluation study should be designed based on similar driver-vehicle combinations in the before and after runs. An equal number of runs with the same driver and vehicle in both the before and after runs will reduce the likelihood of emissions variability due to driver style and/or vehicle make and model.

5.4 Evaluation Study

5.4.1 Site Selection

The site selection criteria used for the pilot study were also used for the evaluation study. Two test corridors were chosen for the evaluation study, of which the traffic characteristics are summarized in Table 5-3.

5.4.2 Vehicle Selection

As learned from the pilot study, it was important to test the exact same vehicles in the before and after runs. Arrangements were made with the North Carolina state motor pool to rent the exact same vehicle twice, once for the before runs and once for the after runs. Two primary vehicles were used for the majority of runs. On Chapel Hill Road, a 1999 Ford Taurus and 1998 Chevrolet Venture minivan were the primary vehicles driven. On Walnut Street, the primary vehicles were a 1999 Ford Taurus and 1996 Oldsmobile Cutlass. Also, two secondary vehicles were driven for a small number of runs on each corridor. A 1998 Toyota Camry and 1998 Dodge Caravan were used for this purpose on both Chapel Hill Road and Walnut Street. In addition, a small number of runs were completed on Chapel Hill Road with a 1997 Jeep Cherokee and 1996 Oldsmobile Cutlass.

5.4.3 Driver Selection

In the pilot study, three primary drivers were used for the majority of runs. In the evaluation study, only two primary drivers were used to reduce some of the variability in emissions caused by driver style. In addition, the evaluation study was designed based on creating the same vehicle-driver pairs in the before and after runs. This would help reduce the emissions variability due to both driver style and vehicle make and model. For example, driver AU drove the same Ford Taurus for 30 runs before signal coordination and 29 runs after signal coordination.

Two secondary drivers were used for the runs with the secondary vehicles. The same vehicle-driver pair was used in the before and after secondary runs.

Table 5-3. Traffic Characteristics of Test Corridors for Evaluation Study

Characteristic	Chapel Hill Rd. (Morrisville Pkwy. to Airport Blvd.)	Walnut Street (Dillard Dr. to Cary Towne Blvd.)
Speed Limit (mph)	45	35, 45[2]
Number of Through Lanes	2	4
Center Turn Lane?	No	Yes
Number of Traffic Signals	4	9
Corridor Length (mi.)	2.6	2.3
Signal Density (signals/mi.)	1.5	3.9
Free Flow Speed (mph)[1]	45	40, 45[3]
Arterial Level of Service[4]	F – AM North C - AM South C – PM North E – PM South	C – AM North C - AM South D – PM North C – PM South

Notes: 1. See Section 3.3.2 for discussion of free flow speed estimation.
2. 35 mph from Dillard Drive to Buck Jones Road, 45 mph from Buck Jones Road to Cary Towne Center Mall Access, and 35 from Mall Access to Cary Towne Boulevard.
3. 40 mph from Dillard Drive to Buck Jones Road, 45 mph from Buck Jones Road to Cary Towne Center Mall Access, and 40 from Mall Access to Cary Towne Boulevard.
4. Based on HCM Table 11-1 (2).

5.4.4 Fuel Selection

Regular unleaded gasoline was used for all runs. Ford Taurus vehicles rented from the North Carolina State motor pool had an ethanol and gasoline blend in the fuel tank when they were picked up from the motor pool. However, the fuel tank was emptied and filled again with regular unleaded gasoline before commencing data collection runs.

5.4.5 Time of Day Selection

Both Chapel Hill Road and Walnut Street had signal coordination plans implemented for only the AM (7-9 AM) and PM (4-6 PM) peaks on weekdays. Thus, an approximately equal number of runs were collected for both these periods.

5.4.6 Route Selection

The majority of the runs were completed by driving through the test corridor without turning, as was done in the pilot study. These runs were referred to as *primary* runs. However, often a signal coordination plan improves traffic flow for the primary route and conversely causes the non-priority routes to experience worse traffic conditions

Table 5-4. Field Data Collection Summary for Priority Runs on Evaluation Study

Test Arterial	Signal Coor.	Total Runs[1]	Peak - Runs	Driver[2] – Runs	Vehicle Make and Model –Runs
Chapel Hill Rd.	Before	214	AM – 128 PM – 86	AU – 95 JC – 96 CF – 15 NR – 8	1999 Ford Taurus – 80 1998 Chevrolet Venture Minivan– 80 1997 Jeep Cherokee – 16 1998 Toyota Camry – 15 1996 Oldsmobile Cutlass – 15 1997 Dodge Caravan – 8
	After	203	AM – 121 PM – 82	AU – 90 JC – 88 CF – 16 NR – 9	1999 Ford Taurus – 85 1998 Chevrolet Venture Minivan– 70 1998 Toyota Camry – 16 1996 Oldsmobile Cutlass – 23 1997 Dodge Caravan – 9
Walnut Street	Before	229	AM – 119 PM – 110	AU – 105 JC – 106 CF – 8 NR - 10	1999 Ford Taurus – 106 1996 Oldsmobile Cutlass – 105 1998 Toyota Camry – 8 1998 Dodge Caravan – 10
	After	227	AM – 118 PM – 109	AU – 102 JC – 106 CF – 9 NR – 10	1999 Ford Taurus – 103 1996 Oldsmobile Cutlass – 105 1998 Toyota Camry – 9 1998 Dodge Caravan – 10

Notes: 1. A run is defined as a one-way trip from one end of the corridor to the other end.

2. Initials of driver's first and last name.

as a trade-off. Thus, a small number of *non-priority* runs were made on the test corridors, following a route with frequent turns onto and off of the test corridor. The non-priority runs will help understand the overall effect of signal coordination on all vehicle movements.

5.4.7 Data Collection Summary

Table 5-4 displays a summary of the priority runs collected for the evaluation study. The table represents the total runs collected, of which some were not used in the data analysis for various reasons as discussed in Chapter 6 on Data Screening. Overall, the number of priority runs of the evaluation study totaled approximately 824 one-way runs, 100 vehicle-hours, and 2,020 vehicle-miles of simultaneous vehicle emissions and engine diagnostic data.

Table 5-5 displays a summary of the non-priority runs collected for the evaluation study. For the non-priority runs, each primary vehicle was driven between ten and 15

Table 5-5. Field Data Collection Summary for Non-Priority Runs on Evaluation Study

Test Arterial	Signal Coor.	Total Runs[1]	Peak - Runs	Driver[2] – Runs	Vehicle Make and Model –Runs
Chapel Hill Rd.	Before	72	AM – 34 PM – 38	AU – 36 JC – 36	1999 Ford Taurus – 36 1998 Chevrolet Venture Minivan– 36
	After	60	AM – 22 PM – 38	AU – 32 JC – 28	1999 Ford Taurus – 32 1998 Chevrolet Venture Minivan– 28
Walnut Street	Before	88	AM – 46 PM – 42	AU – 44 JC – 44	1999 Ford Taurus – 44 1996 Oldsmobile Cutlass – 44
	After	80	AM – 40 PM – 40	AU – 38 JC – 42	1999 Ford Taurus – 38 1996 Oldsmobile Cutlass – 42

one-way runs during both the before and after conditions. Each one-way run consisted of several turns onto and off of the test corridor. Table 5-5 represents the total runs collected, of which some were not used in the data analysis for various reasons as discussed in Chapter 6 on Data Screening. Overall, the number of non-priority runs of the evaluation study totaled approximately 300 one-way runs.

5.4.8 Key Lessons from Evaluation Study

Overall, the design of the evaluation study was much improved over the pilot study design by reducing the amount of emissions variability due to vehicle make and model, driver style, and fuel type that was present in the pilot study.

A lesson learned was that the before and after runs should be performed within a short enough time period to preclude major changes in traffic volumes or weather conditions. Even though the before and after runs for the Chapel Hill Road corridor were completed within a two month period, temperatures were approximately 10 degrees Fahrenheit colder in the after runs. Past research has indicated that ambient temperature can have an effect on vehicle emissions and as such, future experiments of this kind should attempt to minimize the temperature effect by performing the before and after runs in a short time period. However, because ambient temperature cannot be controlled, it may not be possible to eliminate variability in ambient temperature during the course of a field data collection effort. Instead, ambient temperature can be observed and evaluated statistically when analyzing data.

6.0 DATA REDUCTION AND SCREENING

In this chapter, methods for data post-processing are discussed. This work is important in developing an accurate database, and it includes developing protocols for data post-processing, discussion of possible errors in the dataset, and methods for making corrections.

6.1 Data Post-Processing

Each run of data collected by the OEM-2100^{TM} is summarized in a tab-delimited format in the "emissions" file, and then converted to spreadsheet format (Microsoft Excel^{TM}) for ease of data analysis, as shown in the upper left portion of Figure 6-1. The traffic event information in the "field" file, which is comprised of recorded timestamps for each major traffic event, is stored in spreadsheet format in a separate laptop, also indicated in Figure 6-1. Both of these data files are downloaded to a PC in the laboratory. Time-of-day time stamps are matched in the emission and field files, with the help of a program written in Microsoft Visual Basic, to create a single combined emissions and traffic data file.

The data fields in the combined data set include: time stamps; traffic events at each time stamp (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 economy (g/mi); NO concentration (ppm); HC concentration (ppm); CO concentration (volume percent); CO_2 concentration (volume percent); O_2 concentration (volume percent); NO mass emissions (g/sec); HC mass emissions (g/sec); CO mass emissions (g/sec); CO_2 mass emissions (g/sec); and road grade (percent). Information on the vehicle, driver, and weather conditions are reported in the summary sheet of the file. An example data file is given in Appendix II.

6.2 Data Screening

For quality assurance purposes, the combined data set for a vehicle run is screened to check for errors or possible problems. If errors are identified, they are either

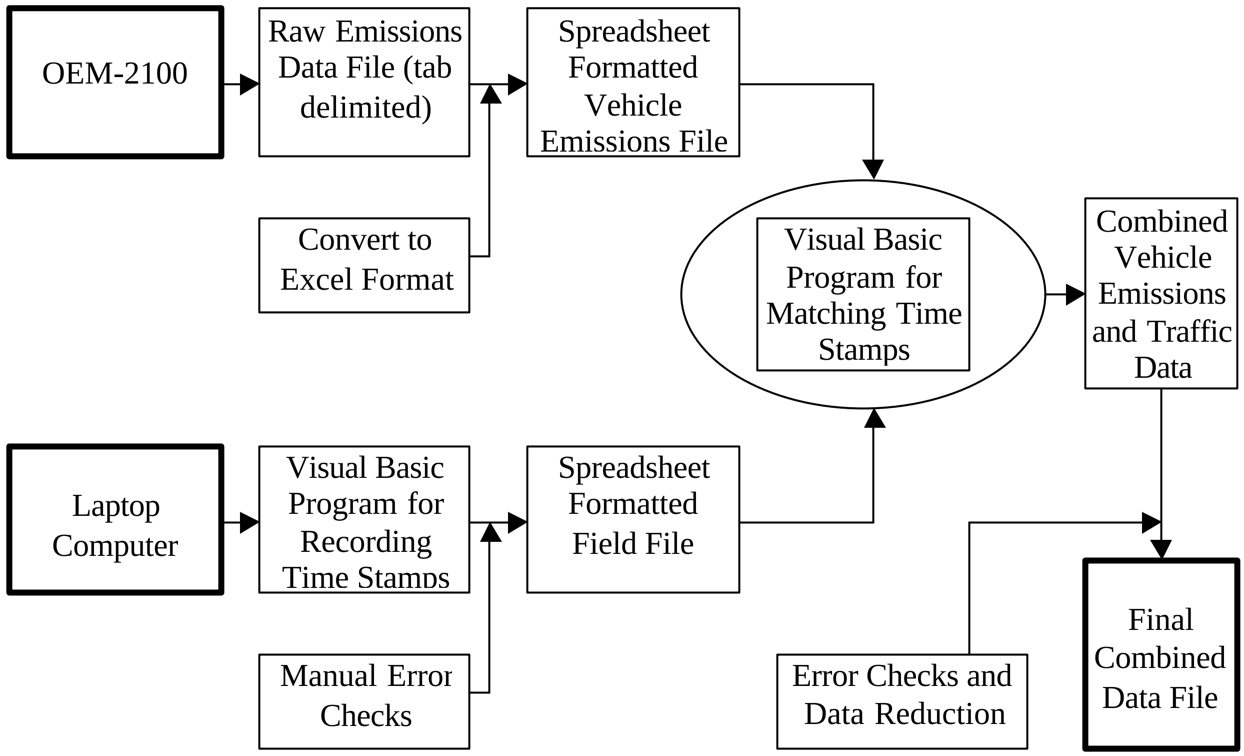


Figure 6-1. Simplified Schematic of Data Collection, Data Processing, and Data Screening.

corrected or the data set is not used for data analysis. First, the types of errors typically encountered are described followed by a discussion of methods for making corrections.

6.2.1 Typical Types of Errors

The predominant types of errors or problems include:

Abnormal Traffic Conditions – A small portion of runs were performed during abnormal traffic conditions. The most common abnormal traffic conditions included vehicle accidents, construction work, traffic signals malfunctioning, or unusually heavy congestion due to an incident on a nearby roadway. Although valid data were collected for these runs, they were not included for analysis regarding traffic parameters because they represent anomalies from the remainder of the runs.

Field Condition Errors – An isolated field condition error occurred on NC 54. The vehicle was being “zeroed” in a gas station parking lot, where ambient emissions were relatively high due to the gas fumes and number of vehicles idling. Thus, the ambient emissions level was higher than normal, thereby causing exhaust emissions during the run to be unrealistically low. These runs were not excluded from the analysis.

Laptop Computer Errors: These errors occur while operating the laptop program, such as not synchronizing the laptop and OEM-2100^{TM} clocks, the laptop battery running out before data collection is complete (leading to an incomplete data set for a run), or not pressing the timestamp keys at the proper place. A Program in the laptop computer gives a warning if more/less than the required number of intersection time stamps are entered. If the user hits a time stamp at an incorrect location, then it is the user's responsibility to enter a warning in the field file.

Engine Analyzer Errors: On occasion, communication between the vehicle's on-board computer and the engine scanner may be lost, leading to loss of data. Sometimes the loss of connection is because of a physical loss of electrical contact, while in other cases it appears to be a malfunction of the vehicle's on-board diagnostic system.

Gas Analyzer Errors: If a zeroing event occurs during a run, then no engine or vehicle emissions data will be measured during the zeroing event, leading to data gaps during a run. On some occasions, the values for one or more pollutants may be frozen during a run, most likely because of some type of error in the gas analyzer computer interface.

Negative Emissions Values: Because of random measurement errors, on occasion some of the measured concentrations, especially for NO, will have negative values that are not statistically different from zero or a small positive value. However, in situations where zeroing may have occurred in the presence of reference air containing significant amounts of a pollutant (e.g., NO), the instrument may systematically measure negative emission values. Typically, negative emissions measurements are assumed to be the same as zero. However, if the frequency and magnitude of negative measurements is too large, leading to suspected errors of more than five percent in the trip total emissions estimate, then the emissions data for that particular pollutant and that particular vehicle run are not used.

Synchronization Errors: In some cases, such as because of blockages in the gas sampling line, the time delay of the response of the gas analyzer may increase, leading to a discrepancy in the synchronization of the gas analyzer and the engine data streams. Methods for correcting this problem are detailed later in this section.

The data file for each run is checked for all but synchronization errors using a program written in Microsoft Visual Basic. The files having errors were flagged. After analyzing these files in detail, they were removed from the database for data analysis.

Table 6-1 provides a summary of data screening both all four corridors tested, including NC 54 and Miami Blvd included as part of the pilot study and Chapel Hill Road and Walnut Street included as part of the evaluation study. For the "before" case on NC 54, 60 of the runs were performed with Ford Taurus vehicles containing an ethanol and gasoline blend. These runs were excluded from further analysis because the fuel used was not comparable to that used for all other runs. Thus, of the 100 runs made during the before case on NC 54, 60 of them were set aside and only 40 valid runs remained for each of the three pollutants. In the after case, there was one run where a problem with the engine scanner resulted in an incomplete data set, and two problems in which a gas analyzer error resulted in an incomplete data set. In addition, in one run the HC emissions baseline appeared to be too low. Therefore, of the 106 attempted measurements, there were 103 valid data sets for CO and NO and 102 valid data sets for HC.

For the “before” case on Miami Blvd, seven of the runs were performed under abnormal traffic conditions. These runs were excluded from further analysis because the conditions were not comparable to all other runs. These conditions include unusually heavy traffic congestion and the occurrence of vehicle accidents. In these runs, data collection for a single one-way run could not be finished in 30 minutes and data for part of the run was not recorded because the OEM-2100^{TM} started zeroing. There were two other runs where problem with the engine scanner resulted in incomplete data sets, and another run in which a gas analyzer error resulted in an incomplete data set. In addition, in one run the HC emissions baseline appeared to be too low. Therefore, of the 100 attempted measurements, there were 90 valid data sets for CO and NO and 89 valid data sets for HC. In the after case, there were two runs where a problem with the engine scanner resulted in an incomplete data set. In one run the HC emissions baseline appeared to be too low. Therefore, of the 102 attempted measurements, there were 100 valid data sets for CO and NO and 99 valid data sets for HC.

For the “before” case on Chapel Hill Road, in 10 of the runs there were laptop computer errors. In the evaluation study, laptop computer entries were done by the driver while driving, whereas in the pilot studies laptop entries were done by another person. Having driver enter the time stamps data to the laptop computer caused a higher error rate in the evaluation study than in the pilot study. Laptop computer errors were mainly the wrong entry of the time stamps. The laptop battery sometimes ran out, causing loss of data. These runs were excluded from further analysis. There was one run where a problem with the engine scanner resulted in incomplete data sets, and nine runs in which a gas analyzer error resulted in an incomplete data set. In addition, in one run the NO emissions baseline appeared to be too low. There were 176 runs where synchronization errors occurred. However, these errors were corrected as discussed later in this chapter. Therefore, of the 214 attempted measurements, there were 194 valid data sets for CO and HC and 193 valid data sets for NO. In the after case, there were ten runs where abnormal traffic conditions occurred. These conditions were mainly due to unusually heavy traffic congestion, in which a one-way run took more than 30 minutes, leading to an unability to record data for the entire run because of instrument zeroing. In eleven of the runs, there were laptop computer errors mainly due to wrong entry of time stamps or the laptop battery running out. There were four runs where a problem with the engine scanner resulted in incomplete data sets, and five runs in which a gas analyzer error resulted in an incomplete data set. In addition, in one run the HC emissions baseline appeared to be too low. In 146 runs there were synchronization errors, however, these runs were corrected later. Therefore, of the 203 attempted measurements, there were 173 valid data sets for CO and NO and 172 valid data sets for HC.

For the “before” case on Walnut Street, in 10 of the runs there were laptop computer errors. Laptop computer errors were mainly wrong entry of the time stamps and the laptop battery running out. These runs were excluded from further analysis. There were seven runs where a problem with the engine scanner resulted in incomplete data sets, and seven runs in which a gas analyzer error resulted in an incomplete data set. In 102 runs, there were synchronization errors. These, however, were corrected later.

Therefore, of the 229 attempted measurements, there were 205 valid data sets for CO and HC and NO. In the after case, in nine of the runs there were laptop computer errors mainly due to wrong entry of time stamps, laptop battery running out, or wrong synchronization of the laptop clock with the OEM-2100™ clock. There were ten runs where problem with the engine scanner resulted in incomplete data sets, and six runs in which a gas analyzer error resulted in an incomplete data set. A total of 97 runs had synchronization errors, however, were corrected later. Therefore, of the 227 attempted measurements, there were 202 valid data sets for CO and NO and HC.

Overall, the most significant error seems to be engine scanner problem that happened for almost all of the datasets. The gas analyzer problem is the second most common type of error. Laptop computer errors occurred only in the evaluation study. Overall, 85 percent of the attempted runs resulted in valid data. In the evaluation study 89 percent of the attempted runs resulted in valid data sets, compared to only 81 percent in the pilot study.

The final result of the data reduction and screening process was a database of error-free files containing the second-by-second emission, engine diagnostic, and traffic event information. Appendix II shows a sample Excel file of the second-by-second data representing one corridor run.

6.2.2 Avoiding or Correcting Errors

The data collection protocol has been modified over time to try to avoid at least some of the errors identified in Section 6.2.1. For example, laptop errors can be avoided in part by making sure that the laptop battery has been fully charged. Some engine scanner errors can be avoided by making sure that the data cable connection is secured with duct tape. Many gas analyzer errors can be avoided by zeroing the instrument before each data collection run and by checking and refreshing the gas analyzer display before the run to make sure that changes in the concentrations of all gases are appropriately reflected in the on-board computer display. Negative emission problems can be avoided in part by zeroing in locations where the reference air is not stagnant or likely to be influenced substantially by emissions of other vehicles.

Table 6-1. Data Screening Process

Description	**NC-54**		**Miami Blvd.**		**Chapel Hill Rd.**		**Walnut Street**	
	Before	*After*	*Before*	*After*	*Before*	*After*	*Before*	*After*
Total Data Collection Runs	100	106	100	102	214	203	229	227
Abnormal Traffic Conditions	0	0	7	0	0	10	0	0
Field Condition Errors	60	0	0	0	0	0	0	0
Laptop Computer Errors	0	0	0	0	10	11	10	9
Engine Scanner Errors	0	1	2	2	1	4	7	10
Gas Analyzer Errors	0	2	1	0	9	5	7	6
Negative Emissions Errors	0	1 - HC	1 - HC	1 - HC	1 - NO	1 - HC	0	0
Synchronization Errors	0	0	0	0	176	146	102	97
Total Runs for Data Analysis	40 – HC 40 – NO 40 – CO	102 –HC 103 –NO 103 –CO	89 – HC 90 – NO 90 – CO	99 – HC 100 –NO 100 –CO	194 –HC 193 –NO 194 –CO	172 –HC 173 –NO 173 –CO	205 –HC 205 –NO 205 –CO	202 –HC 202 –NO 202 –CO

The problem with the time lag identified in the first OEM unit, as described in Section 3.3, was diagnosed first by a direct comparison between the two OEM instruments and, subsequently, by a detailed inspection of both units performed by the manufacturer. As noted in Section 3.3, it appeared from the direct comparison that the first OEM unit had a nine second delay in reporting gas analyzer data compared to the first OEM unit. In order to determine the relationship between the delay and engine data, the time trace of CO emissions was compared with a time trace of selected engine data. An example result is shown in Figure 6-2, for the case of engine RPM. From other studies, it has been reported that a sudden change in engine RPM can cause an increase in CO emissions because the engine tends to go into fuel enrichment mode (e.g., Degobert, 1995; Barth et al., 1997). It is clear from the data that the point of increase in engine RPM associated with a "throttle snap" corresponds to the onset of a CO emission spike as observed simultaneously by the second OEM unit. However, the first OEM unit does not respond until approximately nine seconds later. Thus, it was confirmed not only that the first OEM responds nine seconds later than the second OEM unit, but engine and emissions data for the second OEM unit appear to be well-synchronized, whereas the engine and emissions data for the first OEM unit have a nine second time lag.

In order to identify the reason for the time lag when comparing the two OEM units, both units were taken to Clean Air Technologies International, Inc. in May 2001. CATI concluded that a prefilter, which was present only on the first OEM and not on the second OEM, was clogged, causing a delay in the movement of exhaust gas in the sampling line. It was also concluded that the clogging was possibly a gradual event, implying that the magnitude of the time delay may have varied during the course of the field study. Therefore, a procedure was needed for reviewing the engine data and gas analyzer data streams for all measurements with the first OEM to quantify the discrepancy in the time delay that existed at any given time. Once the discrepancy was identified, the engine and gas analyzer data streams could be properly synchronized and analyzed, without loss of data. The most reliable method identified for identifying the time delay was to compare the engine RPM time series with the CO emissions time series.

Based upon the comparison of engine RPM and CO emissions for individual runs, variability in the time delay for the first OEM was identified. For example, the time delay for the gas analyzer data was three seconds for an August 29, 2000 data collection run with the 1999 Ford Taurus. The delay increased to nine seconds by the time of a December 13, 2000 run with the same vehicle. To illustrate how the time delay was identified, an example data set is provided based upon the August 29, 2000 run as shown in Figure 6-3.

Figure 6-3 shows a portion of the time trace for both CO emissions and engine RPM. A rapid increase in engine RPM occurs at approximately 233 seconds into the run. The increase in CO emissions associated with the change in engine RPM occurs approximately three seconds later. Therefore, the estimated time delay in this case is three seconds.

When the data are re-synchronized to remove the three second delay, there appears to be good agreement between the engine RPM data stream and the CO emissions stream, as shown in Figure 6-4. The process of identifying and correcting apparent errors in the synchronization is a somewhat subjective process, especially for data files in which there is not a clear throttle snap such as there was in the comparison test cases given in Section 3.3. In the field data collection runs, there may or may not be

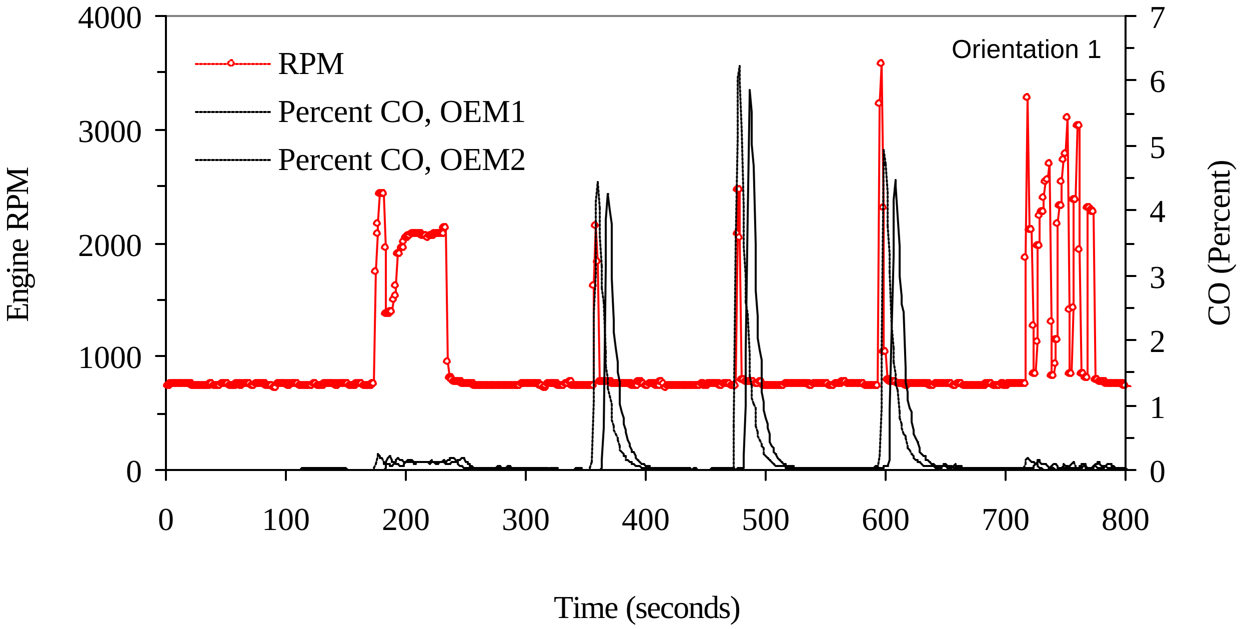


Figure 6-2. OEM-2100™ Comparison Test Results for 1996 Honda Civic

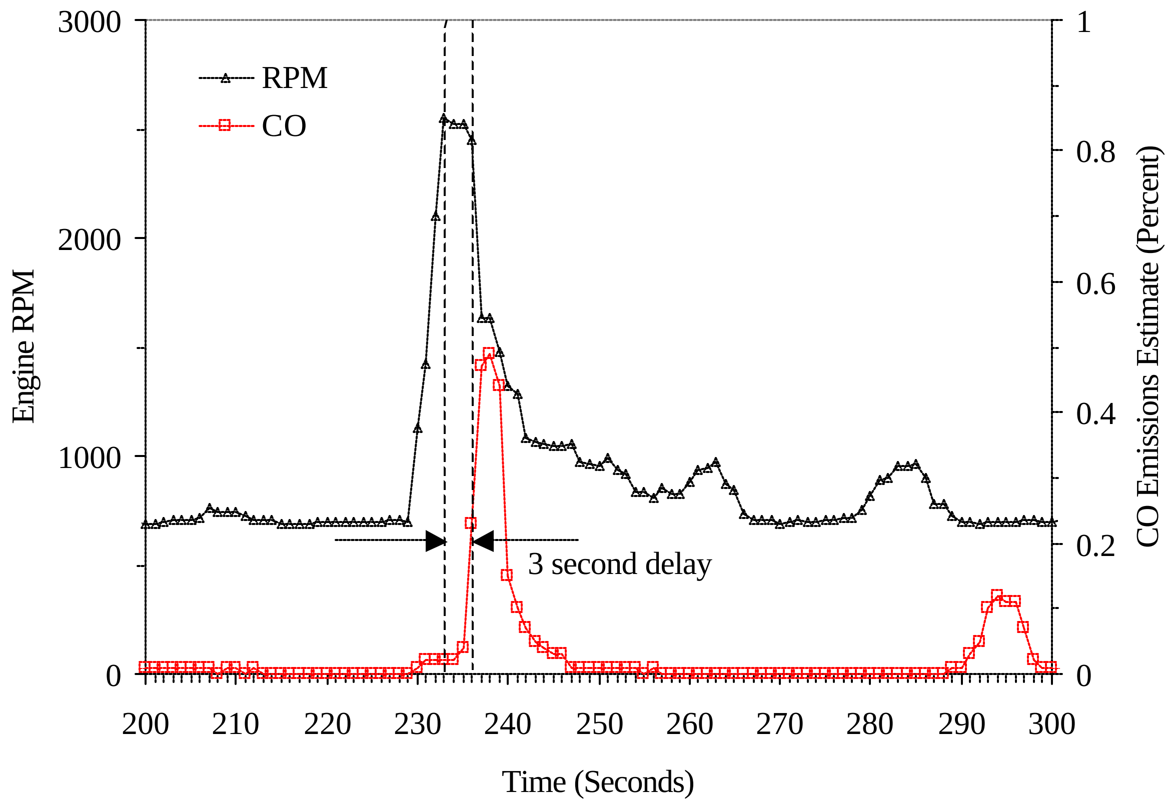


Figure 6-3. Example Data for Time Synchronization Problem

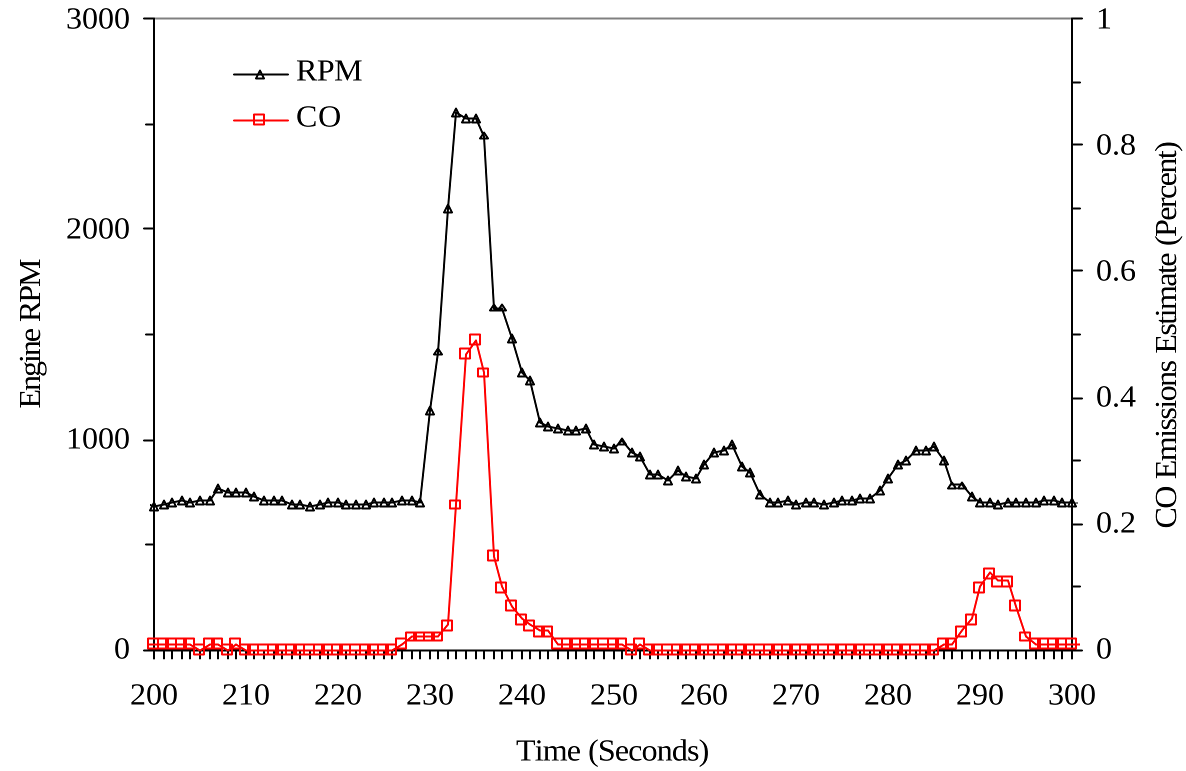


Figure 6-4. Example Data after Correcting for 3 Seconds

sharp changes in RPM. Typically, a sudden and large change in RPM will lead to a sharp increase in CO emissions. However, a moderate or gradual change in RPM may or may not lead to an increase in CO emissions. The width of the peak in RPM may or may not be exactly the same as the width of the peak for CO emissions. To help guide the identification of time lags, an assumption was made that the nine second time lag observed at the time of the comparison test was probably the largest time delay, and that up until that time the time delay had increased.

To assist in identifying time delays in the first OEM data sets, a Visual Basic program was written that interactively determines the time delay by plotting RPM and CO emissions time series together for a run. Then the user inspects the time delay by looking at different parts of the graph for that particular run. After that, the program asks the user for a value of time delay in order to shift the data to correct for the delay for that run. This process is done for each run that was collected by the first OEM unit.

After the engine scanner and gas analyzer data were properly synchronized, the mass emissions rates for each pollutant on a second-by-second basis were calculated using equations provided by CATI, which are the same equations used internally by the software in the OEM units.

To determine when the time delay problem started several runs that were collected by the first OEM unit were checked. The problem started with some Chapel Hill Road runs, but not present with pilot study runs.

During checks for time delay, it was observed that a different type of time delay error was present with data collected from Chevrolet minivan. An example for this type of time delay problem is illustrated in for data set collected on October 10, 2000 on Chapel Hill Road. Figure 6-5 shows a portion of the time trace for both CO emissions and engine RPM for Chevrolet Venture.

In Figure 6-5, a rapid increase in engine RPM occurs at approximately 602 seconds into the run. The increase in CO emissions associated with the change in engine RPM occurs approximately three seconds earlier, at approximately 599 seconds into the run. In this case, different from the previous cases, the increase in CO emissions occurs earlier than change in RPM values. After discussing this problem with CATI it was determined that the problem is due to delay in engine data. This problem is associated with only this type of vehicle and was not found with other vehicles during our diagnostic checks. Therefore, data from Chevrolet Venture were corrected for 3 seconds time delay in the engine data using the same Visual Basic program that was developed for other time delay problems with the exception that the time delay is constant for all runs with Chevrolet Venture.

A total of 521 files were collected in which there was a time lag problem, including 328 files for the 1999 Ford Taurus, 135 files for the 1998 Chevrolet Venture minivan, 42 files for the 1998 Toyota Camry and 16 files for the 1997 Jeep Cherokee. Of these 521 files, 321 files were for the Chapel Hill Road corridor and 200 files were for the Walnut Street corridor. The measurements made on the pilot study corridors were not affected by a time delay problem.

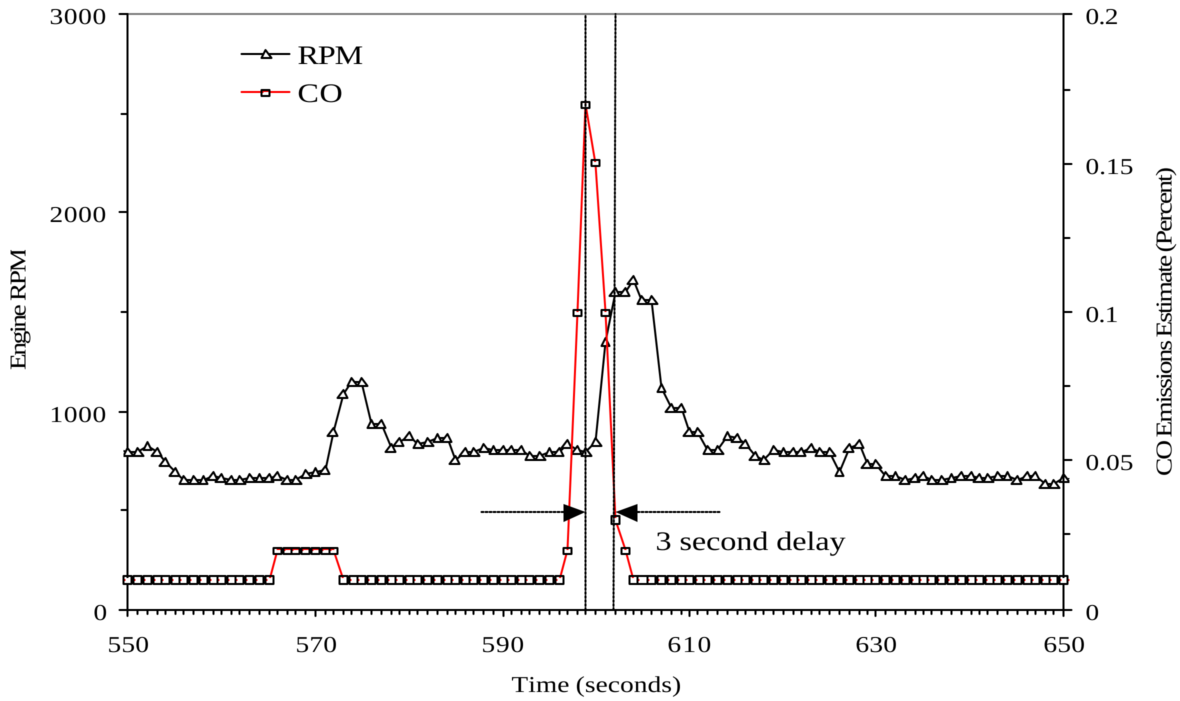


Figure 6-5. Example Data for Time Synchronization Problem for Chevrolet Venture

Since a preliminary analysis of the data had been prepared before the time delay problem for the first OEM unit was identified, it was possible to compare the trip emissions for the same data set before and after the data were corrected for time delay.

To compare the preliminary and corrected trip emissions parity plots were prepared. Figure 6-6 gives these parity plots for three pollutants. Linear regressions were fit to the data to determine whether there is difference between them or not. A slope of unity would indicate that there is no significant difference. A p-value obtained from the linear regression fit is another indication of statistical significance. Regression equations and R^2 values are given in Figure 6-6.

There are 521 data points in each of the plots in Figure 6-6. Each point represents one run collected on Chapel Hill Road or Walnut Street using one of the vehicles that had a time lag problem. For each of the three pollutants, the R^2 value is in excess of 0.99, which indicates that there is large degree of precision when comparing the corrected and preliminary estimates of run average emissions. In the case of NO and HC, the slope of the best fit line for the data in the parity plot is within one percent of a value of one,

Table 6-2. Percent Change in Pollutants for Data Collected on Chapel Hill Road with 1999 Ford Taurus after Correcting for the Time Delay

Mode	**NO (%)**	**HC (%)**	**CO (%)**
Idle	-21	-0.82	-27
Acceleration	45	4.2	51
Deceleration	-53	-0.9	-58
Cruise	1.7	-0.09	-24

indicating that there is also a high degree of accuracy when comparing the corrected and preliminary run average emissions. For CO, the slope of the best fit line is 1.12, indicating that the corrected CO emissions estimates are, on average, 12 percent larger than the preliminary CO emissions estimates. The corrected emissions estimates were calculated based upon properly synchronized raw data. For this reason, it is not expected that the corrected emissions estimates should have the same values as the uncorrected preliminary data. A difference of 12 percent is not considered to be large. The overall inference from Figure 6-6 is that the preliminary run-average emissions estimates are nearly identical to the corrected run-average emissions estimates for HC and NO, and that there is not a substantial difference, from a practical perspective, in the estimates for CO when comparing corrected and preliminary data. For this reason, analyses that were completed based upon run-average preliminary emissions estimates were not recalculated. These results also indicate that emissions estimates are robust to at least some uncertainty regarding the correct synchronization.

In some cases there are substantial differences in micro-scale emissions estimates, such as for second-by-second data and for modal emissions data. For example, for the example file given previously in Figure 6-3 and Figure 6-4, the percent change in pollutants are estimated after correcting the data for time delay. The results are given in Table 6-2. The results in Table 6-2 shows that the change is between a 58 percent decrease for CO during deceleration to a 51 percent increase for CO during acceleration. For acceleration mode changes are all positive. For other modes changes are negative except NO emissions during cruising mode. These results suggest that estimation of modal rates should be done using the corrected data. Therefore, any analyses based upon microscale emissions estimates were redone so that they are based upon the final analyses corrected for time delay problems.

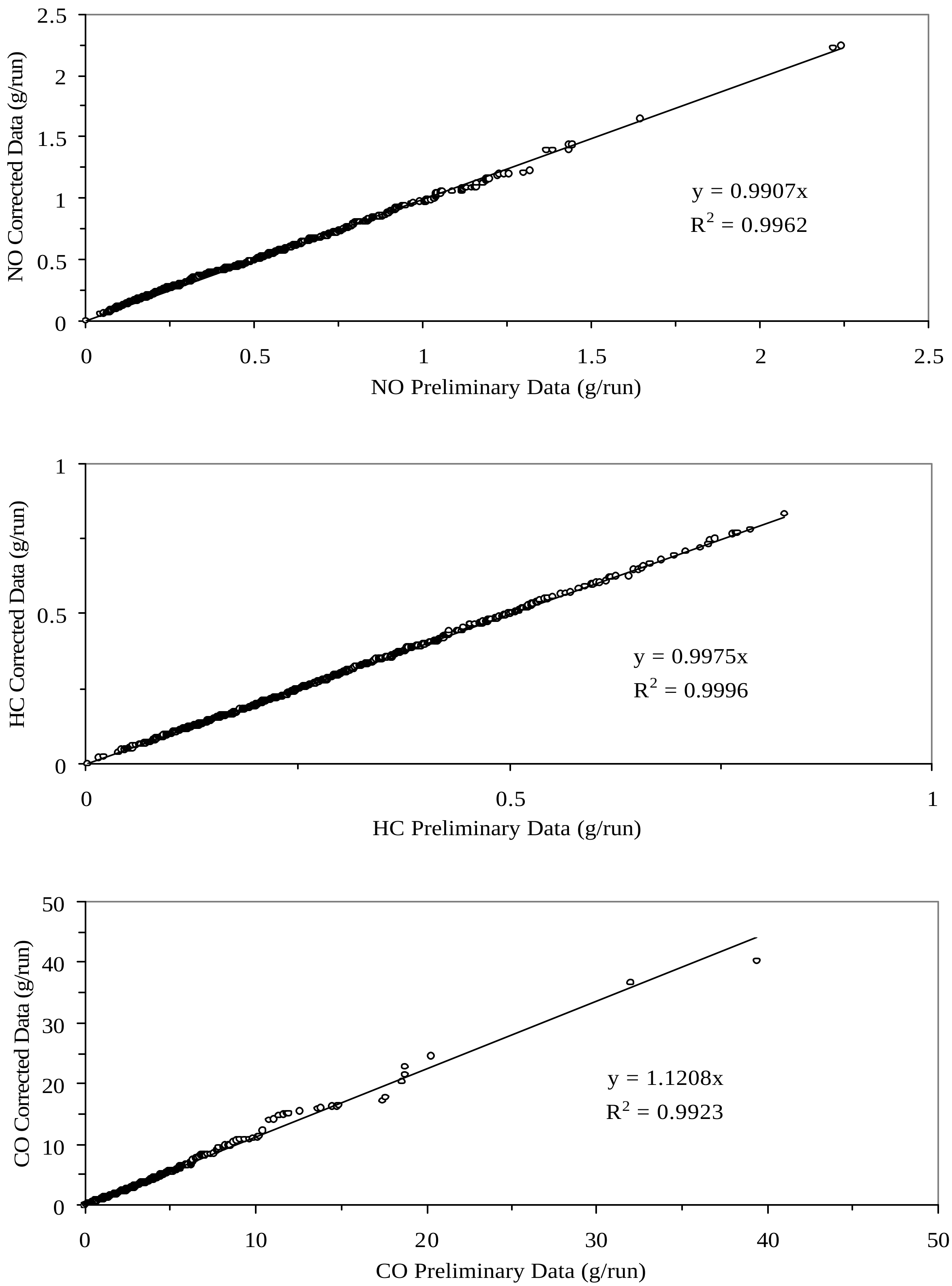


Figure 6-6. Comparison of Preliminary versus Corrected Data

6.3 Estimation of Second-by-Second Corridor Characteristics

6.3.1 Vehicle Position

Vehicle position was determined based upon recording of time stamps when the vehicle passed key landmarks (e.g., the center of each signalized intersection) and by use of the speed trace obtained from the engine scanner to estimate vehicle position between landmarks. The distance of each roadway segment between landmarks was estimated based upon an average of differences in vehicle odometer readings. As an example, the segment between two intersections might have a length of 0.3 miles. The measurement of segment lengths by odometer readings was typically done for four runs using Chevrolet Venture minivan, and then these runs are averaged.

The final data files produced by the data processing procedure include time stamps indicative of specific locations and the second-by-second speed data. Thus, it is possible to use the second-by-second speed data to estimate the vehicle's progress at any given time in going from one end of a segment to the other end of the segment. For example, if the vehicle travels at 30 mph for 12 seconds after leaving an intersection, it has traveled a distance of one-tenth of a mile (30 mph x 1 hr/3,600 sec x 12 sec = 0.1 mile). The segment distance between intersections can be estimated from the speed data by integrating between the time that the vehicle crosses the first intersection and the time that the vehicle crosses the second intersection. The segment distance estimated by integration of the speed trace data may be different than that estimated from an average of vehicle odometer readings. The former method is referred to here as the "speed data" method and the latter as the "odometer" method. The odometer method is taken as a reference. Therefore, for each segment between intersections, the distance traveled between the intersections is estimated by the speed data method but is normalized based upon the odometer method. For example, if the speed data method yields an estimate of a distance traveled of 0.29 miles from the center of one intersection to the next, and if the estimate of the same distance from the odometer method is 0.30 miles, then the distances estimated by the speed data method are corrected by a factor of 0.30/0.29. Thus, the position of the vehicle at any time on the segment is estimated using a normalization procedure. This procedure is repeated for each corridor segment.

6.3.2 Road Grade

A Visual Basic program was written that allowed the road grade to be estimated for each second of data. As described in the Chapter 4, the road grade was measured at 0.1-mile increments. The program matched the second-by-second vehicle position with the two nearest road grade measurements. The program then linearly interpolated between these two grade measurements to assign a road grade to each second of data.

6.4 Estimation of Traffic Flow Characteristics

6.4.1 Driving Modes

Vehicle emissions seem to be different in different operational mode of the vehicles. The analysis of emissions with respect to driving modes, also referred to as modal emissions, has been done in several recent studies by others (Barth *et al*., 1996; Tong *et al.*, Barth *et al.*, 1997; Bachman, 1999). Driving is typically divided into four modes: (1) acceleration; (2) cruise; (3) deceleration; and (4) idle. In this work, the second-by-second emissions data were divided into these four modal categories and the average emissions rates for each mode were calculated.

The defining characteristics of a driving mode are somewhat arbitrary. As an *a priori* assumption, the following definitions have been used. However, these definitions can be modified at a later time if other classifications of modes are found to have better explanatory power. Idle is defined as based upon zero speed and zero acceleration. The definition of the acceleration mode includes several considerations. First, the vehicle must be moving and increasing in speed. Therefore, speed must be greater than zero and the acceleration must be greater than zero. However, vehicle speed can vary slightly during events that would typically be judged as cruising. Therefore, in most instances, the acceleration mode is based upon a minimum acceleration of two mph/sec. However, in some cases, a vehicle may accelerate slowly. Therefore, if the vehicle has a sustained acceleration rate averaging at least one mph/sec for three seconds or more, that is also considered acceleration. Deceleration is defined in a similar manner as acceleration, except that the criteria for deceleration are based upon negative acceleration rates. All other events not classified as idle, acceleration, or deceleration are classified as cruising. Thus, cruising is approximately steady speed driving but some drifting of speed is allowed. These definitions are not the same as those used in other studies. However, whether these definitions are useful or not can be evaluated by analyzing the emissions data.

A program was written in Microsoft Visual Basic that calculates the driving mode for second-by-second data and determines the average value of emissions for each of the driving modes and for the total trip.

6.4.2 Intersection Control Delay

Field control delay was estimated through the use of the second-by-second speed data and the timestamps recorded as a vehicle passes through the center of a signalized intersection. Control delay, as defined in the HCM (TRB, 1997), is the difference in time it takes a vehicle to reach cruising speed at a distance downstream of an intersection (after slowing down and stopping at the intersection) and the time taken had the vehicle maintained its cruising speed through the intersection. Figure 6-6 illustrates the concept of control delay on a time-distance graph.

Another type of delay shown in Figure 6-7 is *total delay*, which is the time from when a vehicle first starts to slow down until the vehicle reaches cruise speed again. The total delay is always larger than the control delay. The third type of delay shown in Figure 6-7 is *stopped delay*, which is the vehicle idling time.

The control delay at a signalized intersection was estimated through a three-step process:

- estimate total delay using a decision tree for determining when a vehicle enters and exits a delay event (time A to B in Figure 6-7),
- estimate stopped delay by summing all seconds when a vehicle is traveling at less than or equal to three mph immediately upstream of the signalized intersection, and
- estimate control delay as a function of total delay and stopped delay.

The first step in estimation is to determine the times when a vehicle enters and exits a delay event using a decision tree. A Visual Basic program was developed that begins by searching through the second-by-second speed trace for the timestamp when the vehicle passes through the center of an intersection. The program then runs through a

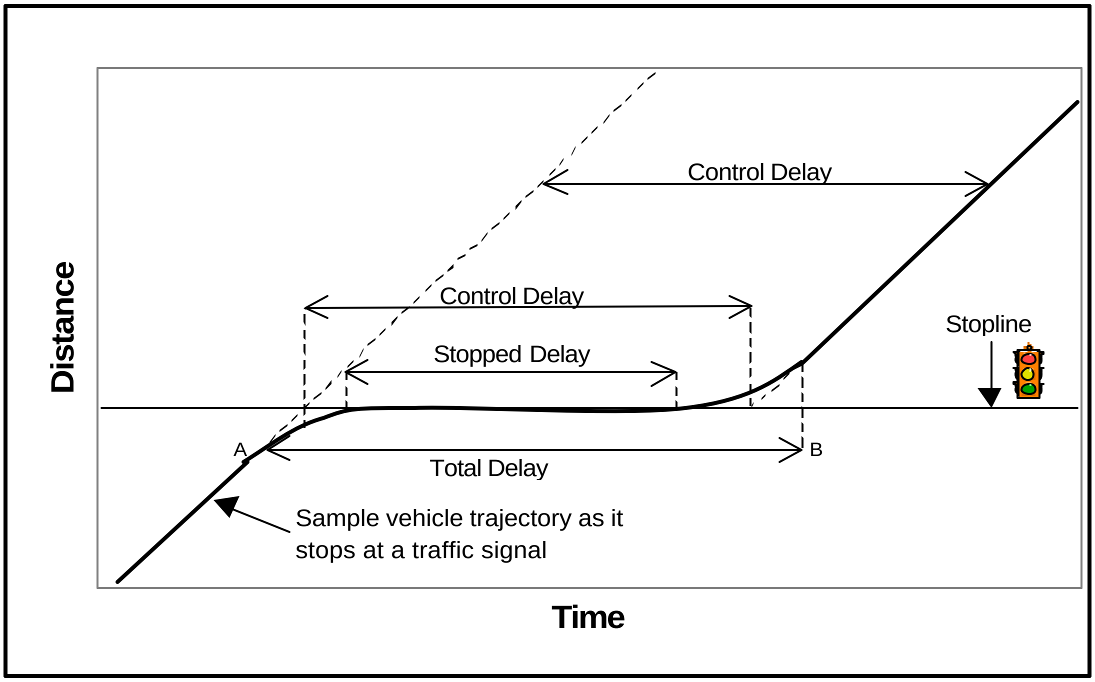


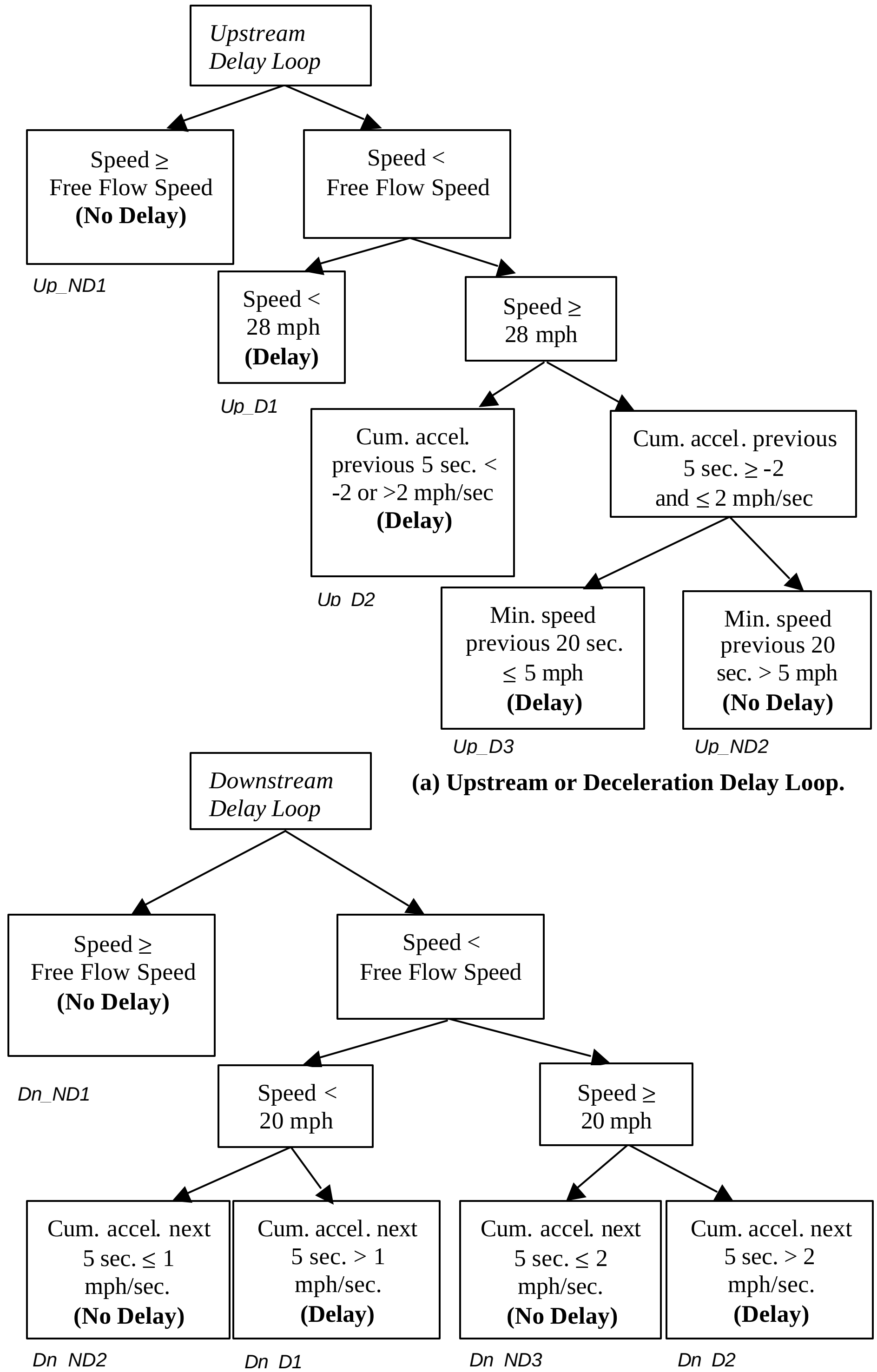
Figure 6-7. Illustration of Delay Types at Signalized Intersection

decision tree both upstream and downstream of the center of intersection to determine when the vehicle entered and exited the delay event.

The basic premise of the decision tree is to check in each second whether the vehicle is experiencing delay. If a 'delay' decision is produced, then the decision tree determines that the second being tested is in delay and continues checking the next upstream or downstream second(s) until if finds the time where the vehicle is no longer in delay. A schematic diagram of the two decision trees (one for upstream delay, and the other for downstream delay) is shown in Figure 6-8.

A number of speed and acceleration parameters are used in the decision tree. For example, the upstream loop places all speeds less than 28 mph in delay and thus loops to the next second. This parameter was calibrated through a sensitivity analysis. Sensitivity tests were also performed on the other parameters in the decision tree. The sensitivity tests helped locate the "breaks" and asymptotes in the decision tree.

The decision trees are designed to check a number of parameters that would create an intersection delay situation. The most obvious parameter is whether the current vehicle speed is lower than the free flow speed. Under ideal conditions, this would be the only parameter needed to measure total delay. However, often in real-world conditions



(a) Upstream or Deceleration Delay Loop.

(b) Downstream or Acceleration Delay Loop.

Note: 'Delay' means the second being tested is experiencing delay and the program loops to the next second. 'No Delay' means the second being tested is not experiencing delay and thus exits the loop.

Figure 6-8. Total Delay Decision Tree

vehicle speeds are less than free flow conditions but not experiencing intersection delay. This occurs during congested conditions, where the operating speed can be less than the free flow speed. This also occurs when the lead vehicle in a platoon is traveling less than the speed limit, forcing all following vehicles to travel less than their desired speed.

For these reasons, the decision tree includes a parameter to check the cumulative acceleration over a five-second period. The vehicle may be traveling less than the free flow speed, but if the vehicle has traveled at approximately the same speed over a five-second period, then the decision tree determines the vehicle is in cruise mode and not experiencing delay. In the downstream delay loop, the criteria for categorizing cruise mode versus acceleration mode is more stringent if the vehicle speed is less than 20 mph.

It is more difficult to measure upstream delay during over-capacity conditions because of the resulting stop-and-go actions experienced during queue move-up times. For example, an over-capacity intersection may create a situation of deceleration, idling, acceleration during queue move-up, then another deceleration and idling period, and a final acceleration through the intersection. Thus, the decision tree cannot simply look for a cruise mode to determine when the vehicle has exited delay, because the cruise mode may be merely a queue move-up condition.

For this purpose, an additional parameter related to the minimum speed over the previous 20 seconds was added for the upstream delay loop. If the vehicle is in cruise mode, but the minimum speed over the previous 20 seconds is less than five mph, then the decision tree determines this is merely a queue move-up condition and is thus still experiencing delay.

Closely spaced intersections cause difficulties in estimating control delay because long queues can extend beyond the next upstream intersection. The Highway Capacity Manual (HCM) calculates intersection control delay assuming isolated conditions (TRB, 1997). This study intended to calculate control delay with the same definition as used in the HCM. Thus, the decision tree continues stepping through the upstream loop even if it extends beyond the upstream intersection. However, when delay continues past the upstream intersection, the program does not attempt to estimate delay at the upstream intersection because any delay would be due to the queues created by the downstream intersection, not the intersection in question.

The next step in the estimation of control delay was calculation of stopped delay. A speed of three-mph or lower was used to indicate a stopped condition. This threshold was needed to ensure that low speeds recorded during idling were classified as stopped delay.

The stopped condition was only checked for the period determined to be in total delay, thereby precluding any stopped conditions not due to signalized intersections.

Once the total delay and stopped delay were determined, the control delay was then estimated using the following equation:

$$
\begin{aligned}
\text{Control Delay} &= \text{Total Delay} - 0.7\,(\text{Acceleration} + \text{Deceleration Delay}) \\
&= \text{Total Delay} - 0.7\,(\text{Total Delay} - \text{Stopped Delay}) \\
&= 0.3\,(\text{Total Delay}) + 0.7\,(\text{Stopped Delay}) \qquad (6\text{-}1)
\end{aligned}
$$

This equation was formulated by checking the average speed just before vehicles entered and exited total delay, as well as the average speed while vehicles were in the deceleration and acceleration portion of delay. These checks were performed for the Miami Boulevard and Chapel Hill Road runs. The difference in the total delay and the stopped delay represents the deceleration and acceleration portion of delay.

The average speed during the three seconds immediately before and the three seconds immediately after a vehicle enters total delay describes the operating speed of the vehicle outside the influence of the traffic signal. On Miami Boulevard and Chapel Hill Road, the average speed immediately before and after experiencing control delay was 40 mph. The average speed during the deceleration and acceleration portion of delay was 27 mph for both corridors. Thus, the deceleration and acceleration portion of delay is approximately 70 percent (27/40) of the operating speed. This ratio describes the portion of the deceleration and acceleration delay that is not part of the control delay because the vehicle would need that much time to travel through the intersection regardless of the traffic signal. Figure 6-9 illustrates the three-step process used to calculate intersection control delay. In the example, the control delay was estimated to be 19.6 seconds for the northbound through movement at the Miami Boulevard/I-40 WB Ramp intersection.

Spreadsheet Output of Second-by-Second Data

Time of Day	Center of Intersection	Speed (mph)	Accel. (mph/s)
8:27:42		35	2
8:27:43		36	1
8:27:44		38	2
8:27:45		39	1
8:27:46		37	-2
8:27:47		35	-2
8:27:48		35	0
8:27:49		34	-1
8:27:50		33	-1
8:27:51		30	-3
8:27:52		28	-2
8:27:53		25	-3
8:27:54		22	-3
8:27:55		19	-3
8:27:56		17	-2
8:27:57		11	-6
8:27:58		11	0
8:27:59		3	-8
8:28:00		3	0
8:28:01		1	-2
8:28:02		0	-1
8:28:03		0	0
8:28:04		0	0
8:28:05		1	1
8:28:06		1	0
8:28:07		1	0
8:28:08		1	0
8:28:09		1	0
8:28:10		3	2
8:28:11		3	0
8:28:12		10	7
8:28:13		11	1
8:28:14		16	5
8:28:15	Miami Blvd/I-40 WB Ramp	18	2
8:28:16		21	3
8:28:17		24	3
8:28:18		27	3
8:28:19		28	1
8:28:20		30	2
8:28:21		32	2
8:28:22		32	0
8:28:23		33	1
8:28:24		33	0
8:28:25		33	0
8:28:26		32	-1
8:28:27		32	0

Steps in Estimating Control Delay

1. Estimate Total Delay.
2. Estimate Stopped Delay.
3. Estimate Control Delay as a function of Total Delay and Stopped Delay.

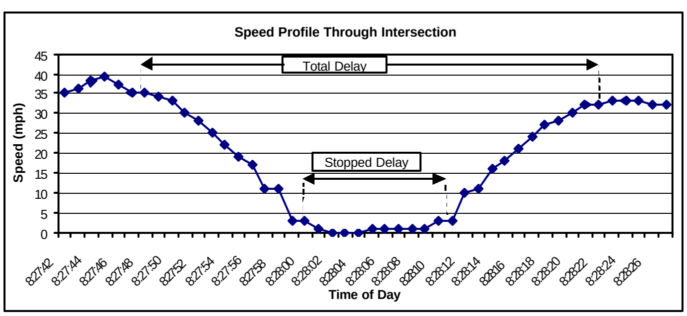
Step 1a: Find time when vehicle passes center of intersection.

Step 1b: Use 'Upstream Delay Loop' to determine when vehicle enters delay. For this example, the loop determines upstream delay starts at 35 mph.

Step 1c: Use 'Downstream Delay Loop' to determine when vehicle exits delay. For this example, the loop determines downstream delay stops at 32 mph.
TD = 35 sec.

Step 2: Estimate stopped delay as time when speed is less than or equal to 3 mph.
SD = 13 sec.

Step 3: Calculate Control Delay using the following formula:
CD = 0.3(TD) + 0.7(SD)
CD = 0.3(35) + 0.7(13)
CD = 19.6 sec.



Notes: Free flow speed was determined to be 45 mph through this intersection. TD = Total Delay, SD = Stopped Delay, CD = Control Delay.

Figure 6-9. Example Calculation of Control Delay

6.4.3 Free Flow Speed

The free flow speed was estimated separately for each study corridor. Free flow speed is defined in the HCM as the average speed during low volume conditions outside the influence area of traffic signals (TRB, 1997). Speeds above 40 mph were estimated to be outside the influence of traffic signals (the speed limit is predominantly 45 mph on the study corridors) and were thus used as the sample range for free flow speeds. The average speed when vehicles were traveling above 40 mph was calculated from the second-by-second speed traces for each run. The resultant speed was then increased slightly to account for some travel under acceleration and deceleration modes (as opposed to cruise mode, where free flow speed should technically be measured). This adjusted speed was used as the free flow speed for the decision tree. A separate free flow speed for each corridor was calculated and was shown previously in Tables 5-1 and 5-3.

6.4.4 Intersection and Corridor Stops

An intersection stop is typically measured in binary form. In other words, if a vehicle stops one or more times at a signalized intersection, then that vehicle registers an intersection stop ('1' in binary form). If a vehicle does not stop at all, then an intersection stop is not registered ('0' in binary form). During over-capacity conditions, a vehicle can stop two or more times while moving up in a queue, but only one intersection stop would be registered.

Intersection stops were measured using the stopped delay parameter discussed previously. If there was no stopped delay at a particular intersection for a run, then no intersection stop was registered. If the stopped delay was greater than zero seconds, then an intersection stop was assigned.

The number of total corridor stops includes all stops along a corridor, including all stops due to a signalized intersection and stops due to mid-block turning vehicles or incidents. At an over-capacity intersection, each stop during the queue move-up period would be counted. Thus, the number of total corridor stops will always be equal or greater than the sum of the intersection stops.

6.5 Estimation of Second-by-Second Engine Characteristics

6.5.1 Equivalence Ratio

The equivalence ratio is considered to be an important parameter that can help explain variation in CO, HC, and NO emissions (Goodwin and Ross, 1996; Sher, 1998; Degobert, 1996). The equivalence ratio is defined as the ratio of the actual fuel-to-air mass ratio in the engine divided by the stoichiometric (sometimes referred to as "theoretical") fuel-to-air mass ratio. If the engine is operating at stoichiometric fuel-to-air ratio, the equivalence ratio is one. If the engine is operating with an excess of fuel compared to the air intake, then the engine is running "fuel-rich" and the equivalence ratio will be greater than one. Conversely, if the engine is running "fuel lean", the equivalence ratio will be less than one. Gasoline-fueled vehicle equipped with a three-way catalyst are computer-controlled to operate very close to an equivalence ratio of one during most driving. However, if higher vehicle performance is required, such as during hard acceleration, the engine will operate in a fuel-rich mode, referred to as "enrichment." Enrichment helps protect the catalyst during high performance events by preventing the catalyst from becoming too hot. It is well known that CO emissions increase during enrichment. OEM-2100™ reports fuel and air use on a second-by-second basis. A program was written in Visual Basic that calculates the equivalence ratio using the fuel and air data.

6.5.2 Power Demand

Vehicle emissions product of engine combustion process which is the result of power requirement or demand from the engine. Previous studies showed that a relation between power demand and emissions of some pollutants such as CO, can be established (Barth *et al.*, 1997; Bachman, 1999).

In order to estimate the power demand of vehicles several different approaches have been proposed. These approaches range from the very complex models where power demand of different parts of the engine are estimated, to coarse approximations. The model selection depends on the types of data available. Complex models require detailed information regarding the vehicle and its environment, such as wind resistance, air density, transmissions efficiency and drive-train efficiency. In this study an approximation widely used by the researchers have been used (e.g., Barth *et al.*, 1997; Bachman, 1999). Equation used for power estimation is given in Equation 6-2 below.

$$P = v \times a \tag{6-2}$$

where:

P: Power Demand

v: Vehicle speed (mph)

a: Vehicle acceleration (mph/sec)

OEM-2100^{TM} reports vehicle speed on a second-by-second basis. One can estimate vehicle acceleration based upon vehicle speed. In this study a program was written in Visual Basic that calculates the power demand using the vehicle speed and acceleration data.

7.0 EXPLORATORY ANALYSIS

After collecting, reducing, and screening the field data, and forming a database, an exploratory analysis was conducted to better understand the variability of vehicle emissions and the basic trends between explanatory parameters and vehicle emissions. This exploratory analysis is a necessary step before developing any relationships between vehicle emissions and explanatory variables.

This chapter first presents the speed and emissions traces in order to show the type of data collected. Then a discussion is given on Analysis of Variance (ANOVA) of parameters that have explanatory power with respect to vehicle emissions. A more detailed discussion of the effect of some explanatory variables is then given.

7.1 Visualization of Data Using Time Traces

In this section, an example of how the engine and emissions data can be visualized is presented. For this purpose, an example file will be used. Examples from the data file of an individual trip made on August 30, 2000 are provided in Figure 7-1 through Figure 7-6 for vehicle speed, CO emissions, NO emissions, HC emissions, CO_2 emissions, and fuel consumption, respectively with 1999 Ford Taurus on Chapel Hill Road.

Figure 7-1 is labeled with the location of the vehicle at specific times. The trip begins south of Morrisville Parkway and ends a short distance north of Airport Boulevard. There is notation in the figure indicating when the vehicle entered the queue for an intersection, and when the vehicle crossed the center of the intersection, such as at Aviation Parkway. The travel time on the corridor was approximately 13 minutes. The instantaneous speed ranged from zero to approximately 50 mph, and the average speed was 11 mph. The longest waiting times occurred in the queue at the intersection with Morrisville Parkway.

For all four pollutants, it is clear that the highest emission rates, on a mass per time basis, occur during small portions of the trip. For example, for CO, the emission rate exceeds 0.02 grams per second only five times during the trip, and emissions exceed 0.10 grams per second only one time. The largest peak in the emission rate occurs at the same time as the acceleration from zero to approximately 40 mph as the vehicle clears the intersection with Aviation Parkway. In fact, most of the peaks in CO emission rate tend to coincide with accelerations. The CO emission rate remains below 0.02 grams per second for the first ten minutes of the trip, corresponding to a period of stop-and-go travel with speeds ranging from zero to less than 25 mph. These data suggest that the CO emission rate during idling or crawling are comparatively low compared to the CO emissions during acceleration.

The emission rate for NO remains below 0.2 mg/sec for almost the first 11 minutes of the trip. The NO emission rate increases by a factor of almost 100 during acceleration through the intersection with Aviation Parkway. The NO emissions appear to be very sensitive to the higher speed travel toward the end of the trip, with several large peaks in emission rate occurring during the last three minutes of the trip.

The emission rate for HC responds in a manner almost qualitatively the same as that for CO. The peaks in HC emissions occur at approximately the same times as the peaks in CO emissions, especially during low speed travel during the first ten minutes of the trip. Similar to both CO and NO, the HC emission rates are highest during the higher speed portion of the trip, also during which there is considerable variation in speed.

The CO_2 emissions trace and the fuel consumption emissions trace are shown to be very similar to each other. Because the emissions of CO and HC are low compared to the CO_2 emissions, over 99.7 percent of the carbon in the fuel is estimated to be emitted as CO_2. Therefore, CO_2 emissions in this case are a good surrogate for fuel consumption. The peaks in CO_2 emissions and fuel consumption occur during acceleration and higher speed driving.

In general, the time traces indicate that there is a relatively large contribution to total emissions from short-term events that occur within the trip. This implies that efforts to reduce on-road emissions should be aimed at understanding and mitigating these short-term events and variables affecting to them. In the following sections, variables that have significant effect on vehicle emissions will be investigated.

7.2 Analysis of Variance Method

Analysis of Variance (ANOVA) is used to help identify variables which can help explain the observed variability in emissions. ANOVA is one of the most widely used statistical techniques. As stated by Neter *et al.* (1990) ANOVA is used for studying the

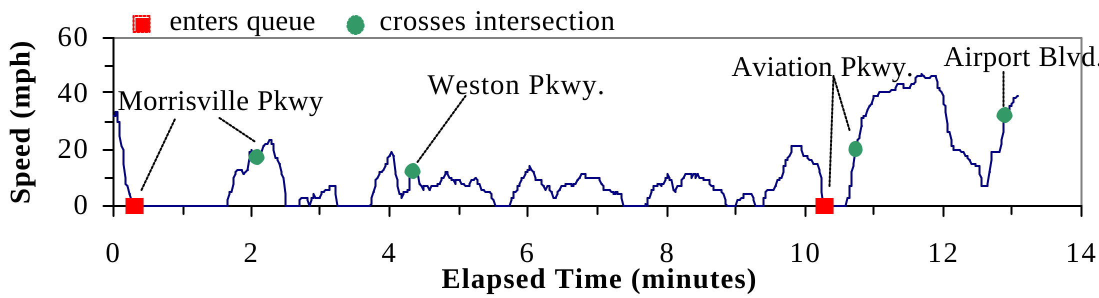


Figure 7-1. Example of Speed versus Time Trace

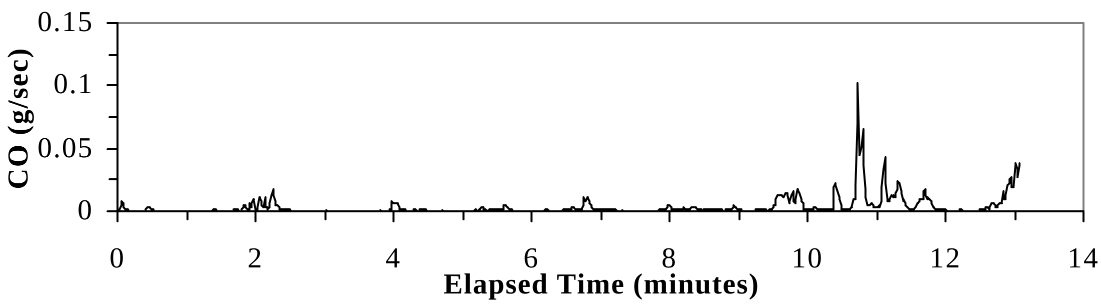


Figure 7-2. Example of CO Emissions versus Time Trace

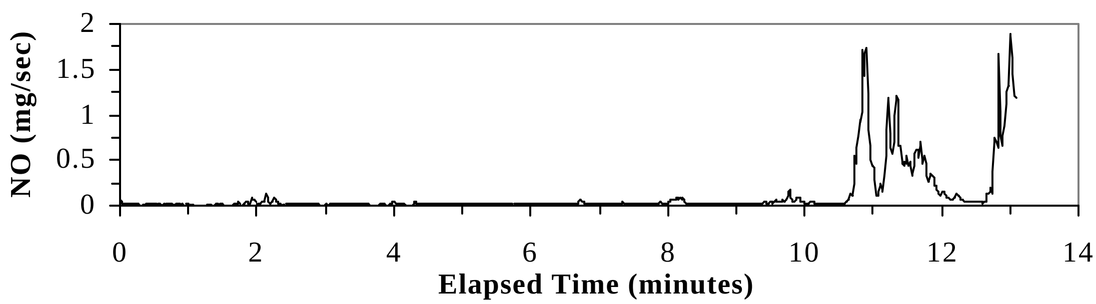


Figure 7-3. Example of NO Emissions versus Time Trace

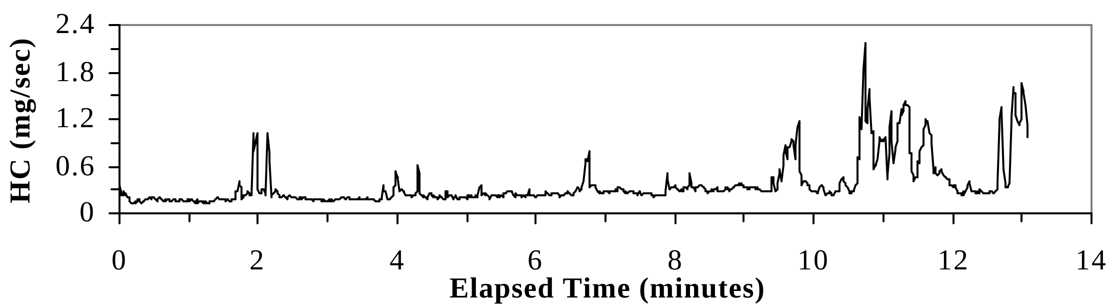


Figure 7-4. Example of HC Emissions versus Time Trace

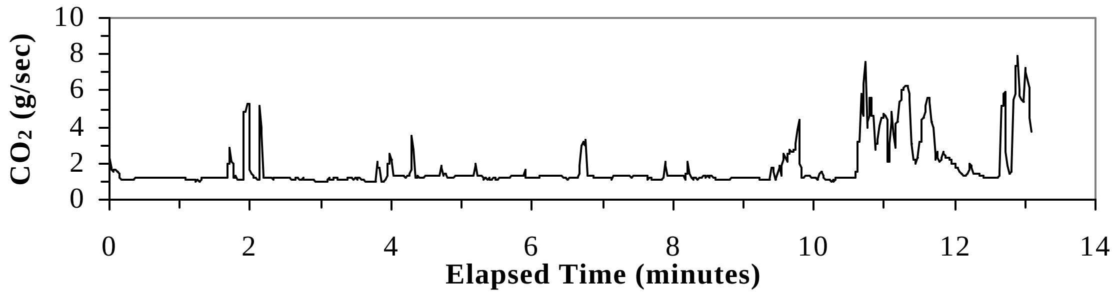


Figure 7-5. Example of CO_2 Emissions versus Time Trace

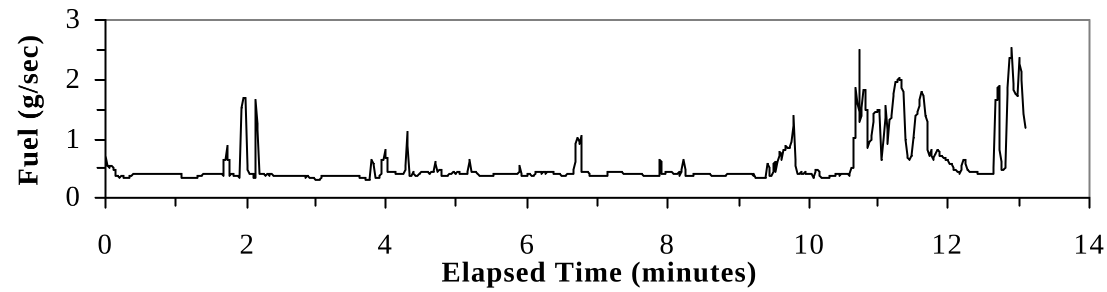


Figure 7-6. Example of Fuel Consumption versus Time Trace

relation between a response variable and one or more explanatory or predictor variables. These models do not require any assumptions about the nature of the statistical relation between the response and explanatory variables. ANOVA does not require that explanatory variables be quantitative, categorical variables can also be used. ANOVA is not concerned with analyzing variances but rather analyzing variation in means (Casella and Berger, 1990).

ANOVA can be used to analyze the simultaneous effects of several parameters together, including interaction effects. Failing to consider interaction effects and correlation between explanatory variables can give erroneous results. ANOVA also enables results to be tested as to whether they are statistically significant unlike other methods such as Regression Trees where statistical tests are not available (Washington *et al.*, 1997). In this section, the results of the ANOVA for our dataset will be discussed after a brief discussion of a theoretical background.

7.2.1 Theoretical Background

The purpose of ANOVA is to test the significance of differences among multiple sampling means by analyzing the variances. The null hypothesis is that the sample means are equal. If the null hypothesis is not rejected, the sampled populations are presumed to have a common mean. All the groups are statistically identical (i.e., explanatory variables have failed to differentiate the initially homogenous population into separate groups). ANOVA is also used to determine whether there are significant interactions between explanatory variables.

In applying ANOVA, one should be aware of the assumptions. One assumption is that there is no intercorrelation of the independent variables as well as no autocorrelation. Another important assumption is that the dependent variable should be normally distributed and the error variances should be homogeneous. If the data cannot provide the normality assumption, transformation methods such as Box-Cox method can be used (Casella and Berger, 1990). Next section describes the preliminary analysis for ANOVA.

7.2.2 Preliminary Analysis

First step in ANOVA is to determine which variables that are going to be used. It is important to remember that variables should not have correlations among each other and any autocorrelation within themselves. The dataset consists of runs that are collected second-by-second over defined time intervals. The analysis of the data revealed that both response and explanatory variables show autocorrelation affects. As an example, an auto regressive model of 4^{th} degree can be fit to speed data from some runs indicating a fourth degree temporal autocorrelation. This is against the assumptions of ANOVA. For this purpose, run-level averages will be utilized for ANOVA, as they do not posses this type of problem. This kind of analysis is useful for finding the effect of variables on a macro-level, such as temperature, humidity and average speed. Micro-level analysis will be done using other methods and will be explained later.

One important criterion is that there should not be any clear relation between the parameters. For example, average speed and traffic variables such as time delay should not both be used since they are correlated. Environmental conditions, such as ambient temperature and relative humidity, and average speed recorded for each test corridors might be specific to each test corridor. In addition, roadway grade and geometry might be different which might affect vehicle emissions. For this reason, combining data from different test corridors might mask the effect of other variables. Therefore, separate ANOVA will be done on data from different test corridors.

Another important consideration in ANOVA is that the response variable should have normal distribution. In order to achieve that a log transform of the emissions estimates was utilized.

It should be noted that ANOVA is a computational extensive method. For that purpose, it is better to reduce the number of explanatory variables entered to the model. For the dataset containing log-transformed emissions estimates, as gram per mile basis, the effect of the vehicle make and model was determined to see if it has significant effect. The effect of traffic signal coordination, simply referred to as coordination from now on, was also checked to determine its significance. In order to determine significance of these parameters an ANOVA was done using these two parameters only. For this purpose S-Plus 2000 was used. The p-values of the ANOVA are given in Tables 7-1 and 7-2 for Chapel Hill and Walnut Street respectively.

As seen in Tables 7-1 and 7-2, vehicle make and model is significant at the 0.05 significance level for all of the pollutants, since p-values are less than 0.05. The same is true for coordination except for the NO emissions estimates for Chapel Hill. When an interaction term between vehicle and coordination are considered, it is seen that except for CO emissions estimates for Walnut Street, there is no significant interaction between these two parameters at a significance level of 0.05. Out of six cases, there is one case where the interaction term is significant at a significance level of 0.05. Physically it does not make sense to have any interaction between Vehicle and Coordination. With this finding, it is assumed that there is no significant interaction between vehicle and coordination. For similar reasons it is assumed that coordination is significant for all of the pollutants.

With results from Tables 7-1 and 7-2, the dataset was divided using these two parameters; hence, the number of parameters that will be utilized for the ANOVA will be reduced, which reduces the computational load. There are four different datasets for each site. For Chapel Hill Road these four data sets are: before data with the Ford Taurus; after

Table 7-1. Statistical Significance of ANOVA Results in terms of p-value for Chapel Hill Data using Vehicle and Coordination

	P-Values		
Parameter	**NO**	**HC**	**CO**
Vehicle	0.00	0.00	0.00
Coordination	0.16	0.037	0.009
Vehicle: Coordination	0.065	0.37	0.37

Table 7-2. Statistical Significance of ANOVA Results in terms of p-value for Walnut Street using Vehicle and Coordination

	P-Values		
Parameter	**NO**	**HC**	**CO**
Vehicle	0.00	0.00	0.00
Coordination	0.001	0.04	0.005
Vehicle: Coordination	0.05	0.79	0.032

Table 7-3. Definition of Variables Used in ANOVA

Parameter	Description
Air Condition Use	Indication of whether air condition (AC) is on (AC=1) or off (AC=0)
Ambient Temperature	Ambient temperature (^{0}F) measured in the field
Relative Humidity	Ambient humidity (Percent) measured in the field
Average Speed	Vehicle speed averaged over the trip (mph)
Driver	Indication of the driver used in the run (Driver=1 or Driver=2)
Date	Indication of date of data collection (e.g., Date=1 for data collected on 08/29/00)
Time/Direction	Indication of time and direction of the data collection (e.g., Time/Direction=1 for AM North)

data with the Ford Taurus; before data with the Chevrolet Venture; and after data with the Chevrolet Venture. For Walnut Street these four data sets are: before data with the Ford Taurus; after data with the Ford Taurus; before data with the Oldsmobile Cutlass; and after data with the Oldsmobile Cutlass. Only primary vehicles will be used for ANOVA, as the others do not have enough data points to justify a statistical analysis.

As discussed previously, ANOVA was applied for macro-level analysis. The parameters that are included in ANOVA are given in Table 7-3 with their definitions.

After determining the explanatory variables ANOVA was done for all pollutants for all four datasets for each site using S-Plus 2000. In these analyses first order interaction terms were also considered. An example ANOVA with results is presented in the next section.

7.2.3 Results of ANOVA

First a full scale ANOVA was done using all the variables including first-order interaction terms. After checking the p-values, insignificant variables were removed and another ANOVA was done on the remaining variables. This procedure was repeated until only significant variables were left. This is important because the significance of variables might be influenced by insignificant variables. As an example, the result of ANOVA for the HC dataset for Oldsmobile Cutlass at Walnut Street before coordination is given in Table 7-4.

As seen in Table 7-4 the only significant variables are the Average Speed and Temperature. Using these two variables another ANOVA was done for the dataset. The p-value for these variables with this new ANOVA were both 0.000, which is significant a significance level of 0.05. So it is concluded that for this dataset Average Speed and Temperature are the only significant variables.

Using a similar ANOVA approach significant variables were obtained for other datasets for all of the pollutants. Tables 7-5 and 7-6 give significant variables obtained from ANOVA for data collected on Chapel Hill and Walnut Street respectively.

In Tables 7-5 and 7-6, Average Speed and Time/Direction are the two variables that are common to almost all datasets. Average speed is significant for 11 of the datasets collected on Chapel Hill Road and seven of the datasets collected on Walnut Street. Time/Direction variable is significant for six of the cases for both Chapel Hill Road and Walnut Street datasets. Ambient temperature is found to be significant for two of the datasets collected from Chapel Hill Road and three of the datasets from Walnut Street.

Humidity is found to be significant in two of the datasets collected each on Chapel Hill Road and Walnut Street. The other variables, date, driver, and AC, were found to be significant in small number of datasets, as seen in Tables 7-5 and 7-6.

Results from ANOVA can be subject to statistical errors and although the results for some variables are significant, one could argue in some cases that the results may arise because of a complex structure of the dataset. For this reason, for the variables

Table 7-4. Results of ANOVA for HC Emissions Estimates for Oldsmobile Cutlass at Walnut Street Before Coordination

Variable	**P-Value**
AC	0.06
Temperature	**0.00**
Humidity	0.758
Average Speed	**0.000**
Driver	0.379
Date	0.116
Time/Direction	0.103
AC: Temperature	0.709
AC: Humidity	0.233
AC: Average Speed	0.070
AC: Driver	0.814
AC: Time/Direction	0.058
Temperature: Humidity	0.779
Temperature: Average Speed	0.976
Temperature: Driver	0.064
Temperature: Date	0.852
Temperature: Time/Direction	0.342
Humidity: Average Speed	0.114
Humidity: Driver	0.761
Humidity: Date	0.121
Humidity: Time/Direction	0.524
Average Speed: Driver	0.877
Average Speed: Date	0.586
Average Speed: Time/Direction	0.815
Driver: Time/Direction	0.070
Date: Time/Direction	0.065

which do not have physical meaning, a more detailed analysis was performed to determine whether they have a significant effect or not. For example, the date of data collection does not have any physical basis for influencing emissions. In order to check these kinds of variables, a Kolmogorov-Smirnov (K-S) test was used to find whether emissions differ for a particular variable vehicle. The K-S test compares the empirical cumulative distribution functions and tests whether they are different from each other. For variables, which have more than two levels, the multi-comparison technique was used (Neter *et al.*, 1990). The variables included in this study are: date of data collection; air conditioner use; and driver.

Table 7-5. Significant variables for data collected on Chapel Hill

	Ford Taurus			Chevrolet Venture		
Coord.	**Pollutant**	**Significant Variables**	**P- Value**	**Pollutant**	**Significant Variables**	**P- Value**
Before	*Log NO (g/mi)*	Time/Direction	0.026	*Log NO (g/mi)*	Time/Direction	0.003
	Log HC (g/mi)	Temperature	0.000		Average Speed	0.000
		Humidity	0.000	*Log HC (g/mi)*	Average Speed	0.006
		Average Speed	0.000		Date	0.000
	Log CO (g/mi)	Average Speed	0.016	*Log CO (g/mi)*	Average Speed	0.045
		Time/Direction	0.018			
After	*Log NO (g/mi)*	Time/Direction	0.000	*Log NO (g/mi)*	Time/Direction	0.038
		Average Speed	0.014		Average Speed	0.001
	Log HC (g/mi)	Temperature	0.001		AC	0.002
		Average Speed	0.000	*Log HC (g/mi)*	Average Speed	0.000
	Log CO (g/mi)	Time/Direction	0.016		Humidity	0.000
		Average Speed	0.000	*Log CO (g/mi)*	Average Speed	0.000

Table 7-6. Significant variables for data collected on Walnut Street

	Ford Taurus			Oldsmobile Cutlass		
Coord.	**Pollutant**	**Significant Variables**	**P- Value**	**Pollutant**	**Significant Variables**	**P- Value**
Before	*Log NO (g/mi)*	Humidity	0.000	*Log NO (g/mi)*	Average Speed	0.002
	Log HC (g/mi)	AC	0.000		AC	0.000
		Temperature	0.006	*Log HC (g/mi)*	Temperature	0.000
		Average Speed	0.000		Average Speed	0.000
		Time/Direction	0.000	*Log CO (g/mi)*	Driver	0.000
	Log CO (g/mi)	Average Speed	0.043		Time/Direction	0.040
After	*Log NO (g/mi)*	Time/Direction	0.012	*Log NO (g/mi)*	Average Speed	0.000
	Log HC (g/mi)	Temperature	0.002		Date	0.003
		Average Speed	0.000	*Log HC (g/mi)*	Time/Direction	0.036
		Driver	0.000		Average Speed	0.000
	Log CO (g/mi)	Time/Direction	0.036		Driver	0.023
					Humidity	0.005
				Log CO (g/mi)	Time/Direction	0.005

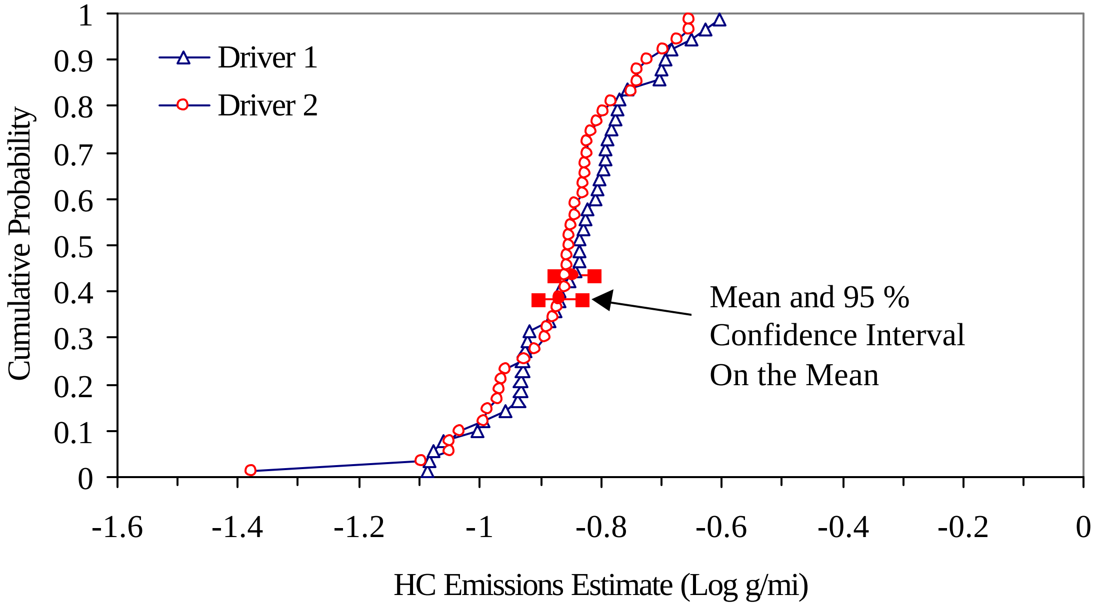


Figure 7-7. Comparison of Driver Effect for Data Collected on Walnut Street with Oldsmobile Cutlass After Coordination

After doing these tests, it was found that out of eight cases where driver, date, and air condition use were found to be significant, as seen in Tables 7-5 and 7-6, five of them were insignificant based upon the K-S test. The results of the K-S test are given in Appendix III. For example, the comparison of two different drivers with respect to HC emissions for the Oldsmobile Cutlass on Walnut Street after coordination was found to be significant based upon ANOVA. However, the comparison of CDFs for the two drivers indicated that they are not statistically significantly different from each other as shown in Figure 7-7.

Similar analysis for other variables were conducted and it was found that in only three cases, air condition use, date of data collection, and driver had a significant effect on vehicle emissions. Figure 7-8 gives the data for HC emissions collected on Chapel Hill Road with the Chevrolet Venture before coordination. In this dataset, the date of data collection was found to be significant based upon ANOVA as given in Table 7-5. Figure 7-8 shows the average HC emissions observed on different data collection days with Chevrolet Venture on Chapel Hill Road before coordination.

As seen in Figure 7-8, the HC emissions collected on Date 5 is higher than the rest of the data. Possible reasons for this difference might be due to weather conditions.

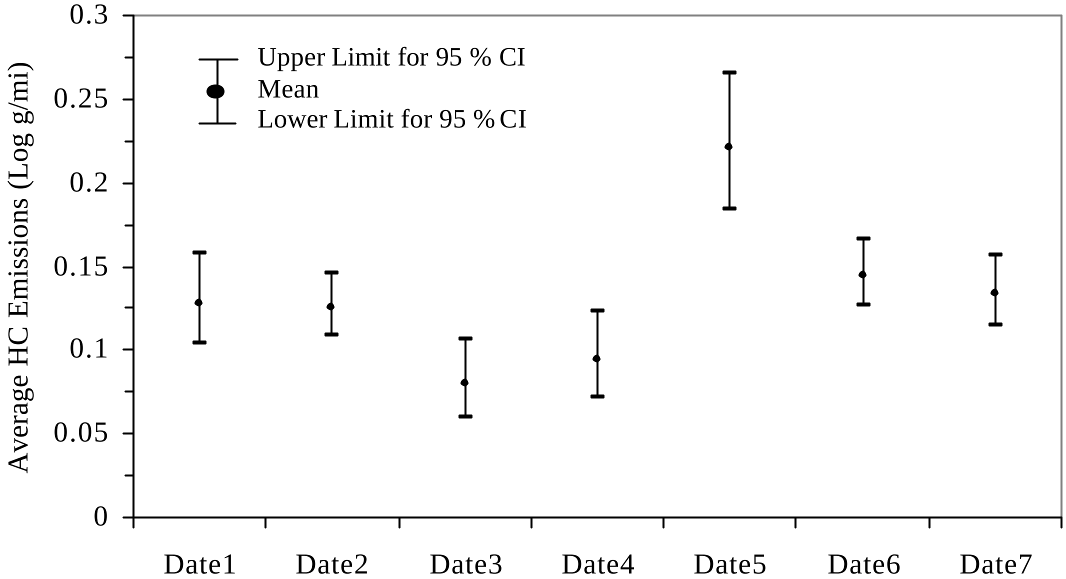


Figure 7-8. Data Collection Date Effect on HC Emissions for Chevrolet Venture Driven on Chapel Hill Before Coordination

The average relative humidity was 92 percent on Date 5 whereas it was 73 percent for the other days. The relation between the average HC emissions and relative humidity is explained in Section 7.2.5 in more detail. There is not much difference in the average temperature of Date 5 versus the other dates. The average temperature is 78^0F on Date 5 versus 75^0F on the other days. Another difference was that all data for Date 5 were collected in the AM whereas most of the other days had both AM and PM measurements, except for Date 2 and Date 7. Therefore, the difference in average HC emissions might be some complex combination of all these effects that is not identified in ANOVA.

Figure 7-9 illustrates the possible influence of air conditioning use for data collected on Walnut Street using the Oldsmobile Cutlass before coordination. Figure shows that there is statistically significant difference between the data with AC on and AC off. It should be noted that there are eight data points with AC on and 85 data points with AC off. Emissions tend to be higher with the AC on, as indicated in the figure.

Figure 7-10 compares drivers with respect to CO emissions for data collected on Walnut Street using the Oldsmobile Cutlass after coordination.

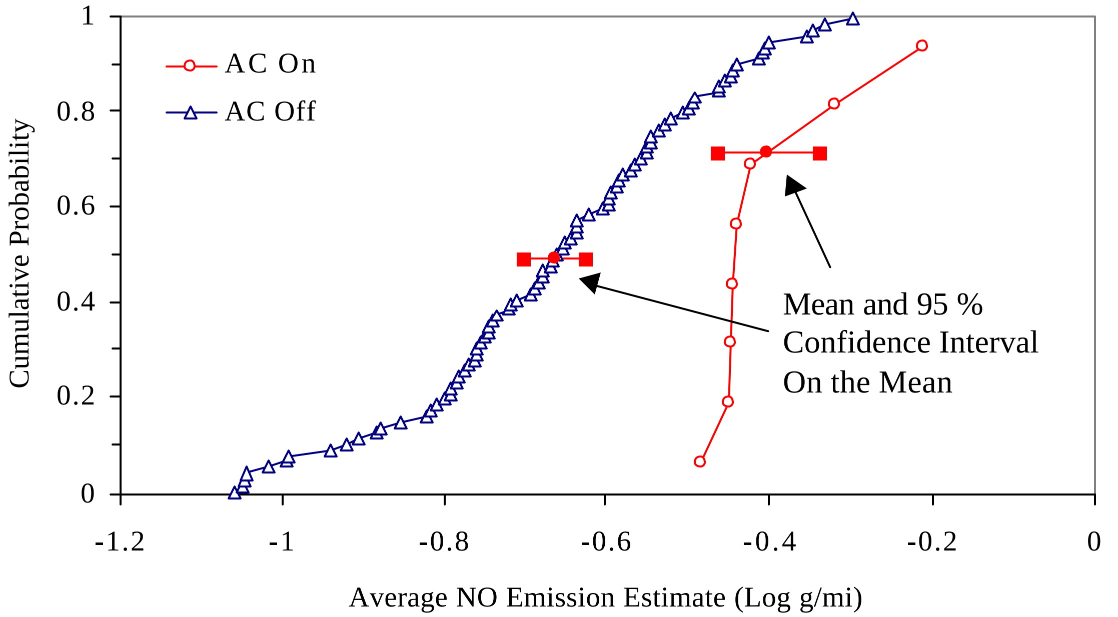


Figure 7-9. Walnut Street Oldsmobile Cutlass Before Coordination with AC On and Off Cases

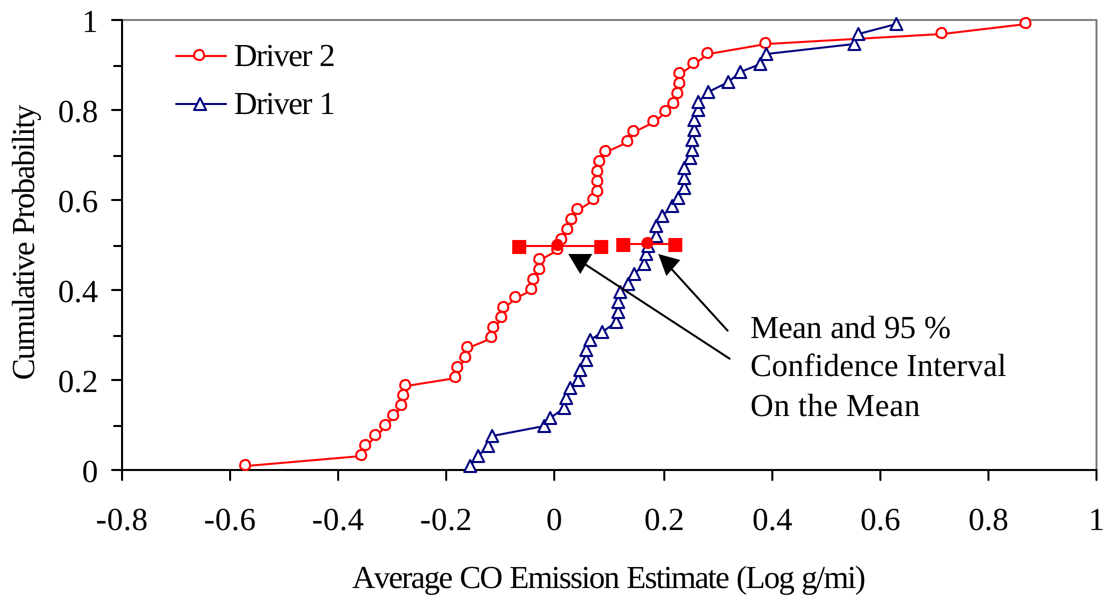


Figure 7-10. Walnut Street Oldsmobile Cutlass After Coordination Data with Different Drivers

There is a statistically significant difference between the data for Driver 1 and Driver 2. It should be noted that except for this dataset no difference has been observed for data collected from these two drivers. Moreover, acceleration noise data given in Appendix III also shows that these two drivers are not different.

In the three cases presented here, A/C use, driver, and date of data collection have been found to be significant from ANOVA. However, it should be noted that out of 24 cases presented in Tables 7-5 and 7-6, these three explanatory variables were found to be significant in only one dataset. This is an indication that these results might be due some random effect of complex structure of the dataset.

Another important issue that needs to be considered is the fact that in statistical analysis, such ANOVA, personal judgment can be used in identifying significant variables. Significant variables from ANOVA can be ignored or insignificant variables can be considered as significant based upon this rational (Fuentes, 2001). In this study, based upon the previous arguments A/C use, driver, and date of data collection were ignored for their significance on vehicle emissions. Significant variables for different datasets are summarized in Table 7-7 and Table 7-8 for Chapel Hill Road and Walnut Street respectively.

In Tables 7-7 and 7-8 significant variables for data collected on Chapel Hill Road and Walnut Street are given as the result of ANOVA respectively. Average Speed and Time/Direction are the two variables that are common to almost all datasets.

After determining the significant variables for each dataset, a more detailed analysis was done to find out more about the relationship between these significant variables and emissions of each of these three pollutants. The next three sections discuss the results of these analyses for NO, HC, and CO, respectively.

7.2.4 Significant Variables for NO Emissions

Average Speed and Time/Direction are the most significant variables related to NO emissions. Regardless of the vehicle and coordination condition, these two variables are revealed by almost all of the ANOVA as significant variables for NO emissions. In addition, humidity was found to be significant in the ANOVA analysis in some cases. The effect of each of these three variables is further explored.

Table 7-7. Significant variables for data collected on Chapel Hill Road

	Ford Taurus			**Chevrolet Venture**		
Coord.	**Pollutant**	**Significant Variables**	**P- Value**	**Pollutant**	**Significant Variables**	**P- Value**
Before	*Log NO (g/mi)*	Time/Direction	0.026	*Log NO (g/mi)*	Time/Direction	0.003
	Log HC (g/mi)	Temperature	0.000		Average Speed	0.000
		Humidity	0.000	*Log HC (g/mi)*	Average Speed	0.006
		Average Speed	0.000	*Log CO (g/mi)*	Average Speed	0.045
	Log CO (g/mi)	Average Speed	0.016			
		Time/Direction	0.018			
After	*Log NO (g/mi)*	Time/Direction	0.000	*Log NO (g/mi)*	Time/Direction	0.038
		Average Speed	0.014		Average Speed	0.001
	Log HC (g/mi)	Temperature	0.001	*Log HC (g/mi)*	Average Speed	0.000
		Average Speed	0.000		Humidity	0.000
	Log CO (g/mi)	Time/Direction	0.016	*Log CO (g/mi)*	Average Speed	0.000
		Average Speed	0.000			

Table 7-8. Significant variables for data collected on Walnut Street

	Ford Taurus			**Oldsmobile Cutlass**		
Coord.	**Pollutant**	**Significant Variables**	**P- Value**	**Pollutant**	**Significant Parameters**	**P- Value**
Before	*Log NO (g/mi)*	Humidity	0.000	*Log NO (g/mi)*	Average Speed	0.002
	Log HC (g/mi)	Temperature	0.006	*Log HC (g/mi)*	Temperature	0.000
		Average Speed	0.000		Average Speed	0.000
		Time/Direction	0.000	*Log CO (g/mi)*	Time/Direction	0.040
	Log CO (g/mi)	Average Speed	0.043			
After	*Log NO (g/mi)*	Time/Direction	0.012	*Log NO (g/mi)*	Average Speed	0.000
	Log HC (g/mi)	Temperature	0.002	*Log HC (g/mi)*	Time/Direction	0.036
		Average Speed	0.000		Average Speed	0.000
	Log CO (g/mi)	Time/Direction	0.000		Humidity	0.005
				Log CO (g/mi)	Time/Direction	0.005

7.2.4.1 Average Speed

In order to see the effect of average speed on NO emissions scatter plots of NO versus average speed were prepared for the datasets where average speed was found to be statistically significant. An example is given in Figure 7-11 for the Oldsmobile Cutlass on Walnut Street after coordination. A non-parametric regression curve was fit to the data to help to see the trend in the data. Non-parametric regression is also known as local regression and does not assume a functional form between x and y. This method is used to visualize the trend in the data; however, this method does not provide any goodness of fit statistics (S-Plus, 2000).

Overall, the nonparametric regression line is able to represent variability in NO emissions from 0.17 g/mi to 0.33 g/mi. However, the variability in the data is from 0.11 g/mi to 0.62 g/mi. Thus, the regression line explains only a portion of the variability in the data. At any given point on the regression line, there is approximately plus or minus 40 percent range of variation in the data that is not explained by the regression model. The average trend revealed by the model is that the slope of the regression curve is negative for entire range of the average speed indicating that NO emissions decrease as average speed increases.

Results similar to Figure 7-11 are obtained for the Ford Taurus on Chapel Hill and the Oldsmobile Cutlass on Walnut Street in the before coordination case. However, a different relation between emissions and speed is obtained for the Chevrolet Venture driven on Chapel Hill for both the before and after coordination cases. Figure 7-12 gives an example of this.

In Figure 7-12, the nonparametric regression line is able to represent variability in NO emissions from 0.13 g/mi to 0.27 g/mi. However, the variability in the data is from 0.07 g/mi to 0.51 g/mi. Thus, the regression line explains only a portion of the variability in the data. At any given point on the regression line, there is an approximately plus 60 percent and minus 40 percent range of variation in the data that is not explained by the regression model.

The average trend revealed by the model is that the slope of the regression curve is positive for the entire range of average speed indicating that NO emissions increase as average speed increases. However, the slope of the regression curve changes at an average speed of approximately 30 mph. Overall, the NO emissions data are well distributed from 10 mph to 50 mph. In comparing Figure 7-11 and Figure 7-12, it appears that the emissions profile of each vehicle differs. These differences could be attributable to the vehicles themselves. More discussion on this topic will be given in Section 7.5.3.

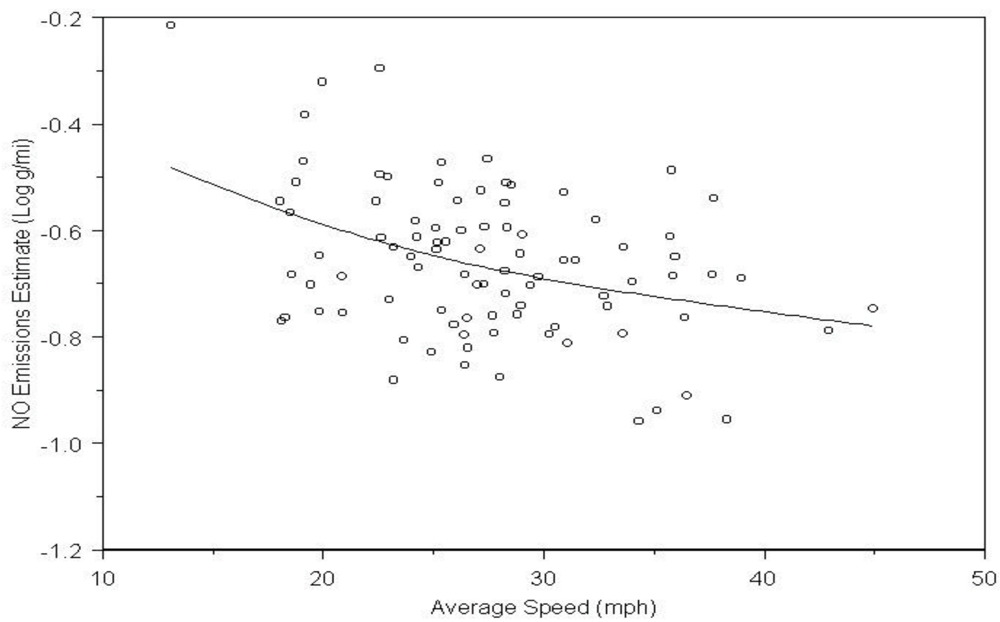


Figure 7-11. Average Speed versus NO Emissions for Oldsmobile Cutlass Driven on Walnut Street After Coordination

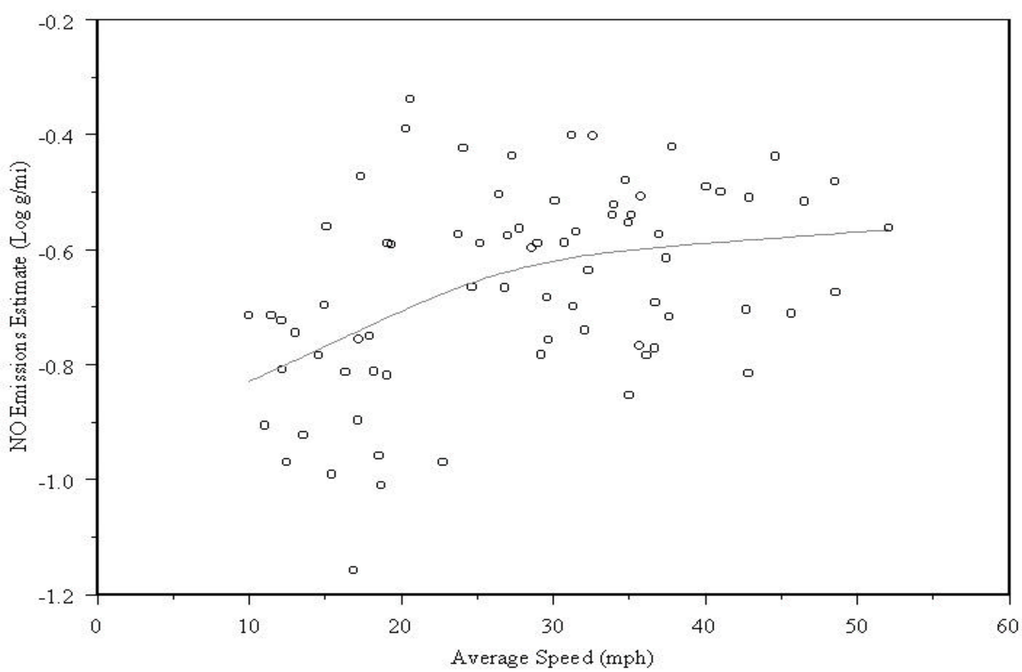


Figure 7-12. Average Speed versus NO Emissions for Chevrolet Venture Driven on Chapel Hill Road Before Coordination

7.2.4.2 *Time/Direction*

In order to find out the relation between Time/Direction and NO emissions, a multicomparison test using S-Plus 2000 was done among the different levels of Time/Direction. The results of these analyses indicate that NO emissions for the North AM case are significantly different than for the South PM case for Chapel Hill Road for the Ford Taurus in both the before and after cases as well as for the Chevrolet Venture in both the before and after cases. For the Ford Taurus after case, NO emissions for the North AM case are significantly different than for the South AM case. For Walnut Street, data NO emissions in the North AM case are different from both the North PM and South AM cases. These differences may be because traffic congestion is different for these cases. For example, traffic was more congested during North AM runs compared to South AM runs for Chapel Hill Road. Although South PM runs were also congested, its level of congestion was different than for the North AM runs. More analysis will be given on the effect of traffic congestion on emissions in Section 10.7. Comparisons of other direction time combinations have some differences but they are not statistically significant at the 0.05 significance level for NO emissions.

7.2.4.3 *Humidity*

For the dataset in which Ford Taurus was driven on Walnut before coordination, humidity was found to be a significant factor influencing NO emissions. To understand what the relationship might be between humidity and NO emissions, these data are plotted in Figure 7-13. A nonparametric regression line is shown to illustrate the average trend in the data.

Overall, the nonparametric regression line is able to represent variability in NO emissions from 0.07 g/mi to 0.13 g/mi. However, the variability in the data is from 0.05 g/mi to 0.49 g/mi. Thus, the regression line explains only a portion of the variability in the data.

The average trend revealed by the model is that for low levels of humidity, such as below approximately 50 percent, the slope of the regression curve is not substantially different from zero. Therefore, there is either no relationship between humidity and NO emissions or only a very weak relationship. However, for higher humidity values, the slope of the regression line appears to be negative, indicating that NO emissions decrease

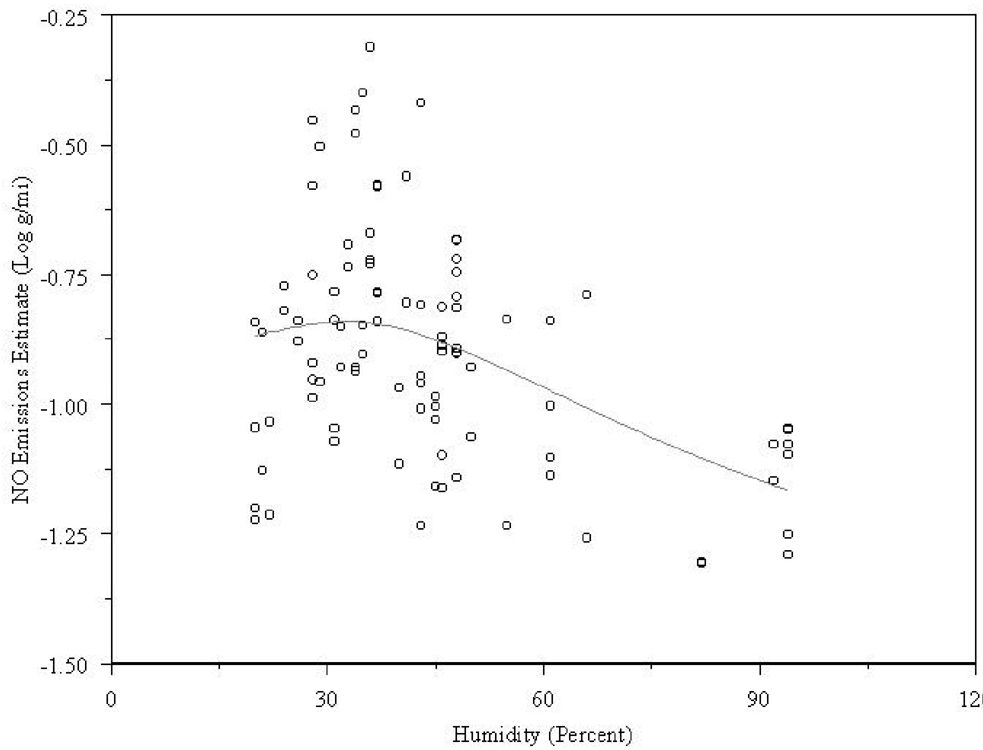


Figure 7-13. Percent Humidity versus NO Emissions for Ford Taurus Driven on Walnut Street Before Coordination

as humidity increases. It is clear that most of the data are in the low humidity ranges, and that the result for higher humidity is based upon a relatively small number of data points. Therefore, the results may not be robust. Nonetheless, the results are quite reasonable. It is well-known that the presence of water vapor in the combustion process, including humidity in the inlet air, will lead to a reduction in the peak flame temperature. In turn, a reduction in peak flame temperature will lead to a reduction in NO emissions, since the formation of NO is kinetically limited by temperature. Therefore, the statistical results in this case appear to be valid from a scientific perspective.

7.2.5 Significant Variables for HC Emissions

7.2.5.1 Average Speed

For all of the datasets average speed is found to be a significant variable for HC emissions based upon ANOVA. An example of this relation is given in Figure 7-14 for dataset where an Oldsmobile Cutlass is driven on Walnut Street before coordination.

Overall, the nonparametric regression line is able to represent variability in HC emissions from 0.09 g/mi to 0.22g/mi. However, the variability in the data is from 0.07 g/mi to 0.37 g/mi. Thus, the regression line explains only a portion of the variability in the data. At any given point on the regression line, there is approximately a plus 57 percent and minus 31 percent range of variation in the data that is not explained by the regression model.

The average trend revealed by the model is that the slope of the regression curve is negative for entire range of the average speed indicating that HC emissions decrease as average speed increases. Increasing average speed means that there will be less stops which is an indication of lower enrichment events associated with acceleration from a stop. A reduction in enrichment events will lower the amount of HC emitted. Therefore, the statistical results in this case appear to be valid from a scientific perspective.

7.2.5.2 Temperature

The relation between ambient temperature and HC emissions is shown as an example in Figure 7-15.

Overall, the nonparametric regression line is able to represent variability in HC emissions from 0.11 g/mi to 0.18 g/mi. However, the variability in the data is from 0.07 g/mi to 0.35 g/mi. Thus, the regression line explains only a portion of the variability in the data. At any given point on the regression line, there is approximately a plus 40 percent and minus 36 percent range of variation in the data that is not explained by the regression model.

The average trend revealed by the model is that for low levels of temperature, such as below approximately 50 ^{0}F, the slope of the regression curve is very low and not substantially different from zero. Therefore, there is either no relationship between temperature and HC emissions or only a very weak relationship. However, for higher temperature values, the slope of the regression line appears to be positive, indicating that

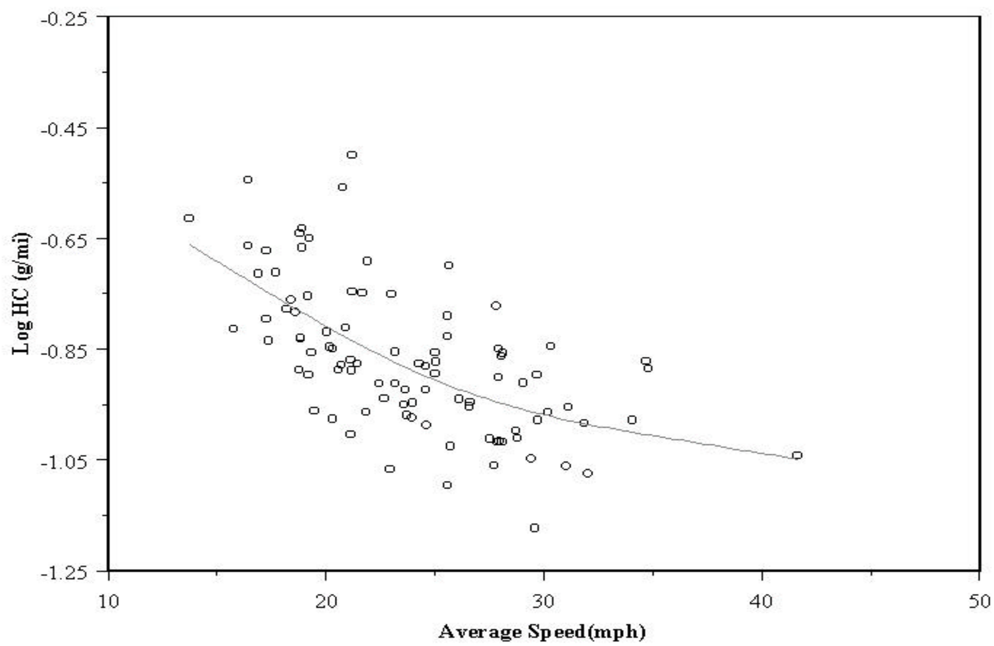


Figure 7-14. Average Speed versus HC Emissions for Oldsmobile Cutlass Driven on Walnut Street Before Coordination

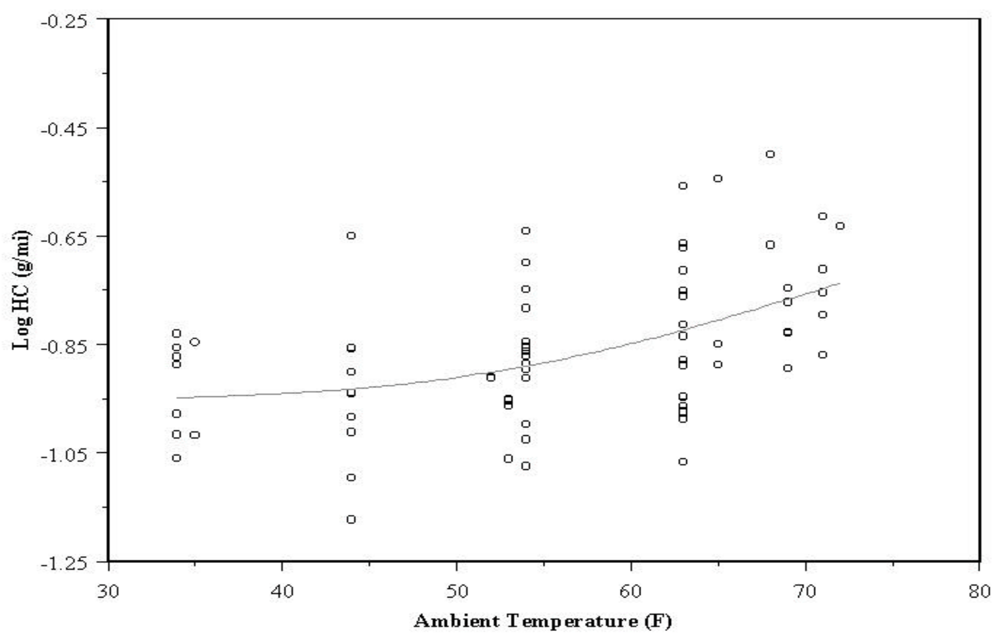


Figure 7-15. Ambient Temperature versus HC Emissions for Oldsmobile Cutlass driven on Walnut Street before coordination

HC emissions decrease as temperature increases. It should be noted that in the literature HC emissions are found to be increasing with decreasing temperature, for temperatures lower than 50 ^{0}F, as discussed in Section 2.6. In this study there is not much data collected in this range. The range of variation represented by the trend line is much less than the overall range of variability in the data. As a practical matter, the trend line may not be significant.

7.2.5.3 Humidity

The relation between humidity and HC emissions is shown for the Ford Taurus driven on Chapel Hill Road in the before case in Figure 7-16.

Overall, the nonparametric regression line is able to represent variability in HC emissions from 0.04 g/mi to 0.12 g/mi. However, the variability in the data is from 0.02 g/mi to 0.18 g/mi. Thus, the regression line explains only a portion of the variability in the data. At any given point on the regression line, there is approximately a plus or minus 35 percent range of variation in the data that is not explained by the regression model.

The average trend revealed by the model is that for entire range of humidity the slope of the regression line appears to be negative, indicating that HC emissions decrease as humidity increases. It is clear that most of the data are in the high humidity ranges, and that the result for lower humidity is based upon a relatively small number of data points. Therefore, the results may not be robust. Similar results were obtained for HC emissions data collected using the Chevrolet Venture on Chapel Hill Road in the after case and the Oldsmobile Cutlass on Walnut Street in the after case.

7.2.5.4 Time/Direction

As in the case of NO emissions, HC emissions in the North PM case are significantly different than emissions of the North AM and South AM cases for data collected on Walnut Street with the Ford Taurus. For data collected on Walnut Street using the Oldsmobile Cutlass, North AM emissions are different than South PM emissions. Comparisons of other direction time combinations have some differences but they are not statistically significantly different at the significance level of 0.05.

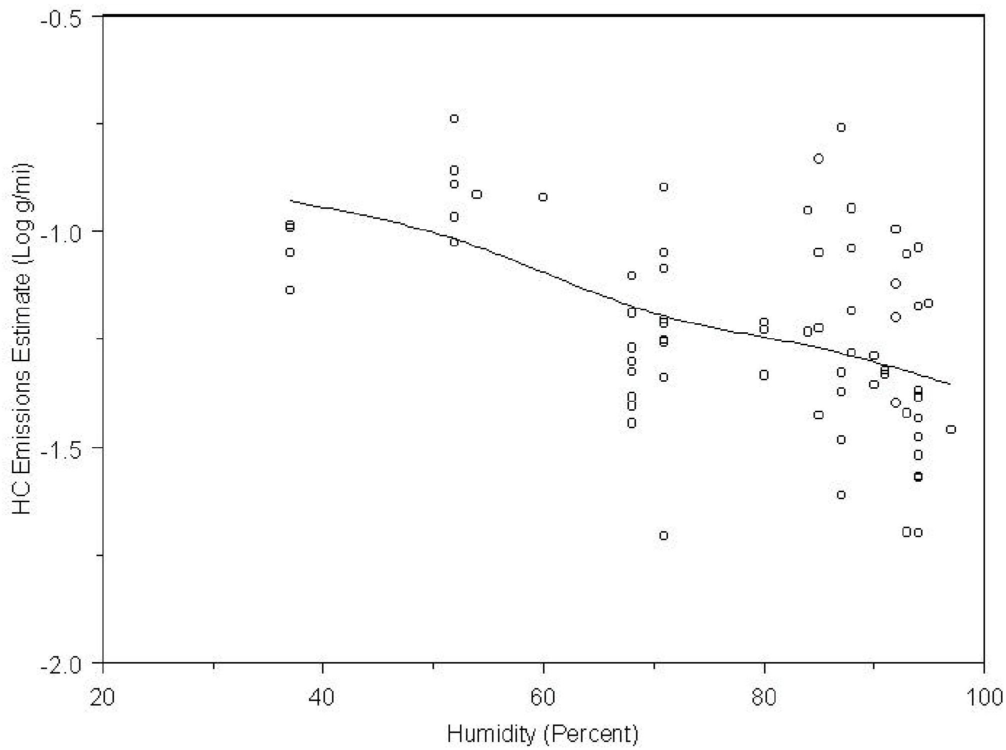


Figure 7-16. Humidity versus HC Emissions for Ford Taurus Driven on Chapel Hill Road Before Coordination

7.2.6 Significant Variables for CO Emissions

7.2.6.1 Average Speed

As for other pollutants average speed is one of the most important significant variables for CO emissions obtained from ANOVA. Figure 7-17 shows the relation between average speed and CO emissions for the Ford Taurus driven on Chapel Hill Road after case.

Overall, the nonparametric regression line is able to represent variability in CO emissions from 0.56 g/mi to 3.6 g/mi. However, the variability in the data is from 0.11 g/mi to 18 g/mi. Thus, the regression line explains some of the variability in the data. At any given point on the regression line, there is approximately plus 94 percent and minus 77 percent range of variation in the data that is not explained by the regression model.

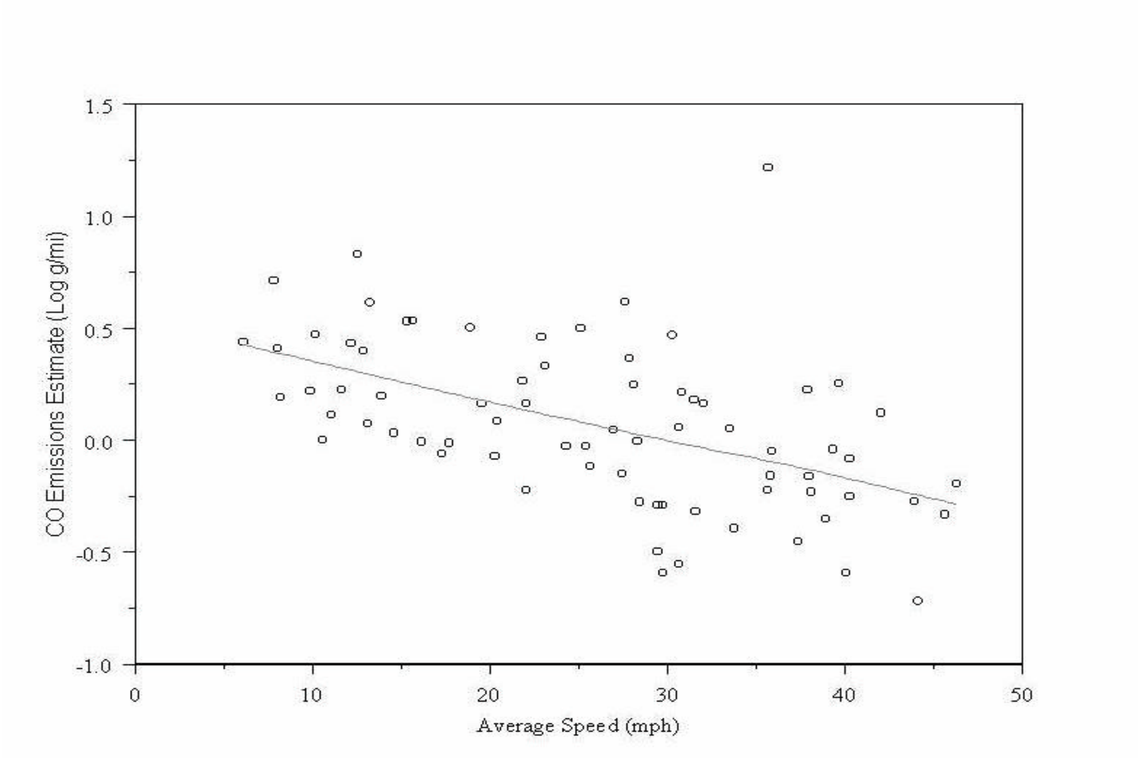


Figure 7-17. Average Speed versus CO Emissions for Ford Taurus Driven on Chapel Hill Road After Coordination

The average trend revealed by the model is that CO emissions decrease as average speed increases. Increasing average speed means that there will be less stops which is an indication of fewer enrichment events occurring during acceleration from a stop. A reduction in enrichment events will lower the amount of CO emitted. Therefore, the statistical results in this case appear to be valid from a scientific perspective.

7.2.6.2 Time/Direction

For the Chapel Hill datasets where Time/Direction is significant based upon ANOVA, the North AM case is significantly different than the South PM case in terms of CO emissions. For Walnut Street data, emissions for the North PM case are significantly different from emissions of both the South AM and South PM cases.

7.2.7 Summary of Results of ANOVA

Three methods were used to statistically analyze the data obtained from the Chapel Hill Road and Walnut Street corridors in order to identify potentially important explanatory variables. First, ANOVA was done to make a preliminary identification of potentially important variables. ANOVA was applied only to trip-based measures of emissions and activity. ANOVA could not be applied to micro-scale data because the second-by-second data, in at least some cases, has significant autocorrelation. The results of ANOVA typically implied that average speed, time and direction of travel, temperature, and humidity are important factors for most of the vehicle and pollutant combinations evaluated. In addition, a few other factors appeared to be important in selected cases, such as the date of data collection, AC usage, and driver.

In order to understand and evaluate the findings from ANOVA, in many cases data were visualized graphically using scatter plots. Nonparametric regression trend lines were superimposed on the scatter plots to identify average trends. In most cases, the apparent relationship between emissions and an explanatory variability identified by ANOVA, such as temperature, humidity, and average speed, is nonlinear. For categorical explanatory variables, such as the time and direction of travel, a multicomparison of confidence intervals for the mean values was done to determine which pairs of time/direction have significant differences. For each pollutant there was at least one time/direction pair which had significant differences in emissions.

The case in which ANOVA identified the driver to be an important explanatory factor was reviewed both visually and statistically with a different method. The overall finding is that the driver is not an important explanatory variable for the primary vehicles in the evaluation study datasets.

AC usage appears to be an important explanatory variable in the case of NO emissions from the Oldsmobile Cutlass before coordination on Walnut Street. The date of data collection cannot by itself be considered a physically meaningful explanatory variable.

Overall, the further inspection of average speed, temperature, and humidity reveal that these variables do have relationships with emissions in a number of cases. Therefore, variation in these variables should be considered when interpreting the results of comparisons of emissions before and after signal timing and coordination changes.

7.3 Effect of Vehicle Characteristics

In this section, a detailed discussion of the effects of vehicle characteristics on vehicle emissions is given.

A total of 17 different vehicles were tested on NC-54, Miami Boulevard, Chapel Hill Road, and Walnut Street. Understanding the variability of vehicle emissions by vehicle make and model is an important consideration in interpreting results of this study.

Table 7-9 shows summary information for each vehicle tested. Each number at the end of the vehicle identification (ID) represents a different vehicle with its own unique vehicle identification number (VIN). If the same vehicle was tested on different corridors, then separate vehicle ID's were assigned to that vehicle for each corridor tested. For example, a total of four different 1996 Oldsmobile Cutlasses were tested (as noted by the numbers one through four on the Vehicle ID column). One of them, Oldsmobile (3) was tested on NC 54, Miami Boulevard, Chapel Hill Road, and Walnut Street.

In addition, the Ford Taurus and Chevrolet Venture tested on Chapel Hill Road, and the Ford Taurus and Oldsmobile Cutlass tested on Walnut Street, have two different vehicle IDs, denoted with the letters 'a' or 'b'. The 'a' represents runs performed after signal coordination and the 'b' represents runs before signal coordination. The before and after runs were collected one to two months apart from each other and were thus collected in potentially different weather conditions, leading to possible different proportions of air conditioning use, and possible different engine maintenance conditions. For this reason, the before and after runs were given different vehicle IDs. Separating the same vehicle with 'a' and 'b' notations were not necessary on NC-54 and Miami Boulevard because no identical vehicles were used in both the before and after runs on these corridors.

By evaluating the emission rates for each vehicle ID, the variability within the same and among different vehicle models becomes evident. Figure 7-18 shows the corridor run average and 95 percent confidence interval emission rates for each vehicle ID on a milligrams per second basis.

The variability of emission rates shown in Figure 7-18 may be influenced by a number of additional factors besides vehicle make and model, such as the OEM unit used for data collection, corridor geometries, driver style, ambient temperature, and air conditioner use. Thus, it is difficult to conclude whether different emission rates within the same vehicle make and model are due to these additional factors or some difference in the maintenance of the vehicle engine or catalyst.

In Figure 7-18, Olds(Ch)-3 appears to have approximately twice as much HC emissions as the other Oldsmobiles. This is the exact same vehicle as the Olds(Mi)-3 and Olds(NC)-3, which were driven on the other two corridors. However, this magnitude of difference in HC emissions is difficult to attribute entirely to corridor geometrics. Another less likely explanation is that Olds(Ch)-3 had been driven approximately 3,000 miles since the runs on the other two corridors and, thus, some engine or catalyst deterioration may have occurred. There is a possibility that this difference might be due to differences in the two OEM-2100™ units used with this vehicle. However, Section 3.3 revealed that there is not significant difference between OEM-2100™ units.

Setting aside the variation in average HC emissions for the Olds(Ch)-3, the variations in emissions among vehicles of the same make and model are relatively minor. For the Ford Taurus vehicles, the confidence intervals of each pollutant overlap each other for most vehicle ID's. The only exceptions are the high HC emissions for the Taur(Wa)-6a, the low HC emissions for the Taur(Mi)-4, and the low NO emissions for the Taur(Ch)-5a. For the Oldsmobile Cutlasses, there is slightly more variation. The Olds(NC)-1, Olds(NC)-2, and Olds(Mi)-2 are slightly higher than the other vehicle ID's (not counting Olds(Ch)-3) for HC emissions and are also notably higher than the other Cutlasses for NO emissions. However, the differences are not remarkably large, that is, they are not order-of-magnitude differences. Rather they are on the order of 2 percent to 38 percent.

While there are minor variations within the same vehicle model, there are even more pronounced variations between different vehicle models. For example, the Plymouth Breeze (Brez(Mi)-1) has similar HC and NO emissions as the Ford Taurus (all vehicle Ids beginning with 'Taur'). Yet, the Breeze has significantly higher CO emissions. This indicates that vehicles can be "high-emitters" in one pollutant but not necessarily all others.

Table 7-9. Summary of Vehicles Used for Data Collection

Unique Vehicle #	Vehicle ID	Description	Odometer	OEM Unit	Runs	Corridor	Mean Temp./ A/C Use
1	Olds(NC)-1	1996 Oldsmobile Cutlass 2.2L Auto	84414	1	40	NC-54	65F 86%
2	Olds(Mi)-2	1996 Oldsmobile Cutlass 2.2L Auto	43350-43501	1	10	Miami Blvd.	56F 100%
	Olds(NC)-2	1996 Oldsmobile Cutlass 2.2L Auto	50123-50476	1	32	NC-54	59F 15%
3	Olds(Mi)-3	1996 Oldsmobile Cutlass 2.2L Auto	24064-24800	1	58	Miami Blvd.	51F 28%
	Olds(NC)-3	1996 Oldsmobile Cutlass 2.2L Auto	27679-27993	1	31	NC-54	55F 0%
	Olds(Ch)-3	1996 Oldsmobile Cutlass 2.2L Auto	30875-31777	2	33	Chapel Hill Rd.	72F 94%
	Olds(Wa)-3a	1996 Oldsmobile Cutlass 2.2L Auto	33155-33801	2	93	Walnut St.	43F 0%
	Olds(Wa)-3b	1996 Oldsmobile Cutlass 2.2L Auto	32139-32629	2	91	Walnut St.	55F 9%
4	Olds(Mi)-4	1996 Oldsmobile Cutlass 2.2L Auto	79567-80397	1	31	Miami Blvd.	61F 87%
5	Taur(NC)-1	1999 Ford Taurus 3.0L Auto	30014-30182	1	20	NC-54	78F 60%
6	Taur(NC)-2	1999 Ford Taurus 3.0L Auto	28193-28362	1	20	NC-54	88F 100%
7	Taur(Mi)-3	1999 Ford Taurus 3.0L Auto	16352-16685	1	28	Miami Blvd.	61F 79%
8	Taur(Mi)-4	1999 Ford Taurus 3.0L Auto	26634-27031	1	32	Miami Blvd.	60F 58%
9	Taur(Ch)-5a	1999 Ford Taurus 3.0L Auto	39030-39566	1	74	Chapel Hill Rd.	70F 48%
	Taur(Ch)-5b	1999 Ford Taurus 3.0L Auto	36837-37499	1	72	Chapel Hill Rd.	75F 58%
10	Taur(Wa)-6a	1999 Ford Taurus 3.0L Auto	41499-42089	1	84	Walnut St.	42F 0%
	Taur(Wa)-6b	1999 Ford Taurus 3.0L Auto	39636-40175	1	94	Walnut St.	59F 22%
11	Vent(Ch)-1a	1998 Chevrolet Venture Minivan 3.4L Auto	51677-52451	2	58	Chapel Hill Rd.	63F 31%
	Vent(Ch)-1b	1998 Chevrolet Venture Minivan 3.4L Auto	49595-50108	2	75	Chapel Hill Rd.	75F 51%
12	Cam(Ch)-1	1997 Toyota Camry 2.2L Manual	34841-36990	1	26	Chapel Hill Rd.	71F 100%
	Cam(Wa)-1	1997 Toyota Camry 2.2L Manual	37642-38957	1	16	Walnut St.	62F 94%
13	Brez(Mi)-1	1998 Plymouth Breeze 2.4L Auto	57689-57774	1	12	Miami Blvd.	50F 36%
14	Jeep(Ch)-1	1998 Jeep Cherokee 4.0L Auto	46182-46228	1	17	Chapel Hill Rd.	79F 94%
15	Carav(Ch)-1	1998 Dodge Caravan 3.3L Auto	77557-79919	2	12	Chapel Hill Rd.	64F 33%
	Carav(Wa)-1	1998 Dodge Caravan 3.3L Auto	80947-83260	2	20	Walnut St.	51F 0%
16	Van(Mi)-1	1998 Ford 15-Pass. Van 5.8L Auto	29421-29518	1	10	Miami Blvd.	55F 0%
17	Van(Mi)-2	1998 Ford 15-Pass. Van 5.8L Auto	22635-22730	1	11	Miami Blvd.	50F 10%

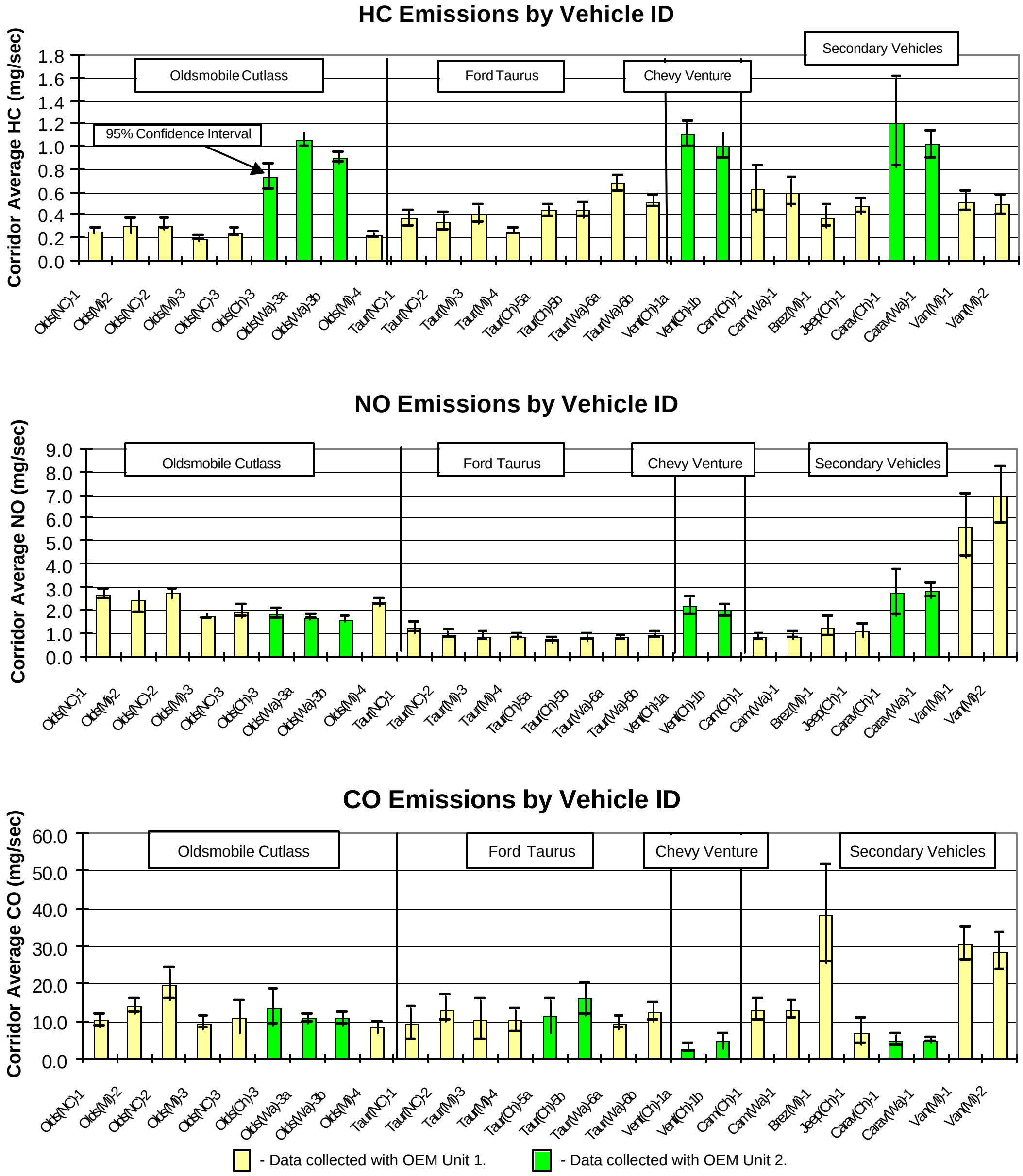


Figure 7-18. Vehicle Emissions by Vehicle ID

Finally, the level of emissions variability within the same vehicle ID is different by pollutant, with the CO emission rate being the most variable. To determine variability within the same vehicle ID, standard errors for each vehicle were estimated and then their ratio to the mean values of the corresponding vehicles were estimated. This procedure is applied for all the pollutants separately.

On the average, across all vehicles, the standard error is approximately 15 percent of the mean for CO emissions. This number ranges between approximately 5 percent and 26 percent over all vehicles. The lowest percent is for the Olds(Wa)-3a, and the highest is for the Taur(Mi)-3. In other words, the 95th percentile confidence level for CO emissions is plus or minus 30 percent of the mean CO rate on the average. Thus, if the mean CO emissions rate is 10 mg/sec, the 95th percentile confidence interval for a given run will be between 7 mg/sec and 13 mg/sec, almost a factor of 2.0 difference from the low to the high estimate.

HC and NO emissions are less variable than CO emissions, as the standard error of both pollutants is approximately eight percent different from the mean values. For HC highest percentage occurred for the Carav(CH)-1 with a value of 17 percent, whereas the lowest percent value is for the Olds(Mi)-3 with a value of 4.6 percent. For NO smallest percent value is for the Olds(Mi)-3 again with a value of 2.8 percent, whereas the highest value is for Carav(CH)-1 again with a value of 18 percent. One reason the CO emissions may be more variable than HC and NO emissions is enrichment activity. Although all three pollutants increase during enrichment activity, Kelly and Groblicki (1993) observed that CO emissions increase at a much higher rate during enrichment than HC and NO emissions. Section 7.5.3 discusses the evidence for enrichment activity with data collected for this study.

7.4 Emissions by Driving Mode

For each corridor run, vehicle emissions were grouped into four driving modes: idle, deceleration, acceleration, and cruise. As an example, Figure 7-19 depicts the modal emission rates for a single 1999 Ford Taurus driven for 72 runs on Chapel Hill Road before coordination. Other modal results are given in Appendix III for other vehicles.

A series of Student's-t tests were performed on the modal emission rates to determine if the modal rates were statistically different from each other. All modal rates for a given pollutant were found to be statistically different from each other at a significance level of $\alpha = 0.05$.

Figure 7-19 shows that emissions are highest during the acceleration mode for each pollutant. The mean HC and NO acceleration emissions rate is approximately 60 percent higher than the respective cruise emission rate, while the mean CO acceleration

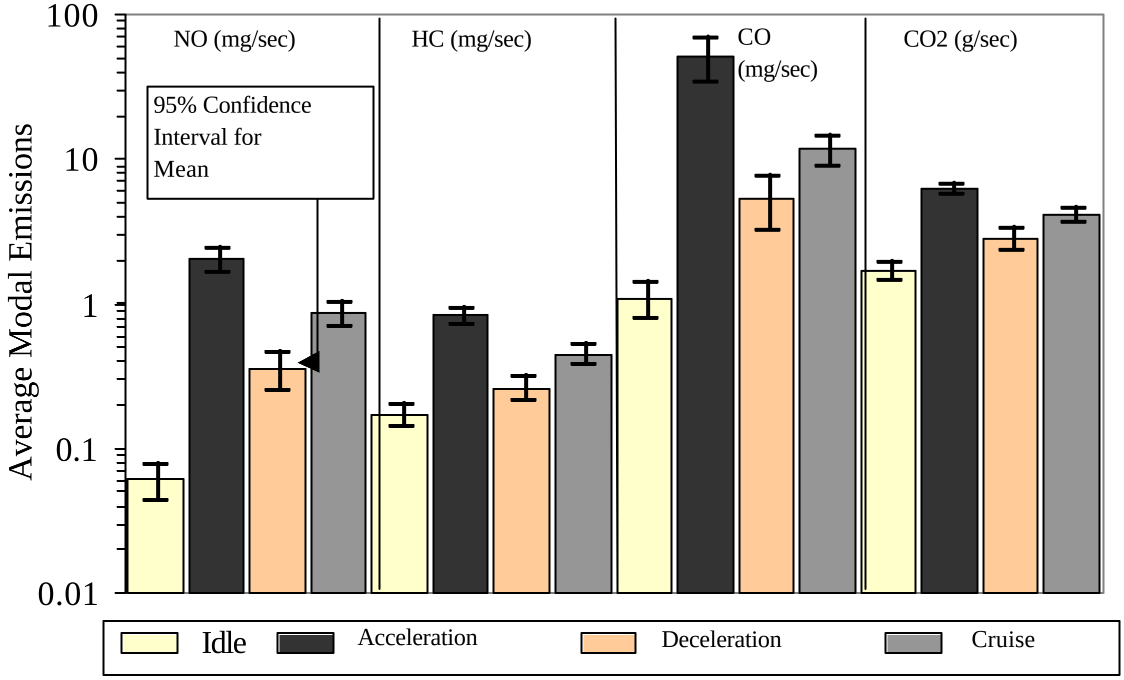


Figure 7-19. Driving Mode Analysis for 1999 Ford Taurus Driven on Chapel Hill Road

emissions rate is approximately 80 percent higher than the cruise emission rate. The cruise mode is the next highest emitting mode after acceleration. Cruising typically occurs at or near the free flow speed, which is 45 mph for Chapel Hill Road. For more congested conditions, cruise mode will most likely occur at a slightly lower speed. The cruise emission rates include some minor acceleration and deceleration activity that did not meet the definitions of acceleration and deceleration. Idling is the lowest emitting mode for all of the pollutants. The idling rate is 80 percent lower than the acceleration rate for HC. Likewise, the idling rate is 45 and 98 percent lower than the acceleration rate for NO and CO, respectively. Thus, for HC emissions one second of acceleration is equivalent to approximately 5 seconds of idling, which is important when considering that signal timing projects often involve a trade-off between intersection delays and stops.

Other vehicles tested for this study exhibited similar relative differences between the modal emission rates. A qualitative observation from these modal rates is that transportation improvement projects aimed at reducing the number of accelerations can lead to substantial air quality benefits, whereas projects aimed at just reducing idling time might yield relatively small air quality benefits.

Another observation is that traffic control devices and geometric designs that cause additional accelerations would likely lead to higher vehicle emissions. For example, ramp metering could cause a vehicle emissions ‘hotspot’ (area of high emissions) due to the accelerations associated with stopping at the ramp meter. Also, traffic calming devices, such as speed humps and chicanes, could create emissions hotspots on local roadways. From a geometric design perspective, lane drops or sharp horizontal curves can lead to increased acceleration activity and, thus, higher vehicle emissions.

The vehicle emissions on a particular corridor run are a function of both the modal emission rates and the amount of time spent in each driving mode. The distribution of time spent in each driving mode depends on the type of facility (i.e. freeway, signalized arterial, or local street) and the congestion level on the roadway. Table 7-10 shows the average time distribution for each study corridor, as well as the sensitivity of time distribution to traffic congestion on Chapel Hill Road. It should be noted that the sensitivity analysis is a function of the modal definitions given in Section 6.4.1, and that changes to these definitions may impact the sensitivity of time spent in each mode for different congestion levels.

As shown in Table 7-10, the study corridors have similar time distributions of modes for the average conditions. The modal distributions for each corridor are similar because they exhibit similar traffic congestion levels, on average. As shown, more time is spent in cruise mode (30% to 52%) than for any of the other three modes for an average run. The time spent in each of the other three modes varies from 14 to 26 percent. The effect of traffic congestion reveals that the modal distribution for very congested runs with average speeds less than 10 mph are not much different than an average congestion level. The only noticeable difference is that the idling rate increases approximately five percent (from 20% to 25%), while the other modes decrease slightly. Even though a very congested run will experience significantly more delay than an average run, this does not translate directly into idle mode, as a delay event includes acceleration and deceleration activity while vehicles move within a queue. As conditions become significantly less congested (speed >40mph), the time spent in idle decreases significantly (as low as one percent) while the time spent in cruise increases up to 80 percent. Even a run with very

Table 7-10. Distribution of Time Spent in Each Driving Mode

Corridor	Avg. Speed (mph)	% Time in Idle	% Time in Acceleration	% Time in Deceleration	% Time in Cruise
Corridor Average					
NC-54 Before	28.9	18	19	16	47
NC-54 After	28.6	20	18	15	47
Miami Blvd Before	27.6	21	20	16	43
Miami Blvd After	28.6	21	19	16	44
Chapel Hill Rd. Before	26.0	18	16	14	52
Chapel Hill Rd. After	26.9	17	14	16	52
Walnut Street Before	23.5	26	24	19	30
Walnut Street After	27.0	18	23	19	40
Sensitivity to Traffic Congestion					
Chapel Hill Rd.	<10	25	15	13	47
Chapel Hill Rd.	10-20	22	16	15	47
Chapel Hill Rd.	20-30	20	17	15	48
Chapel Hill Rd.	30-40	13	16	13	58
Chapel Hill Rd.	> 40	1	10	9	80

little traffic congestion will spend approximately ten percent of time in acceleration and ten percent in deceleration according to Table 7-10. This could be due to a number of factors, including speed adjustments when following slower-moving vehicles, following turning vehicles, or traveling through vertical and horizontal curves.

7.5 Effect of Traffic Flow Characteristics

In this section, the relationship between emissions and selected traffic flow characteristics is explored based upon a preliminary analysis of some of the data sets. Specifically, potential explanatory traffic flow variables, such as average speed, number of stops, and control delay are explored. The analysis is done for data obtained from NC 54, Miami Blvd, Chapel Hill Road, and Walnut Street.

7.5.1 Vehicle Grouping

Before evaluating the relationship between macroscopic traffic parameters and vehicle emissions, the vehicle ID data were grouped into bins of similar emission rates. Because of the high variability in vehicle emissions and the large number of factors that impact vehicle emissions, this grouping process helps reduce the variability of these factors to better capture the true effect of traffic parameters on vehicle emissions.

Three separate groups were identified for each pollutant. In general, one group was chosen for similar 1996 Oldsmobile Cutlasses, one group for 1999 Ford Tauruses,

Table 7-11. Vehicle Emissions Groups

Group	Pollutant	Vehicle ID [1]	Runs
HC-1	HC	Olds(NC)-1, Olds(Mi)-2, Olds(NC)-2, Olds(NC)-3, Olds(Mi)-4, Taur(Mi)-4	176
HC-2	HC	Taur(NC)-1, Taur(NC)-2, Taur(Mi)-3, Taur(Ch)-5a, Taur(Ch)-5b, Brez(Mi)-1, Van(Mi)-2	237
HC-3	HC	Olds(Wa)-3a, Olds(Wa)-3b, Vent(Ch)-1a, Vent(Ch)-1b, Carav(Wa)-1	333
NO-1	NO	Olds(NC)-3, Olds(Ch)-3, Olds(Wa)-3a, Olds(Wa)-3b	248
NO-2	NO	Taur(NC)-2, Taur(Mi)-3, Taur(Mi)-4, Taur(Ch)-5a, Taur(Ch)-5b, Jeep(Ch)-1	243
NO-3	NO	Vent(Ch)-1a, Vent(Ch)-1b, Carav(Ch)-1	145
CO-1	CO	Olds(NC)-1, Olds(Mi)-2, Olds(Mi)-3, Olds(NC)-3, Olds(Ch)-3, Olds(Wa)-3a, Olds(Wa)-3b, Olds(Mi)-4	387
CO-2	CO	Taur(NC)-1, Taur(NC)-2, Taur(Mi)-3, Taur(Mi)-4, Taur(Ch)-5a, Taur(Ch)-5b, Cam(Ch)-1	272
CO-3	CO	Vent(Ch)-1a, Vent(Ch)-1b	133

Notes: 1. See Table 7-6 for a detailed summary of each vehicle ID.

and one group for 1998 Chevrolet Ventures. These vehicles were chosen because they have the highest number of runs. However, each group was not limited to only these vehicles and in some cases included other vehicles if they met the following selection criteria:

- The 95th percentile confidence interval of the mean emission rates should overlap for all vehicle ID's in the same group. Figure 7-18 was used for comparing 95th percentile confidence intervals for each vehicle ID.
- In addition to the mean emission rates, the modal emission rates should be similar for all vehicle ID's in the same group. Detailed modal emission rates for each vehicle ID are given in Appendix III.
- The ratio of idle to cruise emissions should be similar for each vehicle ID in the same group. The idle-to-cruise emission ratio is an indicator of how the emissions relate with traffic parameters. This issue is discussed in more detail in Section 7.5.3..

Based on these criteria, Table 7-11 shows the vehicle emissions groups for each pollutant.

7.5.2 Relationship Between Macroscopic Traffic Parameters

On signalized arterials, the amount of traffic volume, roadway geometry, and timing of the traffic signals determine the magnitude of control delay and stops. The control delay and stops in turn determine the average speed of the corridor. In this sense, average speed is a surrogate variable for control delay and stops.

Figure 7-20 shows the relationship between average speed, control delay, and total stops for all runs on Chapel Hill Road. The three traffic parameters have high R^2 values (between 0.793 and 0.903), indicating the parameters are very closely related to each other. This is expected because an increase in control delay and stops will directly result in a lower arterial speed. The other study corridors (NC 54, Miami Boulevard, and Walnut Street) also exhibit strong correlation between traffic parameters, as displayed in Appendix III.

The relationship between speed and control delay, and speed and total stops, is not linear and the best-fit line for this data was a fourth-order polynomial equation. On the other hand, the best-fit line between total stops and control delay appears to be linear.

7.5.3 Trends of Average Speed and Vehicle Emissions

The trend between average corridor speed and vehicle emissions on a per-mile basis was examined for each emissions group. Figure 7-21 through Figure 7-23 show scatter plots of this relationship for the HC, NO, and CO emission groups, respectively.

Each point represents average emission rates over an entire one-way corridor run. Thus, these figures do not represent the emissions while a vehicle is traveling at a given point speed, but the average emissions over a certain length at a given average speed.

Logarithmic trend lines were fitted to the data points, as this form seems to best fit the data, especially for speeds lower than 20 mph where emissions tend to increase exponentially. More often than not the vehicle emissions decrease as average vehicle speed increases. The significance of this trend varies by pollutant and by emissions group. In general, HC emissions show a more consistent inverse relationship with average speed than the other two pollutants, similar to the findings in Section 7.2.3. Group HC-1 shows a low correlation (R^2 = 0.066) primarily because it has no observations below 20 mph, where emissions seem to increase exponentially with a

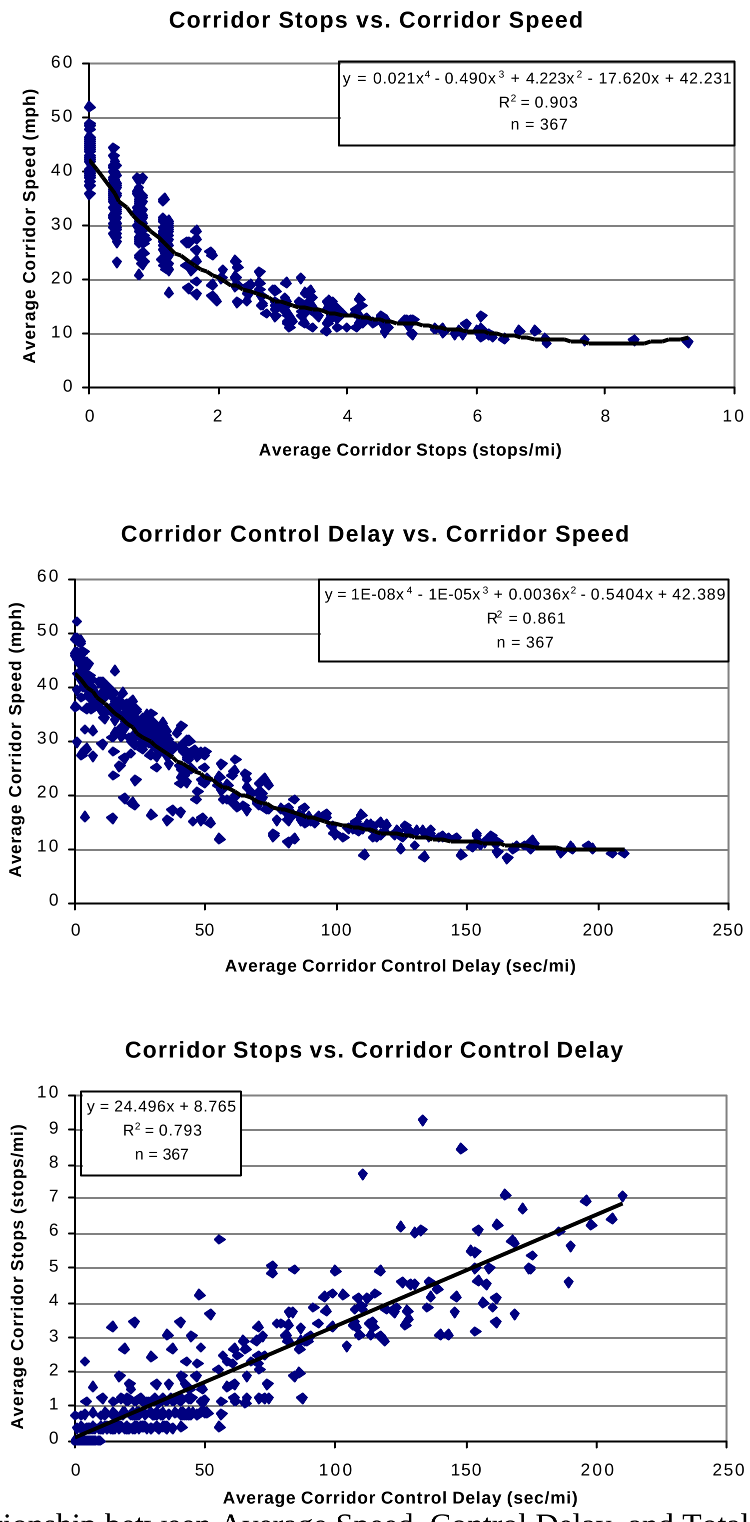


Figure 7-20. Relationship between Average Speed, Control Delay, and Total Stops

decrease in speed. Runs on Chapel Hill Road experienced average speeds below 20 mph, but Group HC-1 only includes runs on Miami Boulevard and NC-54.

Figure 7-21 shows that the trend between NO emissions and average speed varies depending on the emissions group. Group NO-1 shows a strong inverse relationship (similar to findings from Figure 7-11), Group NO-2 shows no relationship, and Group NO-3 shows a weak proportional relationship (i.e. emissions increase as speed increases), similar to findings from Figure 7-12 in Section 7.2.3.

As shown in Figure 7-23, CO emissions show little trend with average speed, as the slopes of the regression lines are nearly flat and the correlation coefficients are low (R^2 from 0.004 to 0.047). In fact, there are a number of runs with very high CO emissions that do not seem to line up with the majority of the data. As mentioned previously, CO emissions are more prone to enrichment activity, which cause short episodes of very high emissions (Kelly and Groblicki, 1993).

The enrichment activity on runs with high CO emissions was investigated to determine if the high-CO runs are in fact due to enrichment activity. A good indicator of whether a vehicle is operating in enrichment mode is the equivalence ratio, which is the ratio of actual fuel use to air intake divided by the ratio of stoichiometric fuel use to air intake (Goodwin and Ross, 1996; Frey, *et al*., 2001). Typically, an equivalence ratio greater than one indicates the vehicle is operating in enrichment mode, and CO emissions generally increase linearly when the equivalence ratio is greater than one. Thus, the maximum equivalence ratio for a given corridor run is an indicator of the magnitude of enrichment activity experienced on that run.

Figure 7-24 shows the general trend between maximum equivalence ratio and average corridor CO emissions for the five highest CO emissions runs and the five runs closest to the average emissions for each CO emissions group (CO-1, CO-2, and CO-3). As shown in the figure, there is a general increasing trend between maximum equivalence ratio and corridor CO emissions. As a result of this trend, the runs with high CO emissions experience higher maximum equivalence ratios than the runs with average CO emissions. This indicates that high CO runs are attributable in part to increased enrichment activity.

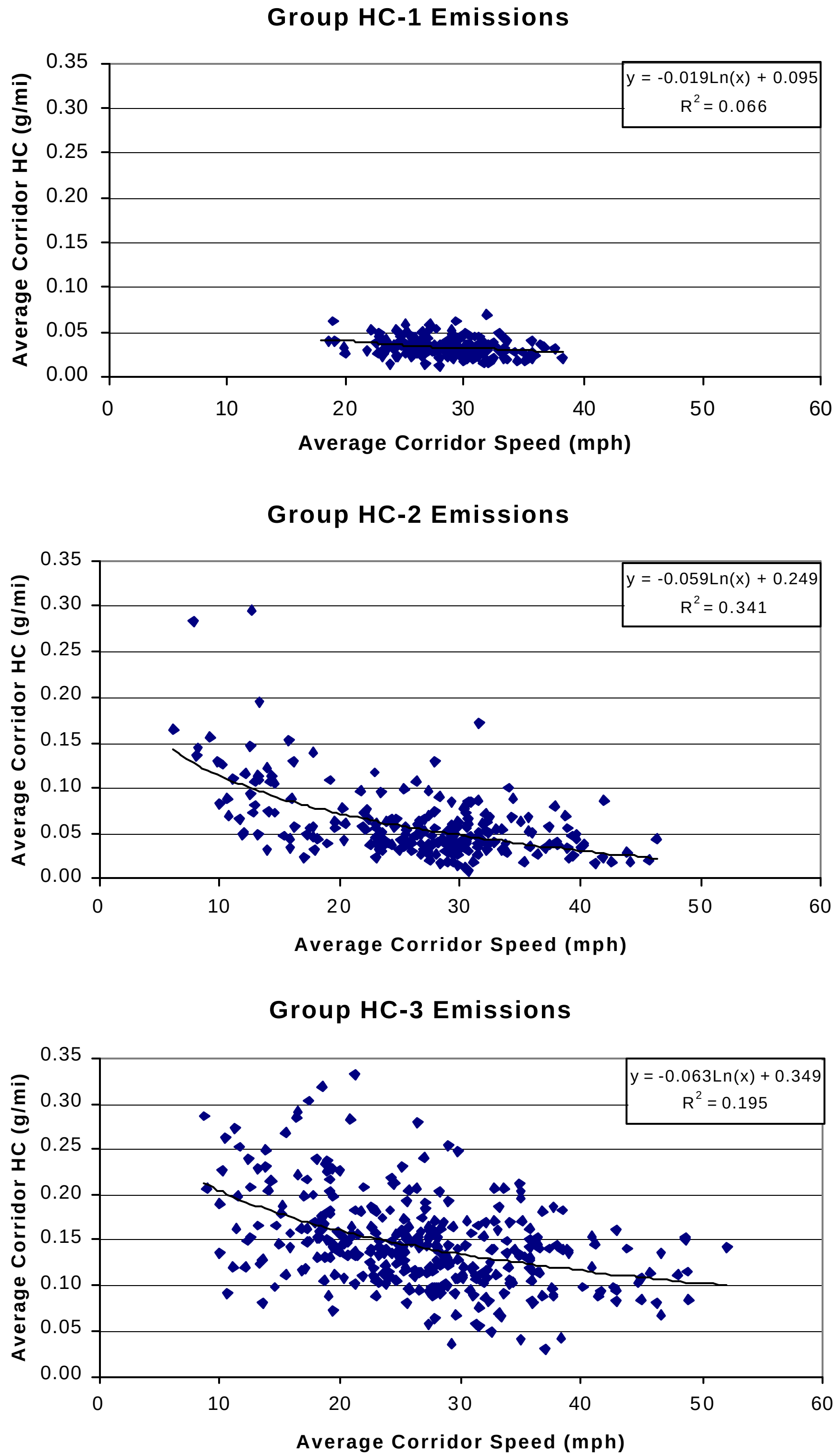


Figure 7-21. Trend between HC Emissions and Average Speed

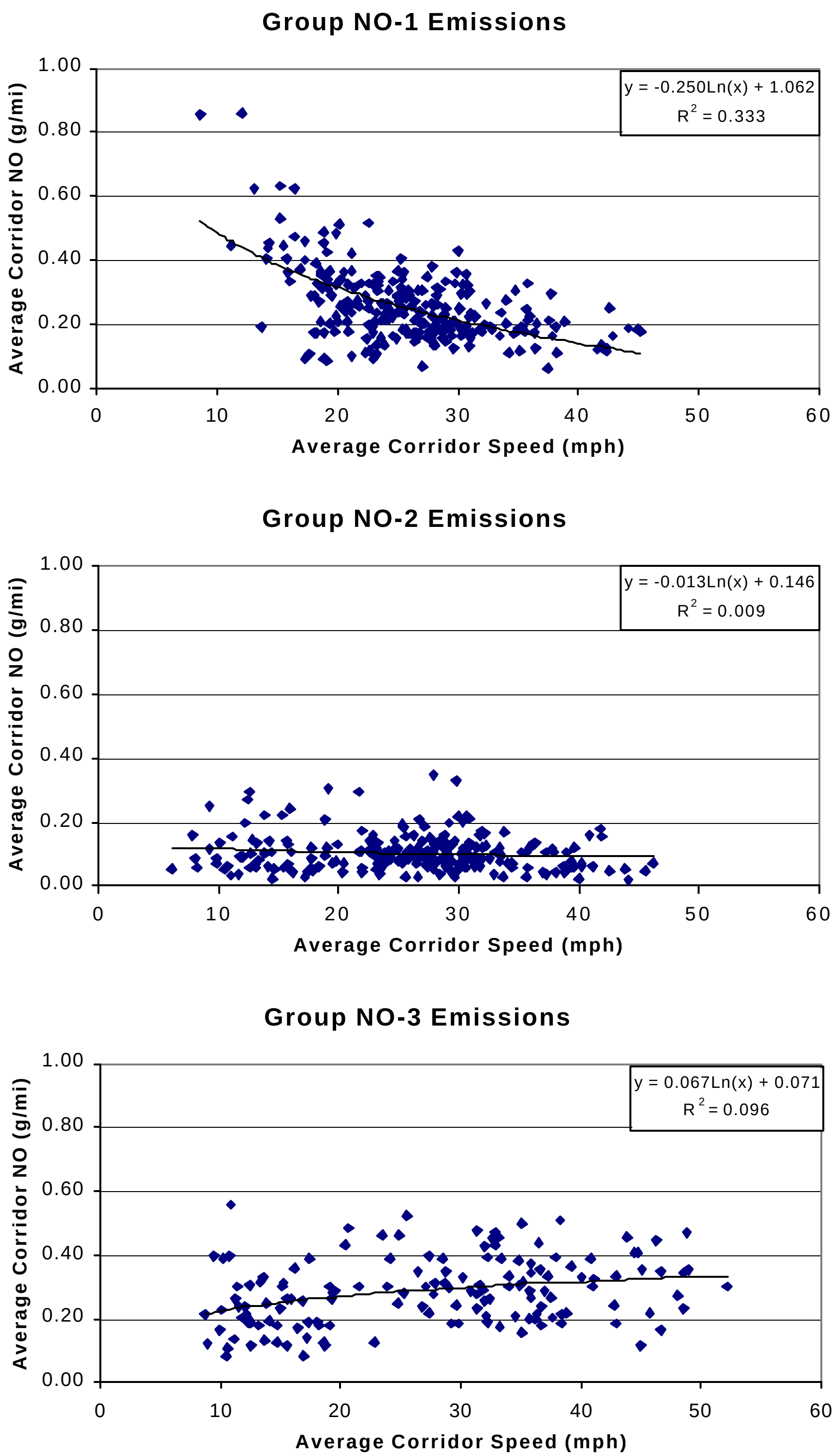


Figure 7-22. Trend between NO Emissions and Average Speed

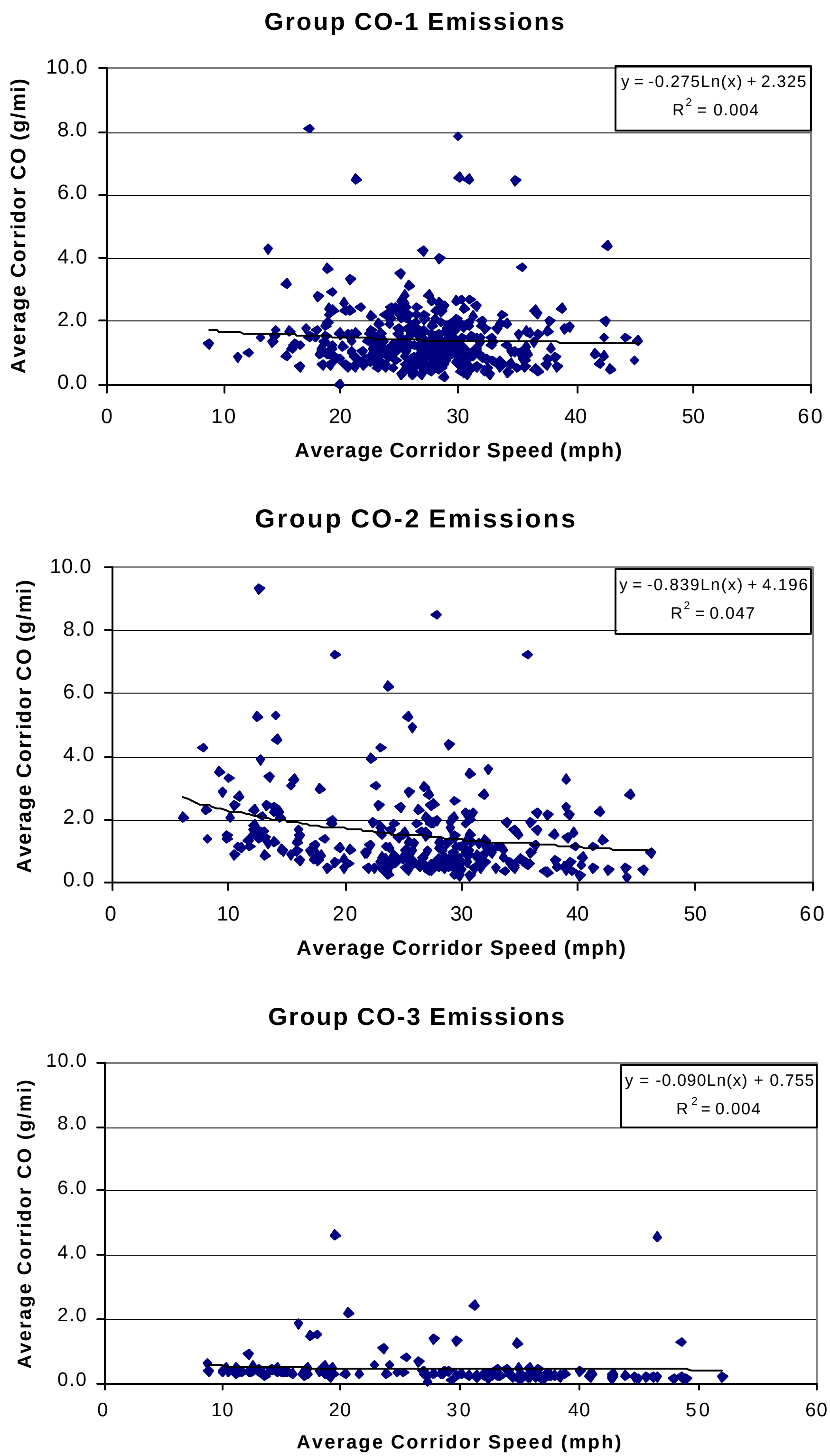


Figure 7-23. Trend between CO Emissions and Average Speed

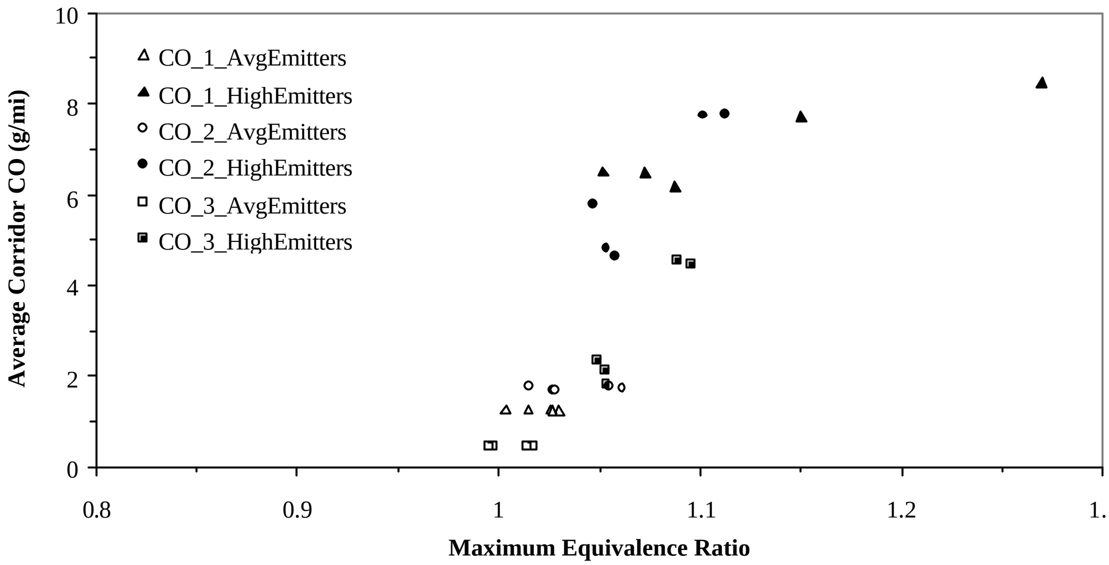


Figure 7-24. Trend Between Maximum Equivalence Ratio and CO Emissions for Runs with Average and High CO Emissions

Figure 7-25 shows a separate graph of the relationship between maximum equivalence ratio and corridor CO emissions for each CO emissions group. As Figure 7-25 shows, the runs with high CO emissions experience higher maximum equivalence ratios than the runs with average CO emissions, on average. This indicates the high-CO runs experienced higher emissions than the average-CO runs due in part to the increased enrichment activity. Also, each emissions group, while showing the same general increasing trend, seem to exhibit different levels of correlation and different magnitudes of maximum equivalency ratio and CO emissions.

The significance and direction of the trend between average emissions on a per-mile basis and average speed is due to two factors. The first is the average emissions on a per-second basis. The second factor is how much time is spent in each mile of travel. The following equation illustrates these two factors:

Distance-Based Emissions = (Time-Based Emissions) x (Travel Time)

with units of: $$\frac{\text{Grams}}{\text{Mile}} = \left(\frac{\text{Grams}}{\text{Second}}\right) \times \left(\frac{\text{Seconds}}{\text{Mile}}\right) \qquad (7\text{-}1)$$

The average time-based emission rate is a function of the time spent in each driving mode. Table 7-10 showed that higher average speeds cause a major shift from time spent in idle to cruise, and a minor shift from acceleration and deceleration to cruise.

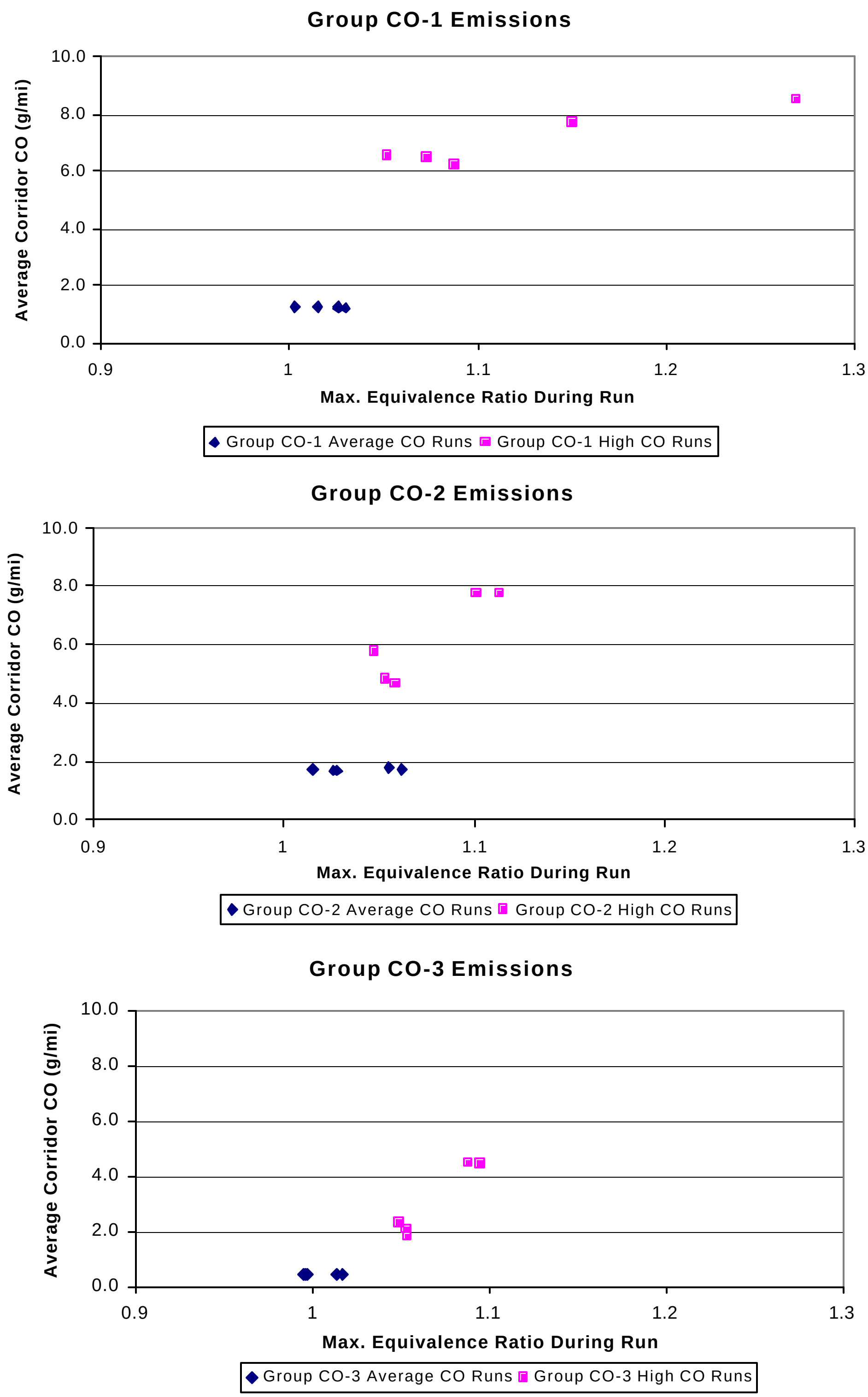


Figure 7-25. Trend Between Maximum Equivalence Ratio and CO Emissions by Emission Group

As a result, a higher average speed could indicate higher time-based emissions due to the major shift from idle to cruise, as emissions are higher in cruise than idle.

The small decrease in time spent in acceleration and deceleration with higher average speeds also affect the relationship between average speed and time-based emissions. In addition, higher average speeds could cause accelerations to occur at higher speeds, which would also affect the relationship between average speed and time-based emissions. Because a change in average speed primarily causes a change in the time spent in idle and cruise modes, one simple indicator of the change in time-based emissions as a function of corridor speed is the ratio of idle-to-cruise emissions. Figure 7-26 shows the ratio of idle-to-cruise emissions for the nine emissions groups.

As shown in Figure 7-26, the HC emissions groups have higher idle-to-cruise ratios than the NO and CO emissions groups, on average. A low idle-to-cruise ratio indicates that the idle rate is much lower than the cruise rate and, thus, an increase in average speed could result in much higher time-based emissions due to the shift from a lower emissions rate (idle) to a higher emissions rate (cruise). On the other hand, a relatively high idle-to-cruise ratio indicates that the idle rate is lower than the cruise rate, but not as much lower as would be with a very low idle-to-cruise ratio. As a result, an increase in average speed could result in a minor increase in time-based emissions. Again, using only the idle and cruise emission rates as an indicator of the relationship between time-based emissions and average speed does not capture the additional effects due to the minor change in the time and nature of acceleration and deceleration modes.

The other factor affecting distance-based emissions is travel time. A higher average speed causes the travel time to decrease because travel time is inversely related to speed. Figure 7-27 illustrates the effect of idle-to-cruise ratio on the trend between emissions and average speed.

The idle-to-cruise ratio explains why each NO emissions group exhibits a different relationship with average speed. For example, Group NO-1 has a relatively high idle-to-cruise ratio, which Figure 7-27 shows can result in a relatively strong inverse relationship between average speed and distance-based emissions. This type of relationship matches the relationship found with the actual corridor-average data shown in Figure 7-22.On the other hand, Groups NO-2 and NO-3 have relatively low idle-to-

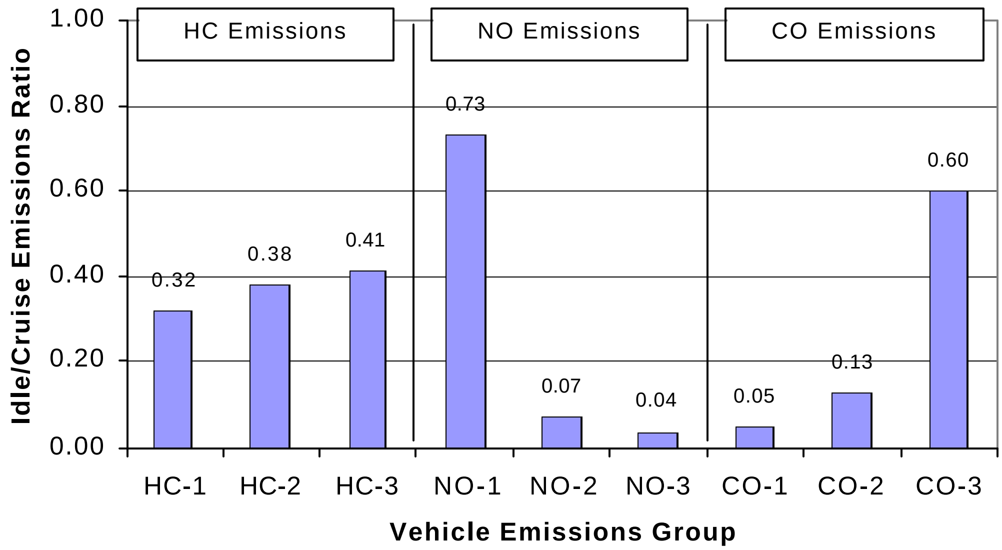


Figure 7-26. Idle/Cruise Emissions Ratio by Vehicle Group

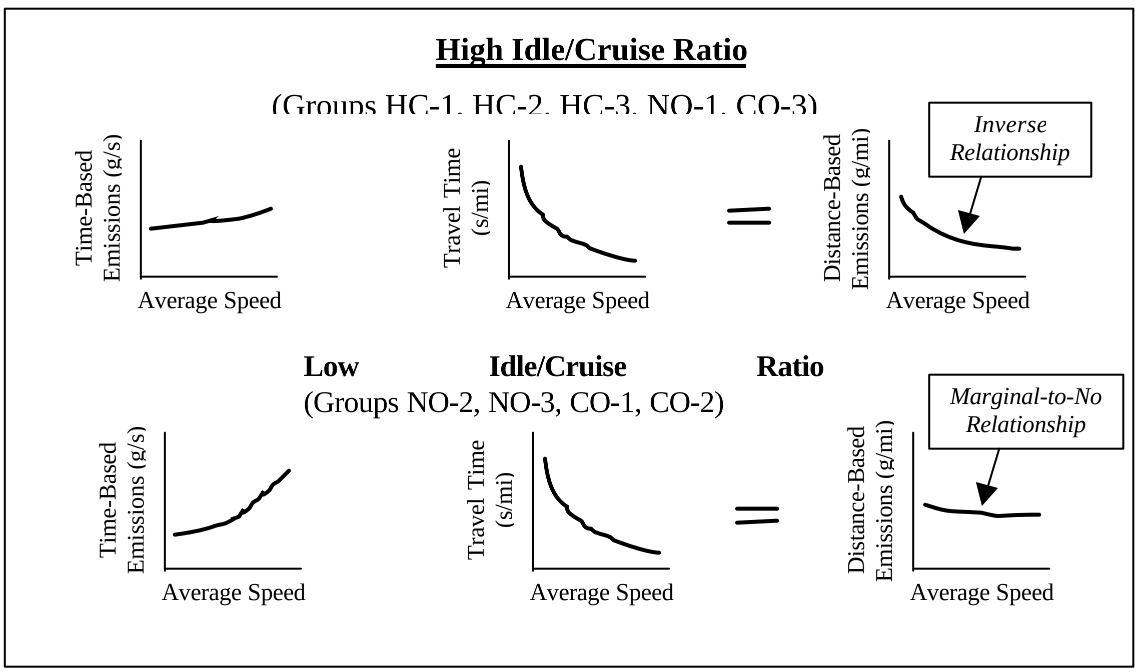


Figure 7-27. Effect of Idle-to-Cruise Ratio on Distance-Based Emissions.

cruise ratios, which Figure 7-27 shows can result in marginal-to-no relationship between average speed and distance-based emissions. This lack of relationship matches the actual corridor-average data for Groups NO-2 and NO-3 (refer to Figure 7-22).

7.5.4 Trend Analysis of Vehicle Emissions Versus Control Delay and Corridor Stops

Average speed is not a good traffic parameter for predicting vehicle emissions on signalized arterials because it does not accurately model the number of accelerations and amount of idling time. For example, consider a change in the timing of the traffic signals that causes fewer stops but increased delay per stop. This trade-off may result in no appreciable change in the average corridor speed. However, the proportion of time in idle, acceleration, and deceleration modes would certainly change. A model based solely on average speed would assume that the two conditions produce equal vehicle emissions. Most likely, however, the run with fewer stops would experience less emissions because of the decrease in acceleration events.

For this reason, corridor-average control delay and stops were examined for trends with vehicle emissions by group. The methodology for measuring control delay and corridor stops during each run was explained in Section 6.4.

Figure 7-28 shows scatter plots of Group NO-1 corridor-average emissions versus corridor-average speed, control delay, and total stops. Appendix III shows similar scatter plots for all emission groups. Control delay and stops are expressed on a per-mile basis to maintain unit consistency with the distance-based emissions. The average control delay per mile was calculated by summing the intersection control delays for the run and dividing by the corridor length. Similarly, the average corridor stops per mile was calculated by summing the total number of stops for the run and dividing by the corridor length.

As shown in the figure, all three traffic parameters show similar correlation with emissions. Average speed correlates with emissions the best of the three traffic parameters (R^2 = 0.333), while control delay showed the least correlation (R^2 = 0.238) with NO emissions for this particular group. The similar correlation is because the traffic parameters themselves are closely related.

The y-intercepts of the control delay and total stops graphs gives the approximate grams per mile of emissions when a corridor run is predominantly in cruise mode (with possibly a small portion of acceleration and deceleration time as well) because it represents a corridor run with no control delay or stops. Thus, the y-intercept estimates

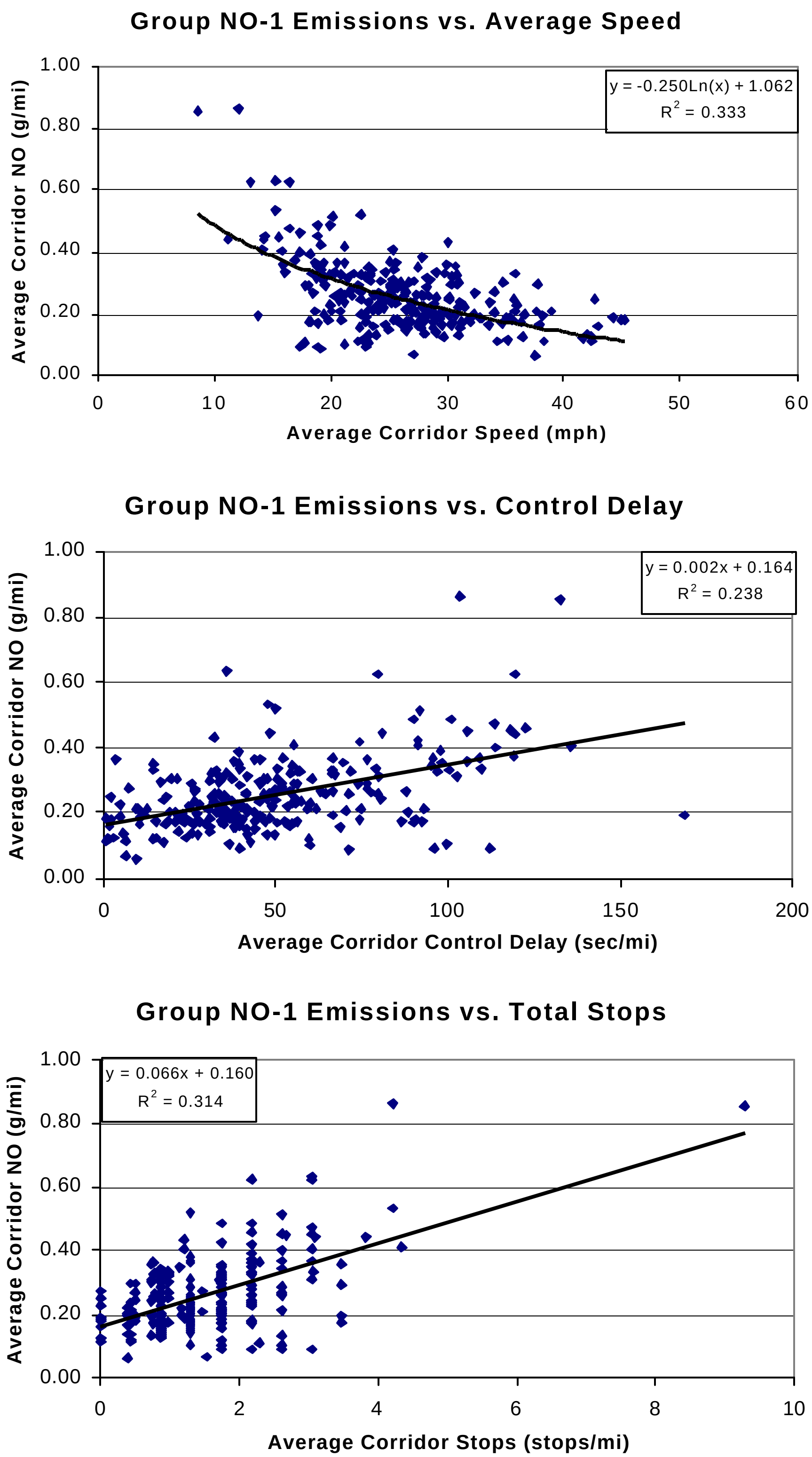


Figure 7-28. Trends Between NO-1 Emissions and Speed, Control Delay, and Total Stops.

Table 7-12. R^2 Value and Standard Error of Relationship Between Traffic Parameters and Vehicle Emissions.

Emissions Group	Average Speed	Control Delay	Total Stops
HC Emissions			
HC-1	0.066 (10.7)	0.038 (10.8)	0.043 (10.9)
HC-2	0.341 (33.2)	0.373 (30.8)	0.369 (31.0)
HC-3	0.195 (45.0)	0.156 (45.7)	0.186 (44.9)
NO Emissions			
NO-1	0.333 (100.)	0.238 (102.)	0.314 (96.7)
NO-2	0.009 (55.6)	0.009 (55.8)	0.006 (55.8)
NO-3	0.096 (101.)	0.048 (103.)	0.074 (101.)
CO Emissions			
CO-1	0.004 (1004.)	0.010 (1000.)	0.013 (999.)
CO-2	0.047 (1505.)	0.052 (1497.)	0.049 (1499.)
CO-3	0.004 (633.)	0.000 (635.)	0.007 (633.)

Note: 0.066 (10.7) – Correlation R^2 value (standard error in predicted emissions in mg/mi based on regression with traffic parameter).

the minimum amount of distance-based emissions possible. Any control delay and stops would then increase the emissions rate due to increased idle, acceleration, and deceleration time.

The slope of the control delay and total stops graphs are in units of grams per second of emissions. The steepness of the slope indicates how much control delay and stops together add to a base-case run consisting of mostly cruise mode. Because control delay and stops are not independent, the incremental contribution of just one variable cannot be obtained from these graphs.

Table 7-12 shows the R^2 values and standard errors of vehicle emissions based on the regression equations with average speed, control delay, and corridor stops for all emissions groups.

As evident from the table, the emissions groups exhibit similar correlation for each traffic parameter. This is expected because, as stated previously, the traffic parameters are not independent (see Figure 7-20) and thus the R^2 values reflect the effect of a combination of the traffic parameters rather than the impact of one individual traffic parameter. This analysis revealed that any one of these traffic parameters can not explain much of the variability in vehicle emissions.

7.6 Effects of Road Grade

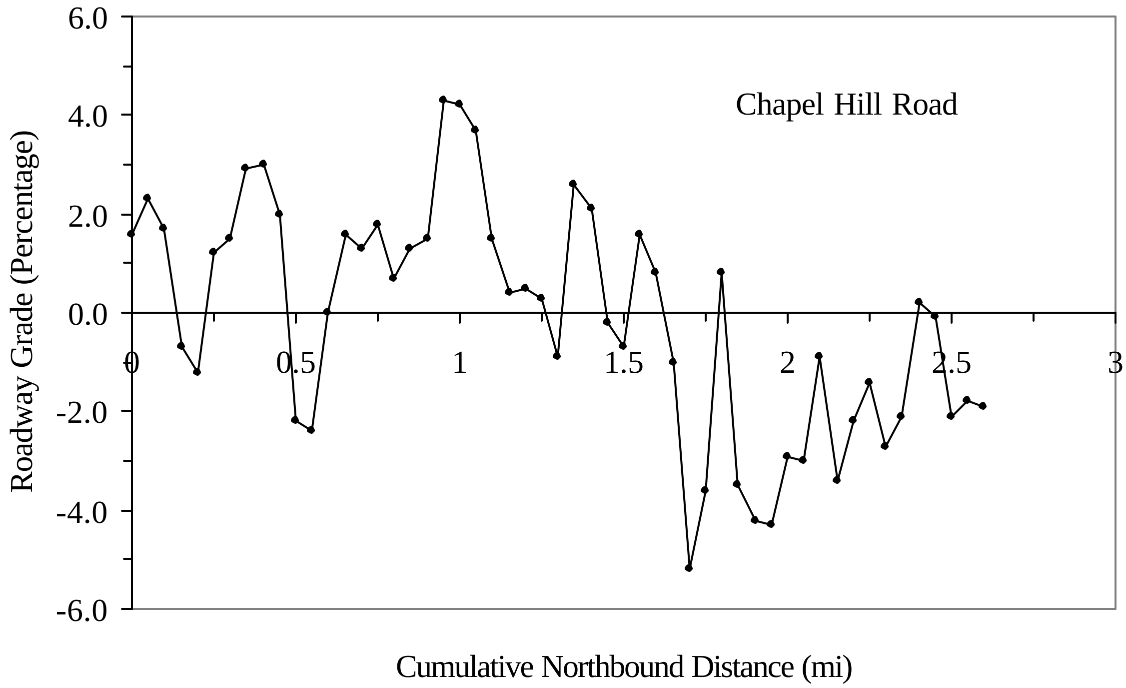
One of the roadway characteristics that may have an effect on vehicle emissions is road grade. Road grade can affect vehicle emissions by impacting the load on the engine. Several researchers studied the effect of road grade on vehicle emissions (Bachman, 1999; Cicero-Fernandez and Long, 1997).

The potential effects of roadway grade on vehicle emissions was investigated through a spatial analysis of grade and vehicle emissions data for the evaluation sites, Chapel Hill Road and Walnut Street corridors. The spatial analysis considered the differences in traffic and emissions data on one-tenth of a mile segments of the corridors. The roadway grade was measured every tenth of a mile using a digital level as described in Section 4. Figure 7-29 shows the measured road grades for Chapel Hill and Walnut Street.

The average road grade on Chapel Hill Road is +0.1% in the southbound direction and –0.1% in the northbound direction. However, the maximum grade in the southbound direction is approximately five percent, and the maximum grade in the northbound direction is approximately four percent. Thus, there are locations on the corridor where there is variation in road grade as illustrated in Figure 7-29. Walnut Street has an average grade of +0.1percent in the southbound direction and –0.1percent in the northbound direction. The maximum grade in the southbound direction is approximately four percent, and the maximum grade in the northbound direction is approximately three percent.

The emissions data for each run on a given corridor were grouped into bins of one-tenth of a mile. In order not to account for the effect of acceleration from intersections, data within a 0.1 mile range of intersections were excluded. The “binned” data were then averaged by vehicle make and model to find the relations between roadway grade and vehicle emissions.

Figure 7-30 presents average emission rates versus road grades along with 95 percent confidence interval on the mean for data collected using Chevrolet Venture on Chapel Hill Road. Figure 7-31 shows the same analysis for Ford Taurus driven on Walnut Street.



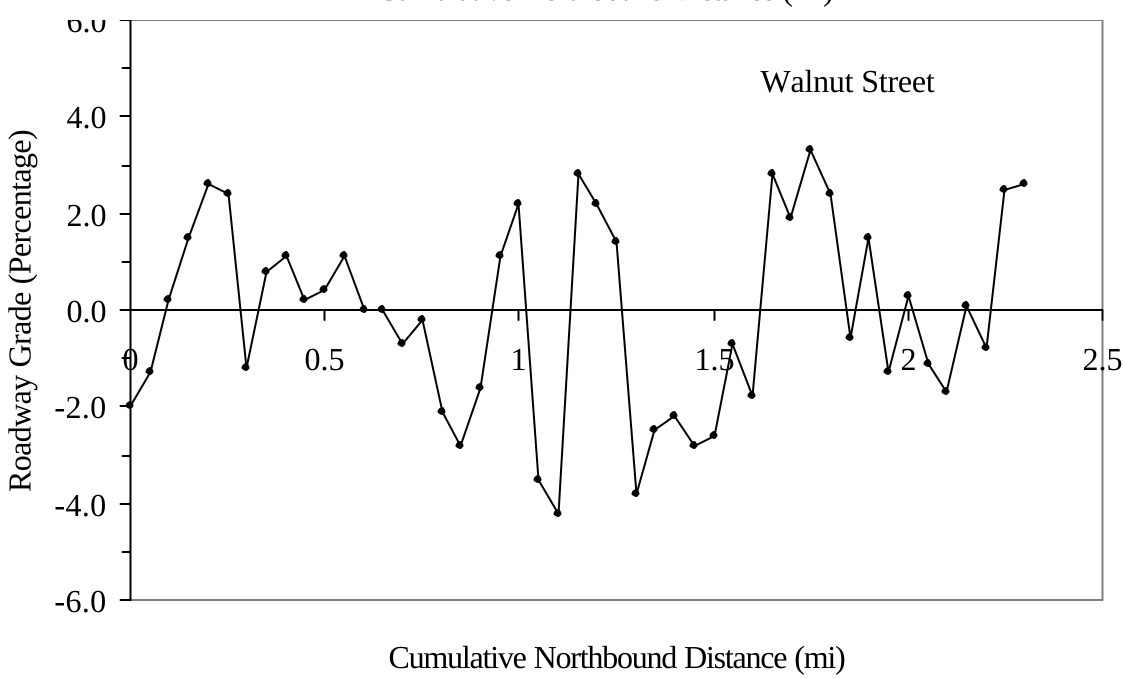


Figure 7-29. Roadway Grade Measured on Chapel Hill and Walnut Street

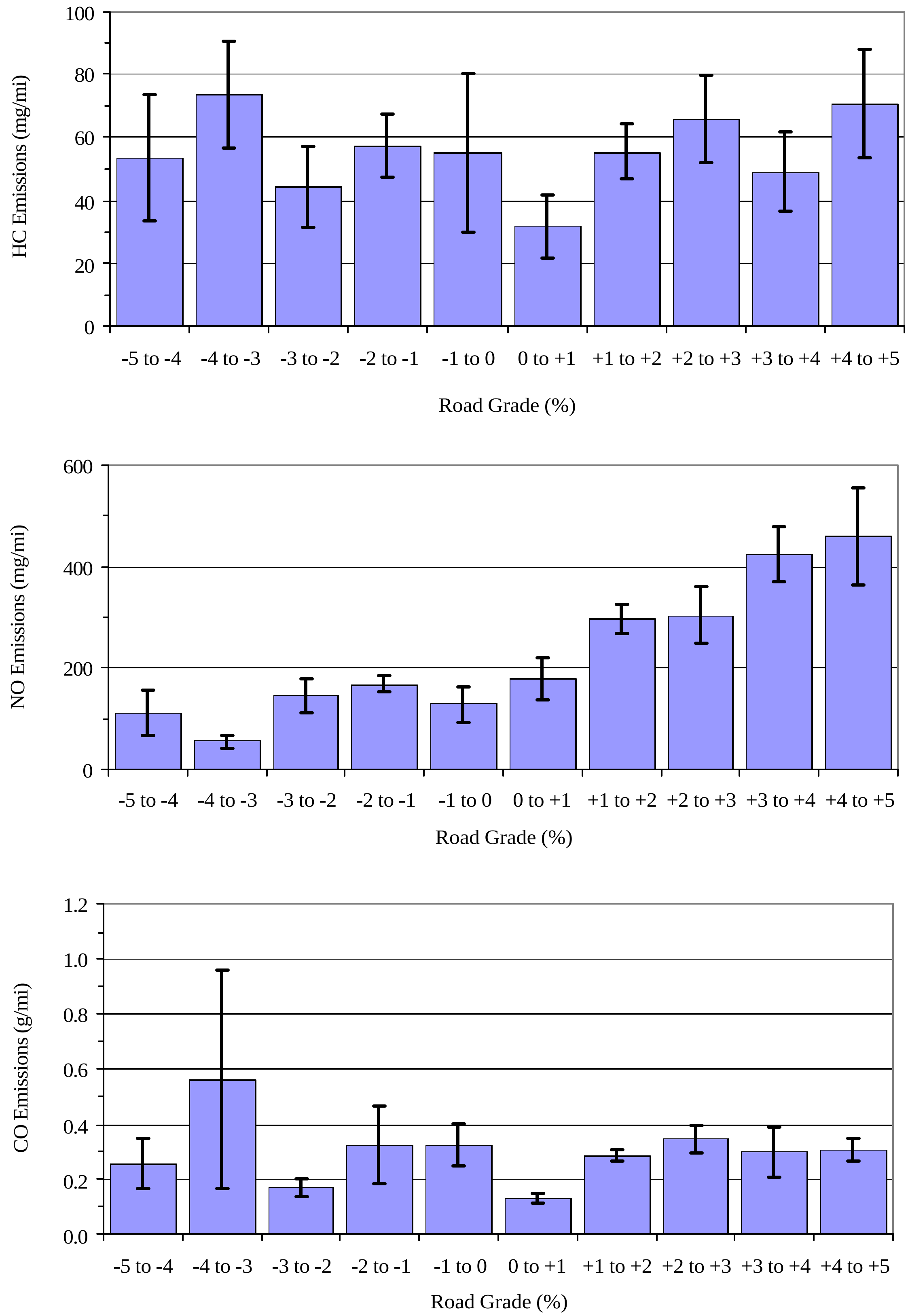


Figure 7-30. Relation between Roadway Grade and Vehicle Emissions for Data Collected using Chevrolet Venture on Chapel Hill [Error bars denote the 95 percent confidence interval of the mean]

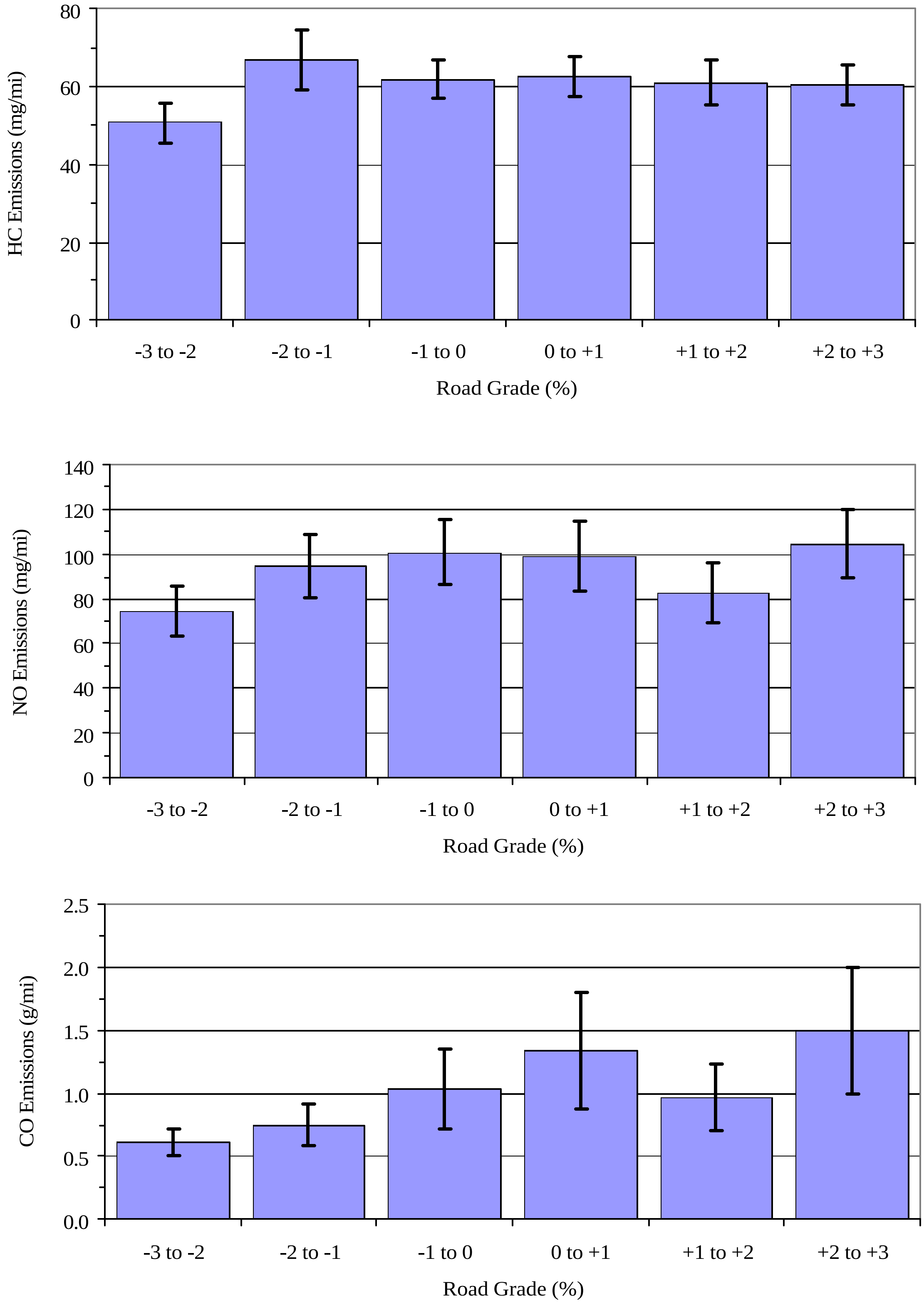


Figure 7-31. Relation between Roadway Grade and Vehicle Emissions for Data Collected using Ford Taurus on Walnut Street [Error bars denote the 95 percent confidence interval of the mean]

The relationship between road grade and NO emissions shown in Figure 7-30 is reasonable. NO emissions would be expected to increase with an increase in positive road grade, because of the simultaneous increase on engine load. For the Chevrolet Venture, there appears to be a factor of three increase in NO emissions from negative or no road grade to the highest positive road grades. For HC and CO for the Chevrolet Venture, there is no significant variation of emissions with respect to road grade.

For the Ford Taurus data obtained on Walnut Street, it appears that HC and NO emissions are insensitive to the observed variation in road grade. There appears to be an increase in CO emissions with an increase in road grade. However, the emission rate for positive road grade does not appear to vary significantly.

7.7 Summary

The exploratory analysis included several complementary techniques for exploring the database. These techniques included:

- Visualization of Time Traces
- Analysis of Variance
- Statistical Multicomparisons
- Regression Analysis

The insights obtained from application of each of these techniques are summarized here.

1.1.1 Insights from Visualization of Data

Examples of data regarding vehicle activity (e.g., speed) and emissions were visualized as time traces in Section 7.1. A comparison of the emissions traces with the speed trace reveals that vehicle emissions appear to be influenced by accelerations that are associated with higher emission rates compared to those occurring at other times during a trip.

1.1.2 Insights from Analysis of Variance

Analysis of Variance (ANOVA) is a statistical technique for identifying dependencies between individual factors and an output of interest. The individual factors can also be based upon a grouping of specific variables and can take into account interactions among variables. In Section 7.2, a brief theoretical background on ANOVA was presented. A preliminary analysis was conducted mainly for the purpose of identifying which variables should be the focus of more detailed analysis. The preliminary analysis was based upon trip average values of activity and emissions data. Data from the Chapel Hill Road corridor were analyzed separately from data for the Walnut Street corridor. For a given corridor, results were found to depend on the vehicle and on whether data were collected before or after the change in signal timing and coordination. Therefore, for each corridor, four separate databases were created, for each of the two primary vehicles and for each of the "before" and "after" time periods. For each database, three pollutants were evaluated as the dependent variable in ANOVA. Therefore, a total of 24 data sets (2 corridors x 4 databases per corridor x 3 pollutants per data set) were evaluated using ANOVA.

Average vehicle speed and the time and direction of vehicle travel were found to be important explanatory variables in many of the data sets. Some variables were important in only a small number of datasets, such as ambient temperature, ambient humidity, date of data collection, driver, and air conditioning usage.

ANOVA has some limitations and can give potentially misleading findings if not carefully interpreted or confirmed. The results in which driver, date, and air conditioning usage were found to be significant based upon ANOVA were revisited using another statistical method. Based upon the second approach, these variables were found to be statistically insignificant in most cases.

The effect of corridor average speed, time and direction of travel, and relative humidity were evaluated with respect to NO emissions using statistical trends analysis methods based upon non-parametric regression. The trend between NO emissions and average speed was found to be vehicle-specific. A statistical multicomparison test was done to evaluate the effect of time of day and direction of travel with respect to trip average emissions. Statistically significant differences in emissions when comparing some time/direction pairs were found, motivating additional work that is reported in Chapters 10 and 11. In one case, humidity was found by ANOVA to be a significant factor with respect to NO emissions. A scatter plot and non-parametric regression revealed that NO emissions tend to decrease as humidity levels become very high, which is an expected result.

For HC emissions, the effect of average speed, ambient temperature, humidity, and time and direction of travel were explored more thoroughly based upon the results of the preliminary ANOVA analysis. Typically, average HC emissions decrease with average speed, increase with average temperature, and decrease with average relative humidity. However, there is also a large amount of variability in the trends. There were statistically significant differences in average HC emissions when comparing some pairs of time/direction data sets.

Average CO emissions were found to decrease with an increase in average speed. There were significant differences in average CO emissions when comparing at least some pairs of time/direction data sets.

Overall, the findings from ANOVA suggest that average speed, time and direction of travel, ambient temperature, and relative humidity are potentially important explanatory variables, although not all of these are important in all cases. Results of ANOVA were evaluated more thoroughly using scatter plots, non-parametric regression approaches, and multicomparisons.

1.1.3 Insights Regarding Effect of Vehicle Characteristics

The trip average emissions rates for 17 different vehicles deployed on four different corridors were compared for each of the three pollutants. In some cases, the same vehicle was tested on more than one corridor. In other cases, different vehicles of the same year, make, and model were tested on the same corridor. Comparison of results for these special cases reveals that there can be variability in emissions for the same vehicle driven under different conditions on two different corridors. Vehicles of the same year, make, and model may have statistically similar emissions in most cases, but in some cases one of the vehicles can be significantly different.

The variation in emissions between vehicles of different make and model are more pronounced than the variation in emissions among vehicles of the same make and model. Some vehicles may have a high emission rate for one pollutant but not for other pollutants. For any given vehicle, CO emissions tended to have the most inter-run variability compared to NO and HC emissions.

An overall implication of the comparison of vehicles is that it may be important to perform before and after comparisons separately for each vehicle, rather than to aggregate results for multiple vehicles prior to making before and after comparisons.

7.7.1 Insights Regarding the Effect of Driving Modes

This study featured the use of a definition of driving modes for acceleration, cruise, deceleration, and idle based upon criteria for speed and acceleration, both of which can be readily inferred from a speed trace. In practice, the definitions are found to be useful because the emission rates for each mode are typically statistically significantly different than the emission rates for the other three modes, for a given pollutant and vehicle. Typically, the time-based emission rate (e.g., mg/sec) is much higher in acceleration than in cruise, which in turn is higher than deceleration, which in turn is higher than idle. For example, for a 1999 Ford Taurus, the acceleration emission rate was found to be ten times the idle emission rate for both NO and CO. The relative comparison of emission rates among the four modes is typically found for all pollutants and for all vehicles, although at times there may be exceptions. These data suggest that more attention should be paid to the role of accelerations in contributing to total trip emissions.

7.7.2 Insights Regarding Traffic Flow Characteristics

Key measures of traffic flow, including average speed, number of stops, and control delay, were explored as potential explanatory variables with respect to emissions. In general, most vehicles displayed an decrease in average HC emissions as average speed increased. For NO, vehicles exhibited a variety of behaviors. For some vehicles, average NO emissions decreased as average speed increased. For some, there was no relationship between average emissions and average speed. For others, average emissions increased slightly as average speed increased. For CO, average emissions typically decreased at least slightly in going from low average speeds to high average speeds. However, for CO, it was shown that the average emission rate has a strong relationship with the maximum equivalence ratio during a trip. The latter is an indication of fuel enrichment.

Control delay and the total number of stops in a trip were found to have a statistically significant impact on trip average emissions for at least some groups of vehicles and pollutants. Typically, average emissions increase with an increase in average corridor control delay and/or average corridor stops.

7.7.3 Insights Regarding the Effect of Road Grade

On the two evaluation corridors, road grade varied within an overall range of plus or minus five percent. The effect of road grade was evaluated by binning emissions data into bins representing specific ranges of road grade, and comparing the average emissions in different bins for a given vehicle. For the Chevrolet Venture driving on Chapel Hill Road, there was a well-defined trend of NO emissions increasing as positive road grade increased. For other vehicles and pollutants, there were not clear trends. Overall, the influence of road grade in this study may have been relatively small because road grades may not have been large enough, nor the grades long enough, to generate sustained high engine power demand during vehicle operation. Overall, road grade was not found to be an important factor.

7.7.4 Overall Insights from the Exploratory Analysis

Using a variety of analysis methods, including ANOVA, scatter plots, nonparametric and parametric regression, multicomparisons, and comparisons of distributions, some of the key potential explanatory variables identified include: average speed, temperature, humidity, time/direction, control delay, and number of stops. There are other explanatory variables that may be important in selected cases, but that are not systematically important throughout the entire data set. Examples include air conditioning usage and road grade.

8.0 A MACRO-SCALE TRAFFIC FLOW-BASED APPROACH FOR ESTIMATING EMISSIONS

In this section an approach for modeling vehicle emissions by using traffic parameters will be presented.

8.1 Normalized Trends of Emissions Versus Control Delay and Corridor Stops

When modeling vehicle emissions on signalized arterials, it is important to account for the contributions of both delay and stops. A model just based on stops would not take into account increases in delay when the stops remain constant. Conversely, a model just based on delay would not take into account increases in stops when the delay remains constant. Therefore, both control delay and stops should be considered because they have different effects on the time spent in each driving mode.

To normalize the emissions contribution of control delay and stops, average corridor emissions per stop was chosen as the dependent variable and average corridor control delay per stop was chosen as the independent variable. By dividing the variables by the number of stops, both control delay and stops become independent of each other, allowing the individual effects of control delay and stops on vehicle emissions to be properly captured on a corridor-average level. Both variables were also divided by corridor length, in miles, to capture the effect of corridor length. Thus, the units of the dependent variable are milligrams of emissions per stop-mile and for the independent variable the units are seconds of control delay per stop-mile.

Figure 8-1 through Figure 8-3 show scatter plots of the normalized trends between control delay and stops versus vehicle emissions for the HC, NO, and CO emission groups, respectively. The y-intercept and slope of the regression lines provide insight into the relative effects of total stops and control delay. For example, Group HC-1 has a y-intercept of 2.575 and slope of 0.602. This means each stop/mile increases HC emissions by 2.575 mg/mile, while each second/stop of control delay increases HC emissions by 0.602 mg/mile. Thus, the magnitude of the y-intercept indicates the normalized contribution of total stops on vehicle emissions, while the slope indicates the contribution of control delay.

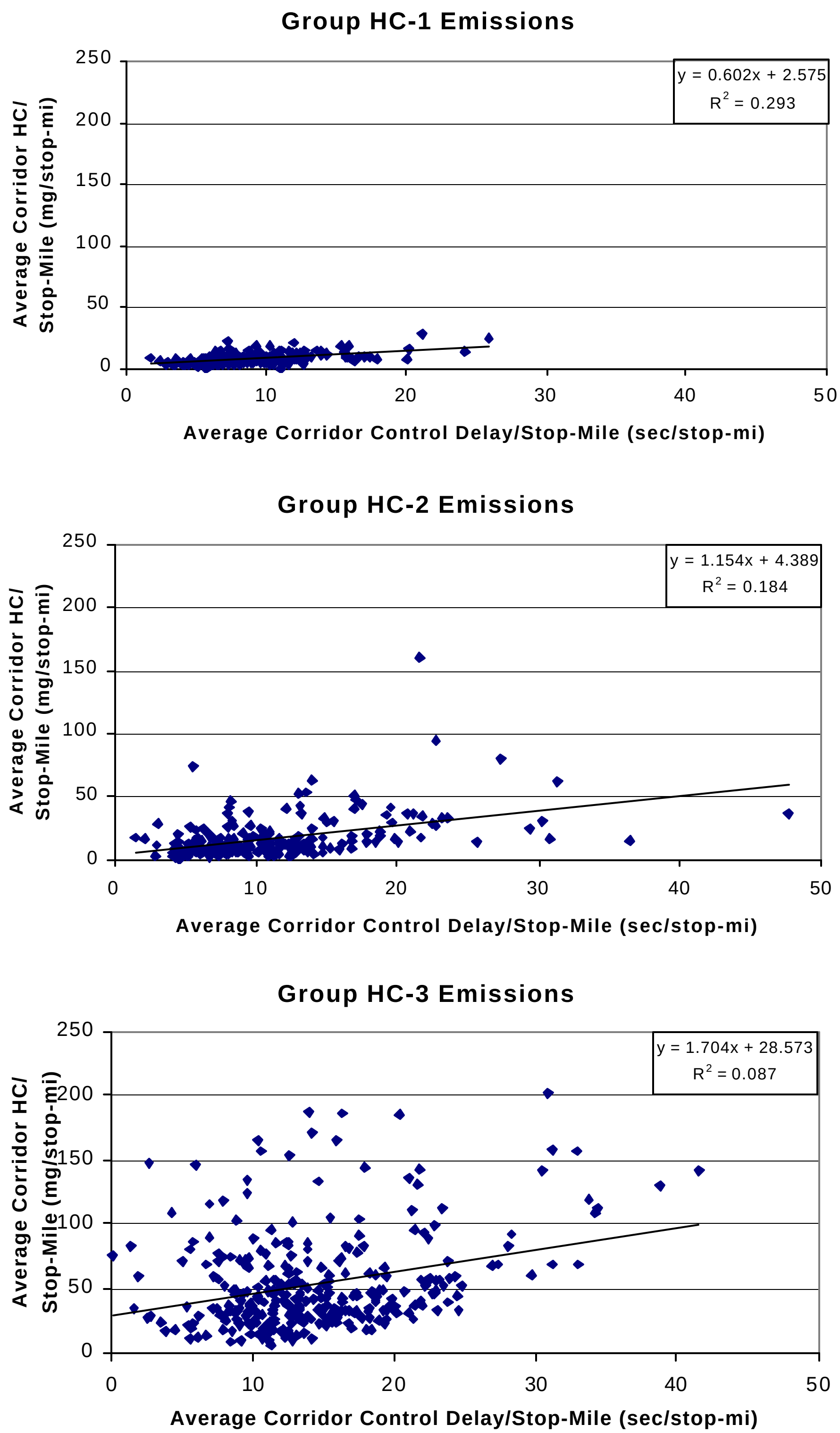


Figure 8-1. Normalized Effects of Control Delay and Total Stops on HC Emissions

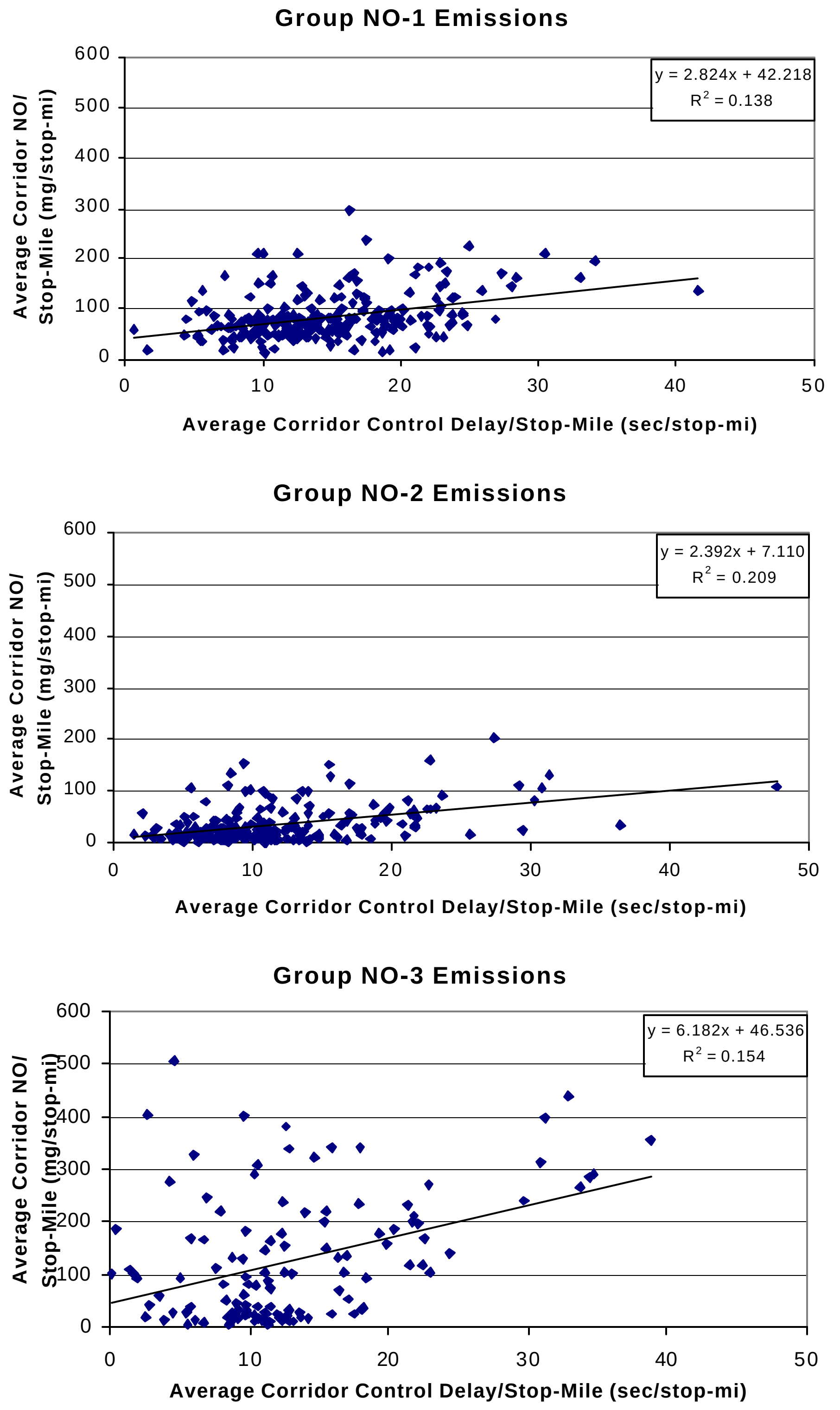


Figure 8-2. Normalized Effects of Control Delay and Total Stops on NO Emissions

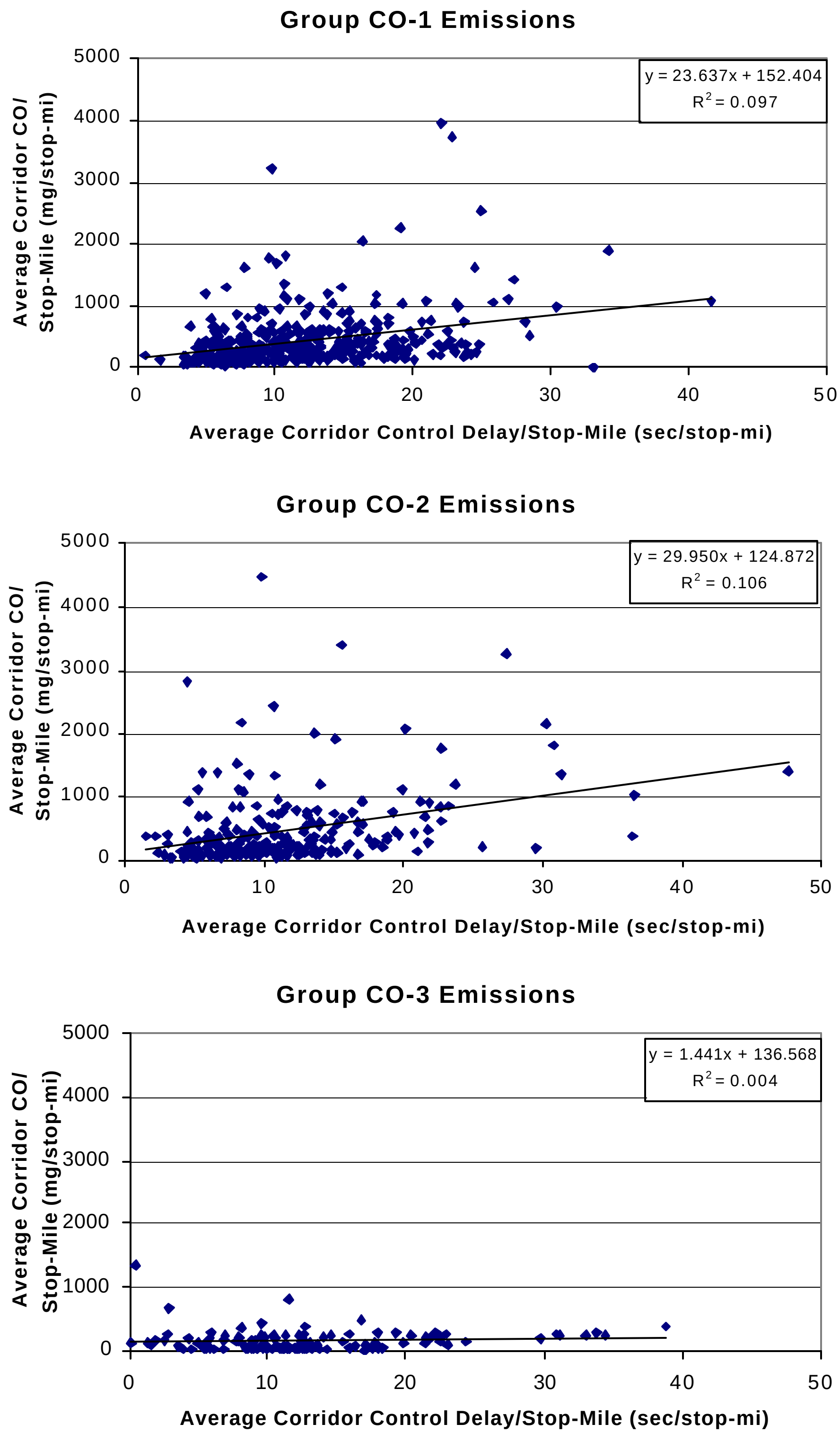


Figure 8-3. Normalized Effects of Control Delay and Total Stops on CO Emissions

CALCULATION STEPS	EXAMPLE APPLICATION
Step 1: Obtain Traffic Input Information - Corridor Length (mi) - Total Corridor Control Delay (sec) - Total Corridor Stops (stops)	Corridor Length = 5.0 mi Total Cont. Del. = 200 sec Total Stops = 7 stops
Step 2: Calculate Control Delay/Stop-Mile $= \frac{\text{(Total Control Delay)}}{\text{(Total Stops)x(Corridor Length)}}$	Control Delay/Stop-Mile = 200/(7x5.0) = 5.71 sec/stop-mi
Step 3: Determine Emissions/Stop-Mile - Use regression equations in normalized trend figures (Fig. 4.11, 4.12, 4.13) - Equations calculate Emissions/Stop-Mile based on Control Delay/Stop-Mile	For HC-1 Emissions: y = 0.602x + 2.575 y = 0.602(5.71) + 2.575 y = 6.01mg/Stop-Mile
Step 4: Calculate Total Emissions for Single Vehicle (g/vehicle) = (Emissions/Stop-Mile)x(Total Stops)x(Corridor Length)	Total Emissions per Veh. = 6.01x7x5.0 = 210.4 mg/vehicle = 0.2104 g/vehicle

Figure 8-4. Example Application of Calculating Vehicle Emissions Based on Control Delay and Stops Using Normalized Trends

Figure 8-4 shows an example application of calculating the corridor-level vehicle emissions for a single vehicle based on control delay and total stops using the normalized trends.

Because the y-intercept and slope of these trends are indicators of the normalized trends, it is important to test the statistical significance of each value. Table 8-1 summarizes the statistical testing on the slope, y-intercept, and R^2 values for the normalized trends.

As shown in Table 8-1, the majority of the slopes and intercepts are statistically different from zero. The slope and the R^2 values of the CO-3 emissions group are not

Table 8-1. Statistical Testing of Normalized Effects of Control Delay and Total Stops on Vehicle Emissions

Emissions Group	Sample Size	Slope		Intercept		R^2 Value	
		Coefficient	P-value < 0.05?	Coefficient	P-value < 0.05?	Value	R > Rcrit.? [1]
HC Emissions							
HC-1	170	0.602	Yes	2.58	Yes	0.293	Yes
HC-2	215	1.15	Yes	4.39	Yes	0.184	Yes
HC-3	319	1.70	Yes	28.6	Yes	0.087	Yes
NO Emissions							
NO-1	238	2.82	Yes	42.2	Yes	0.138	Yes
NO-2	222	2.39	Yes	7.11	No (0.09)	0.209	Yes
NO-3	128	6.18	Yes	46.5	Yes	0.154	Yes
CO Emissions							
CO-1	372	23.6	Yes	152.	Yes	0.097	Yes
CO-2	248	29.9	Yes	125.	No (0.09)	0.106	Yes
CO-3	117	1.44	No (0.50)	137.	Yes	0.004	No

Notes: 1. Source: (Crow, *et al.*, 1960).

significantly different than zero. This is not surprising considering there was no trend found between average speed and CO-3 emissions in Figure 7-23. The intercepts of the NO-2 and CO-2 groups are not statistically different than zero, but this again is not surprising considering the lack of correlation found between traffic parameters and vehicle emissions for these emissions groups as shown in Table 8-2.

One shortcoming of this normalized approach is that runs with zero stops cannot be predicted, as the variables cannot be calculated when dividing by zero. Thus, a separate trend was developed for the corridor runs with zero stops. The dependent variable is emissions in grams per mile and the independent variable is control delay per mile. Of the zero-stop runs collected for this project, the majority had very low control delay (0-10 seconds/mile), and there was no apparent trend between distance-based emissions and seconds per mile of delay. Thus, a mean emissions rate in milligrams per mile was calculated for each emission group. Table 8-2 shows the mean zero-stop emission rates for each emissions group.

As shown in Table 8-2, most emission groups had low sample sizes resulting in very large 95th percentile confidence intervals. With more sample runs, the confidence

Table 8-2. Mean Zero-Stop Emission Rates

Emissions Group	Sample Size	Mean Emission Rate (mg/mi)	Standard Error of Mean	95th Percentile Confidence Interval
HC Emissions				
HC-1	1	24.0	N/A	N/A
HC-2	18	39.3	4.06	31.3 – 47.2
HC-3	23	103.	5.71	91.7 – 114.
NO Emissions				
NO-1	11	176.	16.9	143. - 209.
NO-2	18	69.8	9.78	50.7 – 89.0
NO-3	19	310.	24.1	263. – 357.
CO Emissions				
CO-1	6	1775.	531.	734. – 2815.
CO-2	19	792.	141.	516. – 1067.
CO-3	15	255.	72.2	114. – 397.

Notes: N/A = Not Applicable.

interval should decrease and a more detailed evaluation of trends during zero-stop runs can be performed. Overall, this section illustrates a corridor-level approach to using control delay and stops to predict vehicle emissions. The absolute values of these trends are only valid for the vehicles within the defined emissions groups and cannot be used for a fleet-wide model. However, the qualitative trends themselves are valid and with a more robust data collection effort this approach could be used to develop a fleet-wide emissions model based on control delay and corridor stops.

8.2 Sensitivity Analysis

By normalizing the control delay and corridor stops, the individual impacts of these measures on vehicle emissions can be quantified. Based on the normalized trends, an analysis was conducted of the sensitivity of vehicle emissions to control delay and total stops. As mentioned previously, the slope and y-intercept of the normalized regression lines indicate the individual impacts of control delay and total stops, respectively. Thus, one measure of the relative importance of control delay and total stops on vehicle emissions is the slope-to-intercept ratio. As the slope-to-intercept ratio increases, the relative importance of control delay compared to total stops regarding vehicle emissions increases. Table 8-3 shows the slope-to-intercept ratio for the nine emissions groups.

As shown in Table 8-3, there are a wide variety of slope-to-intercept ratios, indicating that control delay and total stops have varying impacts on vehicle emissions

Table 8-3 Relative Impact of Traffic Measures on Vehicle Emissions

Emissions Group	Slope[1] (Control Delay)	Y-Intercept[1] (Total Stops)	Slope/Intercept Ratio
HC Emissions			
HC-1	0.602	2.58	0.234
HC-2	1.15	4.39	0.260
HC-3	1.70	28.6	0.060
NO Emissions			
NO-1	2.82	42.2	0.067
NO-2	2.39	7.11	0.336
NO-3	6.18	46.5	0.133
CO Emissions			
CO-1	23.6	152.	0.155
CO-2	30.0	125.	0.240
CO-3	1.44	137.	0.011

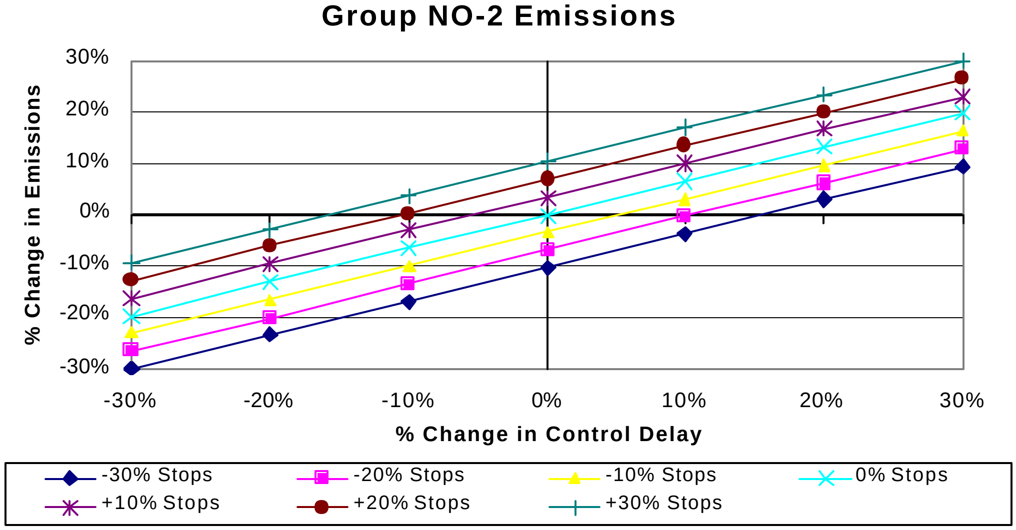
Note: 1. Slope and Y-Intercept are from the normalized regression lines shown in Figure 8-1 through Figure 8-3.

depending on the emissions group. Groups CO-3 and HC-3 have the lowest slope-to-intercept ratios. For these groups, control delay has very little impact on vehicle emissions in comparison to total stops. On the other hand, Group NO-2 has the highest slope-to-intercept ratio, indicating control delay has more importance than total stops in determining vehicle emissions.

Figure 8-5 summarizes a sensitivity analysis of vehicle emissions when altering control delay and total stops. Groups NO-2 and HC-3 emissions were selected because they represent the extreme emissions groups in terms of the relative impact of control delay and corridor stops.

As shown in Figure 8-5, Group NO-2 emissions experience minor changes when altering the total stops variable and moderate changes when altering the control delay term. A 30 percent increase in control delay, with constant total stops, results in a 20 percent increase in NO emissions for Group NO-2.

As shown in Figure 8-5, Group HC-3 shows the opposite trend from Group NO-2, as control delay does not have as large an impact on vehicle emissions as total stops. As shown in the Group HC-3 graph, a 30 percent increase in total stops with no change in control delay would result in a 22 percent increase in HC emissions.



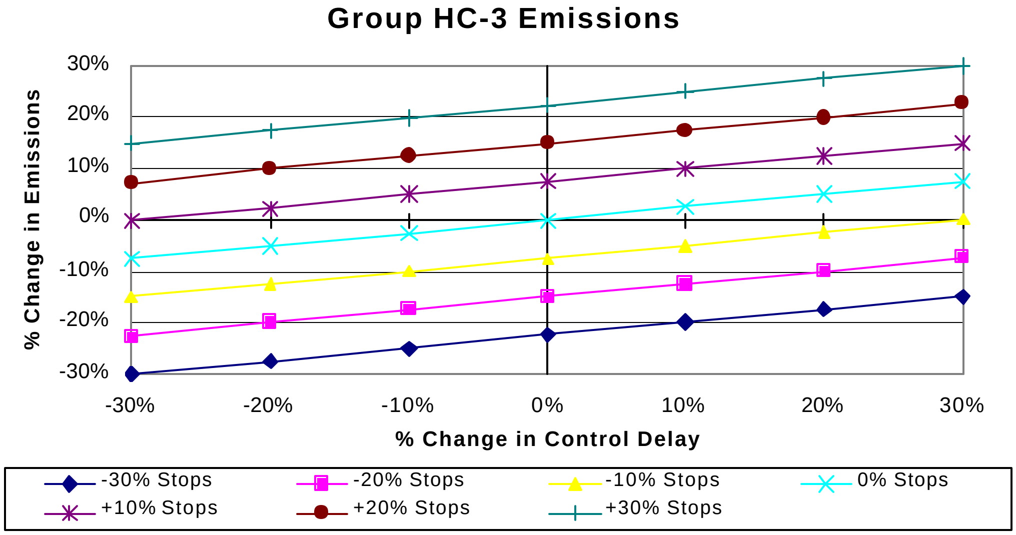


Figure 8-5. Sensitivity Analysis of Control Delay and Total Stops on Vehicle Emissions

As mentioned previously, there is often a trade-off in control delay and total stops when changing traffic signal timings. This sensitivity analysis allows the analyst to investigate the overall impact of vehicle emissions when increasing one traffic parameter and decreasing the other. For example, in the case of a 20 percent *increase* in stops and 20 percent *decrease* in control delay, the group HC-3 graph predicts a 10 percent *increase* in vehicle emissions. This net increase in vehicle emissions is expected for Group HC-3 because, as shown in Table 8-3, total stops are relatively more important than control delay for this emissions group.

8.3 A Delay Event-Based Approach

The approach described above for determining the individual impacts of control delay and total stops on vehicle emissions is a corridor-level approach. Thus, emissions during cruise mode are embedded in the relationships. One shortcoming of this approach is that the true effects of control delay and total stops are somewhat masked by this background level of cruise mode built into the relationship.

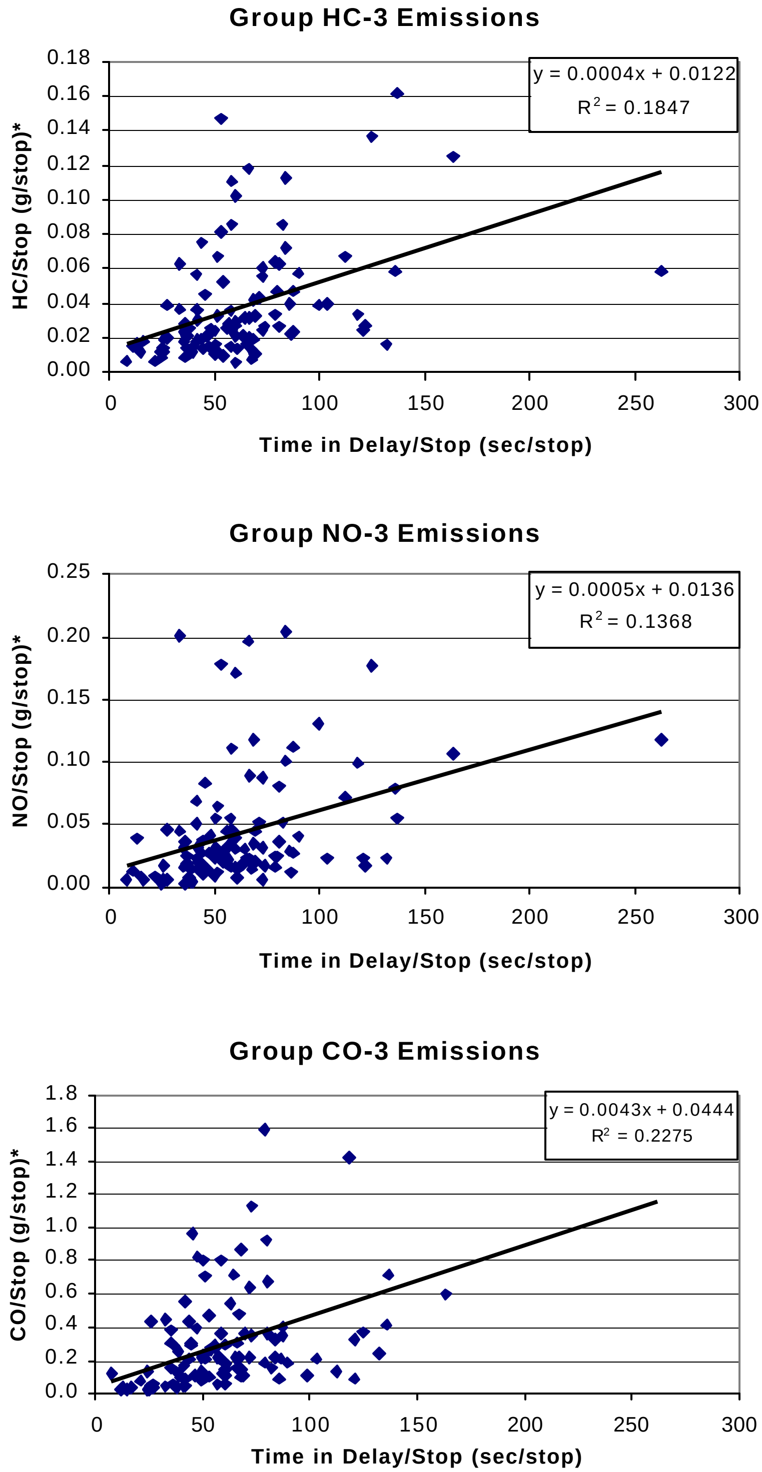
A more accurate approach to determining the true impacts of delay and stops may be to only model emissions during delay events. Because delay and stops occur within a delay event, these traffic parameters can only describe the variability in emissions within a delay event.

"Delay-event" trends were developed for Groups HC-3, NO-3, and CO-3 for the purpose of contrasting the two approaches. A delay event is defined as the duration of time-in-delay at signalized intersections (see Figure 6-7). The time and emissions during each delay event were summed for each run. For example, if a given run had three delay events, the total delay time and delay emissions for that run were the sum of the three events. The total stops for each run were combined with the time and emissions within delay events for that run. This assumes that each stop occurs within a delay event, which is reasonable considering the vast majority of stops are due to delay events at traffic signals.

The resulting database categorizes one corridor run as one data point. Thus, it is still a corridor-level approach. However, the difference is the delay-event approach only includes the emissions during delay events, whereas the corridor-level approach presented earlier includes the emissions during an entire run.

Figure 8-6 shows the normalized trends of control delay and total stops with vehicle emissions for the delay-event approach for Groups HC-3, NO-3, and CO-3.

The units for the x- and y-axis for the delay-event trends are similar to those for the corridor-level trends, with two exceptions. The first exception is the delay-event axes do not include the corridor length. The second exception is that the x-axis defines delay as 'time in delay' for the intersection-level approach, not control delay. The difference between time in delay and control delay is described in Section 6.4.2.



* - Corridor Average Emissions During Delay Events.

Figure 8-6. Delay Event Normalized Effects of Control Delay and Total Stops on Vehicle Emission

A comparison of the R^2 values in Figure 8-6 to those in Figure 8-1, Figure 8-2, and Figure 8-3 illustrates the explanatory capability of control delay and total stops using the two alternative approaches. The R^2 value increased from 0.087 to 0.185 for Group HC-3 when using the delay-event approach. The R^2 value decreased from 0.154 to 0.137 for Group NO-3 emissions. For Group CO-3 emissions, the R^2 value increased from 0.004 to 0.228. The general increase in R^2 values show that the delay-event approach may better explain the relationship between control delay and total stops than the corridor-level approach. In particular, the CO-3 group had a large increase in R^2 value. This may be attributable to enrichment events occurring outside of delay events, which would decrease the R^2 for the corridor-level approach.

The delay-event approach does not allow predictions of emissions for an entire corridor. However, if this approach were combined with a model predicting emissions outside of delay events (i.e. during cruise mode), then corridor-level vehicle emissions could be predicted in a similar fashion to the approach shown in Section 8.1.

The delay-event approach was not pursued to the same detail as the corridor-level approach in this study because the objective of the research was to develop trends between corridor-level traffic parameters and vehicle emissions.

8.4 Factors Not Considered in the Analysis

The analysis presented here has focused on relating average speed, control delay, and total stops to vehicle emissions. However, there may be other factors that have significant impacts on vehicle emissions which traffic analysts can easily collect.

One such traffic measure is free flow speed. A signalized arterial with a free flow speed of 30 mph will likely have lower emissions than an arterial with a free flow speed of 50 mph, even with the same amount of control delay and total stops. A lower free flow speed means the acceleration events are shorter after stopping, and thus lower emissions would result. Because the three study corridors for this project all had similar free flow speeds of 40-50 mph, it is not possible to test the sensitivity of emissions to free flow speed without collecting further data on corridors with different free flow speeds.

Another factor is the spacing of traffic signals. Closely spaced signals do not allow vehicles to accelerate fully to the free flow speed if they must slow down or stop at the next upstream traffic signal. Thus, even with the same control delay and stops, a corridor with a number of closely spaced signals may have lower emissions than a corridor with well-spaced signals.

A third factor that can be easily collected by traffic analysts is roadway grade. A positive roadway grade has been shown to increase vehicle emissions due to the increased engine power needed to overcome the force of gravity (Cicero-Fernandez and Long, 1997). The spatial analysis in Section 10.5 shows that roadway grade likely contributes to a high emissions hotspot in the southbound direction of Chapel Hill Road. More detailed analyses of spatial data on additional corridors could help understand the effect of roadway grade on vehicle emissions.

These measures should be analyzed for trends with vehicle emissions and, if significant, could be combined with control delay and total stops in a future comprehensive macroscopic traffic emissions model.

8.5 Summary

The analysis in this section has focused on relating average speed, control delay, and total stops to vehicle emissions. Vehicle emissions on a per-mile basis generally increase with an increase in traffic congestion (i.e. decrease in average speed or increase in delay and stops) for the signalized arterials tested in this study. Of the three pollutants, HC emissions most consistently show this trend, with NO and CO emissions showing a weaker trend.

The majority of emissions groups show that control delay and stops do have a significant impact on vehicle emissions. The corridor-level approach presented allows traffic analysts to test the individual impacts of delay and stops, which is important because signal timing improvements sometimes increase one measure but decrease the other.

9.0 MICRO-SCALE TRAFFIC AND ENGINE-BASED APPROACH FOR ESTIMATING EMISSIONS

In this section, relationships between second-by-second engine activity parameters and vehicle emissions are explored. First, analysis regarding equivalence ratio is presented. Then the relation between vehicle emissions and fuel flow is given. Both of these analyses are based upon engine data. Finally, effects of power demand on vehicle emissions are discussed. Power demand can be estimated approximately based upon the speed trace; hence, this is considered a vehicle activity parameter.

9.1 Equivalence Ratio Analysis

The equivalence ratio is considered an important parameter that can help explain variation in CO, HC, and NO emissions (Goodwin and Ross, 1996; Sher, 1998; Degobert, 1996). The definition of equivalence ratio and its relation to vehicle emissions were explained previously in Section 6.5.1.

The OEM-2100™ reports fuel and air use on a second-by-second basis. A program was written in Visual Basic that calculates the equivalence ratio using the fuel and air data. In order to illustrate the results obtained from equivalence ratio analysis of the emissions data, example results are developed based upon the second-by-second data for 72 one-way trips obtained using the 1999 Ford Taurus on Chapel Hill Road. In Figure 9-1, grams of CO emitted per gram of fuel consumed are plotted against equivalence ratio estimates. A total of 28,910 data points were used for this plot, each representing one second.

The high CO emission rates occur only when the vehicle is in enrichment. When the vehicle is operating fuel rich or near stoichiometric, CO emissions tend to be comparatively lower. For example, the emission rates are less than 0.2 grams of CO per gram of fuel consumed when the equivalence ratio is one or lower, but are as high as 0.8 grams of CO per gram of fuel consumed at an equivalence ratio of 1.23. There is a clear linear relation between equivalence ratio and CO emissions. However, there is also considerable amount of variability. For example, for an equivalence ratio of 1.1, the fuel-normalized CO emissions vary approximately plus or minus 40 percent. The unexplained

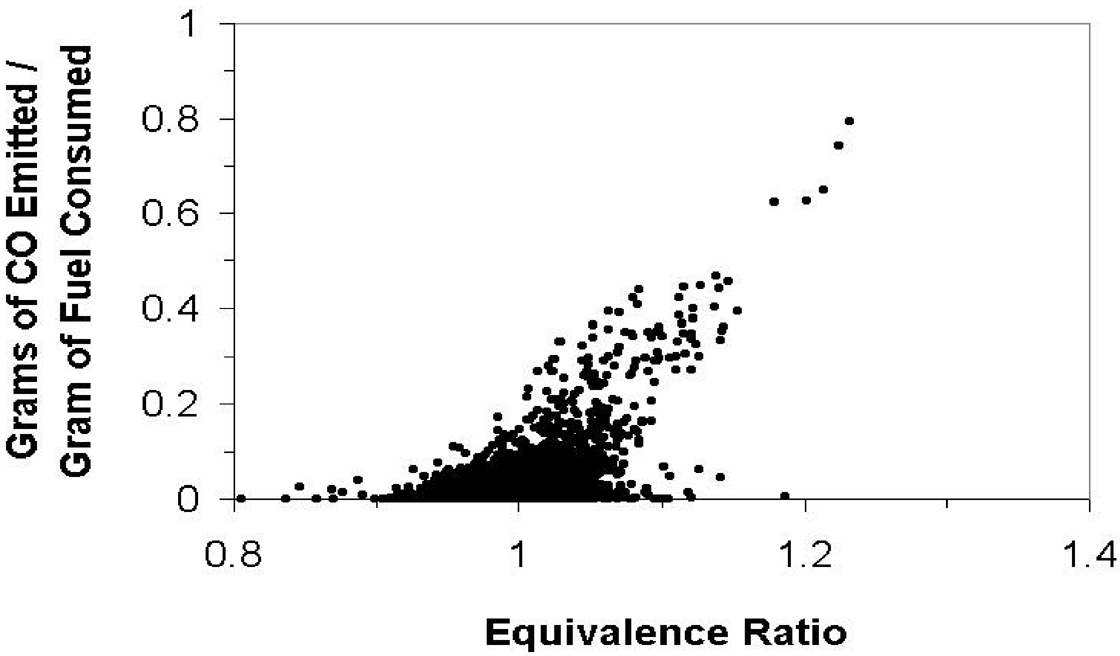


Figure 9-1. Relation Between Equivalence Ratio and CO Emitted per Gram of Fuel Consumed for 1999 Ford Taurus Driven on Chapel Hill Road

variability could be because other engine parameters might also be affecting second-by-second CO emissions.

9.2 Fuel Flow Analysis

Fuel flow is another parameter that has been used by researchers to explain variability in vehicle emissions (Goodwin and Ross, 1996; Barth *et al.*, 1997). HC and NO emissions especially have been shown to have relation with fuel flow.

In this section, an illustration of the relation between vehicle emissions and fuel flow will be given. For this purpose results based upon the second-by-second data for 72 one-way trips obtained using the 1999 Ford Taurus on Chapel Hill Road are utilized. In Figure 9-2 grams of NO emitted are plotted against fuel flow data, which is given in log scale. Figure 9-3 presents fuel flow versus HC emissions. A total of 28,910 data points were used for these plots. In both Figure 9-2 and Figure 9-3, fuel flow and data for equivalence ratio greater than 1 and for equivalence ratio less than 1 are shown separately.

In Figure 9-2, there is a general trend of an increase in NO emissions as fuel flow increases. The highest NO emission rates occur at high fuel flow rates for both

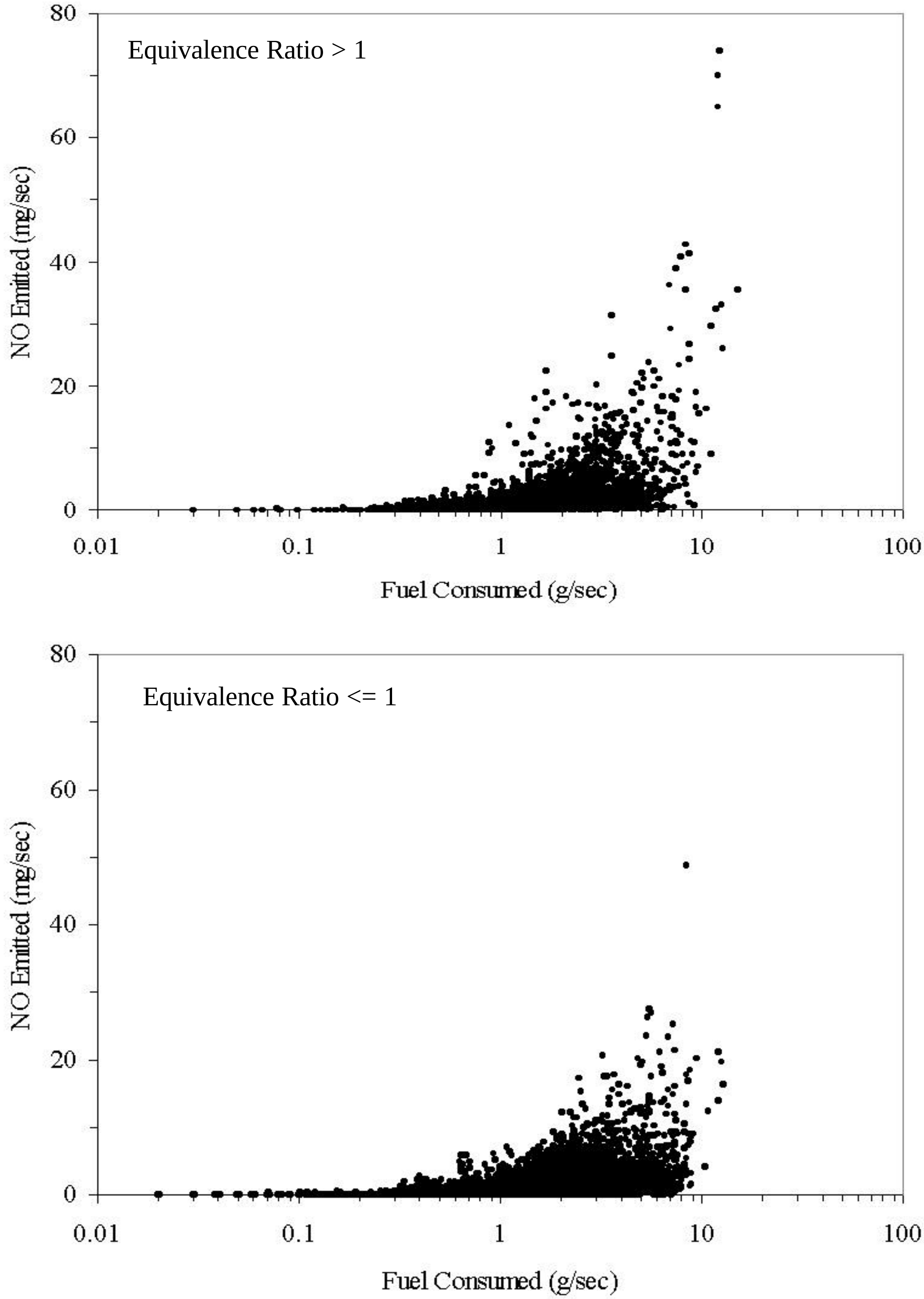
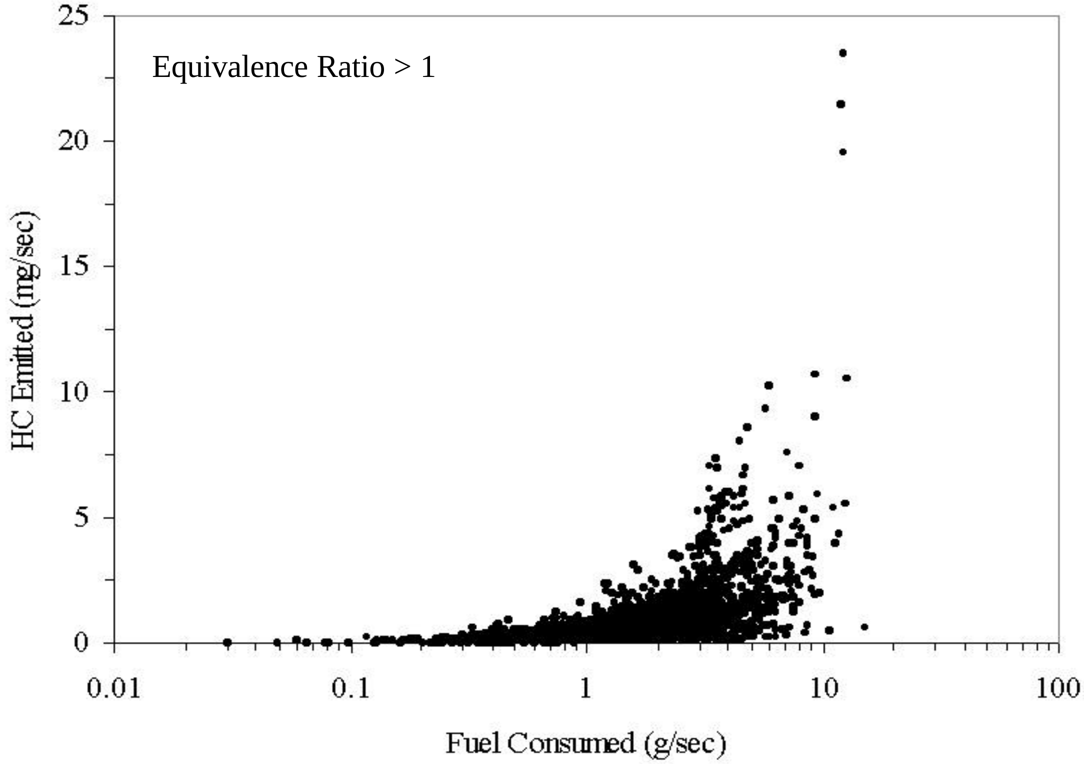


Figure 9-2. Fuel Flow versus NO Emissions Estimate for 1999 Ford Taurus Driven on Chapel Hill Road



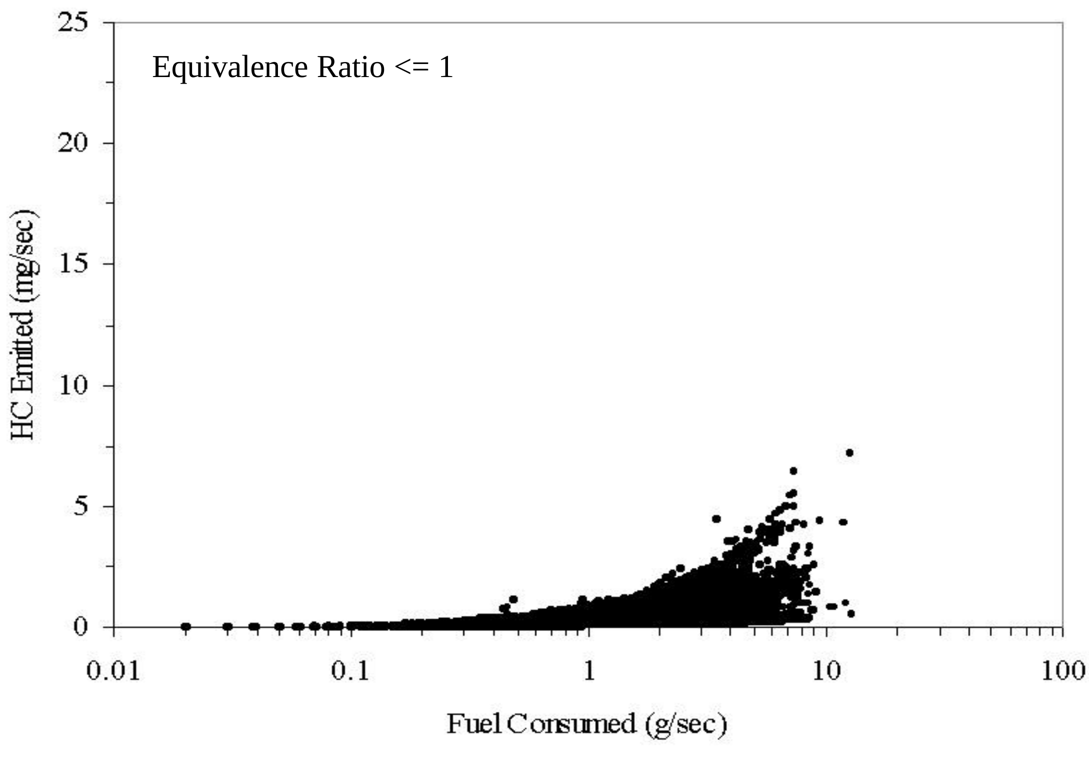


Figure 9-3. Fuel Flow versus HC Emissions Estimates for 1999 Ford Taurus Driven on Chapel Hill Road

equivalence ratio greater than and equivalence ratio less than or equal to 1 cases. However, a high fuel flow rate may be a necessary but not sufficient condition for high NO emissions. For example, fuel flow in the range of 8 g/sec to 12 g/sec is associated with NO emission rates as low as 0.1 mg/sec and as high as 74 mg/sec for equivalence ratio greater than 1 and 0.1 mg/sec and 48 mg/sec for equivalence ratio less than or equal to 1. Thus, both low and high NO emissions are observed at high fuel flow rates. In contrast, for low fuel flow rates such as in the range from 0.02. g/sec to 2 g/sec, NO emissions are typically in the range of 0.1 mg/sec to 10 mg/sec, with a few values in the range of 10 mg/sec to 20 mg/sec for both of the cases. Thus, while vehicle emissions can be low at almost any fuel flow rate, the highest emissions tend to occur only at the higher fuel flow rates.

To help explain the variability in the data, data under fuel enrichment conditions were plotted separately. The highest emissions rates correspond in some, but not all, cases to fuel enrichment.

The results obtained for HC are qualitatively similar to those for NO. However, there seems to be a clearer relationship between emissions and fuel flow for cases with equivalence ratio greater than one. For example, all emission rates greater than 7.5 mg/sec occur during enrichment.

9.3 Power Demand Analysis

As stated in Section6.5.2, power demand can be used to analyze vehicle emissions. In this study an approximation of power demand was used which is given in Equation 6-1. Relations between power demand and vehicle emissions were investigated; however, no clear relation was found. As an example the relation between power demand and NO emissions is given in Figure 9-4 for second-by-second data for 72 one-way trips obtained using the 1999 Ford Taurus on Chapel Hill Road. Graphs for CO vs. power demand and HC vs. power demand are given in Appendix IV.

As seen in Figure 9-4, the relation between NO emissions and power demand is not clear. NO emissions higher than 20 mg/sec tend to occur for moderate to high power demand between approximately 30 and 230 mi^2/h^2sec. There is high variability in the data for a given power demand value. For example, NO emissions for power demand of 100 mi^2/h^2sec range from 0.04 mg/sec to 35 mg/sec. Averaging techniques were also

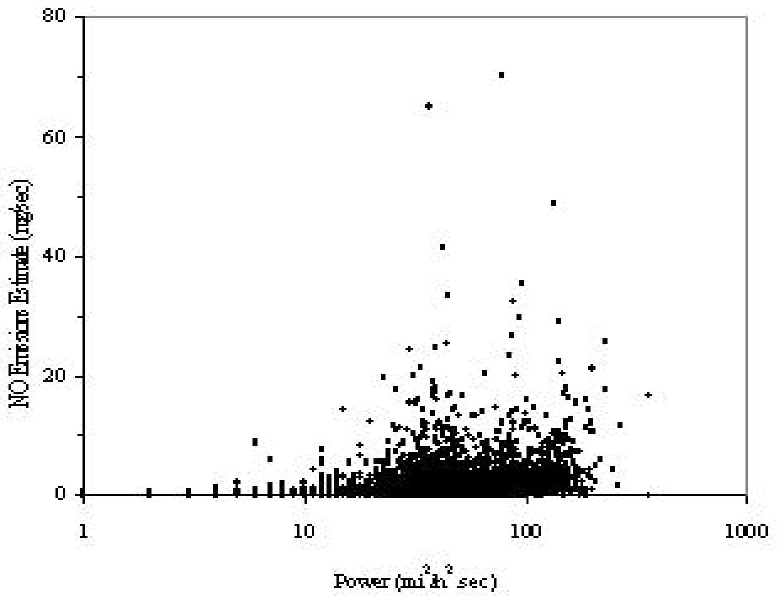


Figure 9-4. Relation Between NO Emissions and Power Demand for 1999 Ford Taurus Driven on Chapel Hill Road

investigated to see if better results were observed, however, there was no clear relationship. Examples of relations for averaged NO and power demand values are given in Appendix IV.

The relation between equivalence ratio and power demand was also investigated. This analysis gave some indication of relation between these two parameters. Results based upon the second-by-second data for 72 one-way trips obtained using the 1999 Ford Taurus on Chapel Hill Road are utilized. Only positive values of power demand are utilized for this analysis since as stated by Barth *et al.* (1996) only positive changes in power would cause changes in equivalence ratio and hence in vehicle emissions. Therefore, negative values of power demand are set to zero in this analysis.

Figure 9-5 shows the relation between equivalence ratio and power demand for 1999 Ford Taurus driven on Chapel Hill Road. Each point in Figure 9-5 represents second-by-second data obtained from OEM-2100^{TM}. As seen in Figure 9-5, there is not a clear relation between equivalence ratio and power demand. The highest equivalence ratio, 1.19, occurred for zero power value. There is high variability in the data. For example, power demand in the range of 50 mi^2/h^2.sec to 100 mi^2/h^2.sec is associated with equivalence ratio as low as 0.92 and as high as 1.12. Different averaging periods were applied to see if they give better relation, however, still there is no clear relation between power demand and equivalence ratio. Examples of relations for averaged equivalence ratio and power demand values are given in Appendix IV.

The relation between change in power demand and change in equivalence ratio was also investigated. For this purpose data used for Figure 9-5 were utilized. Change in equivalence ratio is plotted against change in power demand in Figure 9-6.

Each point in Figure 9-6 represents second-by-second change in power demand against change in equivalence ratio. As seen in the figure, there is not clear relationship. Highest changes in equivalence ratio are caused by almost no change in power demand.

Previous research at Georgia Tech. showed that there is a relation between power demand and emissions. However, they worked on trip-based averages of power demand and emissions. In CERT study, as given in Section 2.3.2, second-by-second power was used as a threshold in determining whether the engine is in enrichment condition or not. Power demand was not used directly to estimate emissions. Findings in this study suggest that second-by-second relation between power demand and emissions as well as equivalence ratio is not clear.

9.4 Relation Among the Pollutants

In this section, relations among different pollutants are investigated. For this purpose results based upon the second-by-second data for 72 one-way trips obtained using the 1999 Ford Taurus on Chapel Hill Road will be utilized.

Figure 9-7 presents scatter plots of pairwise comparisons of HC, NO, and CO emissions for the 1999 Ford Taurus driven on Chapel Hill Road. Each of the three scatter plots indicates that there is a positive correlation between any two pairs of emissions estimates. For example, if NO emissions are high, then HC and CO emissions also tend to be high.

However, there is also a large degree of scatter in the graphs, indicating that emissions of a given pollutant can vary substantially independently of other pollutants. For example, if the NO emission rate is 1 mg/sec, the HC emission rate varies between 0.03 mg/sec and 7 mg/sec, which is more than two orders-of-magnitude variation.

Of the three pairwise comparisons shown in Figure 9-7, the most clearly defined one appears to be for CO and HC. In this case, there appears to be a linear trend in the

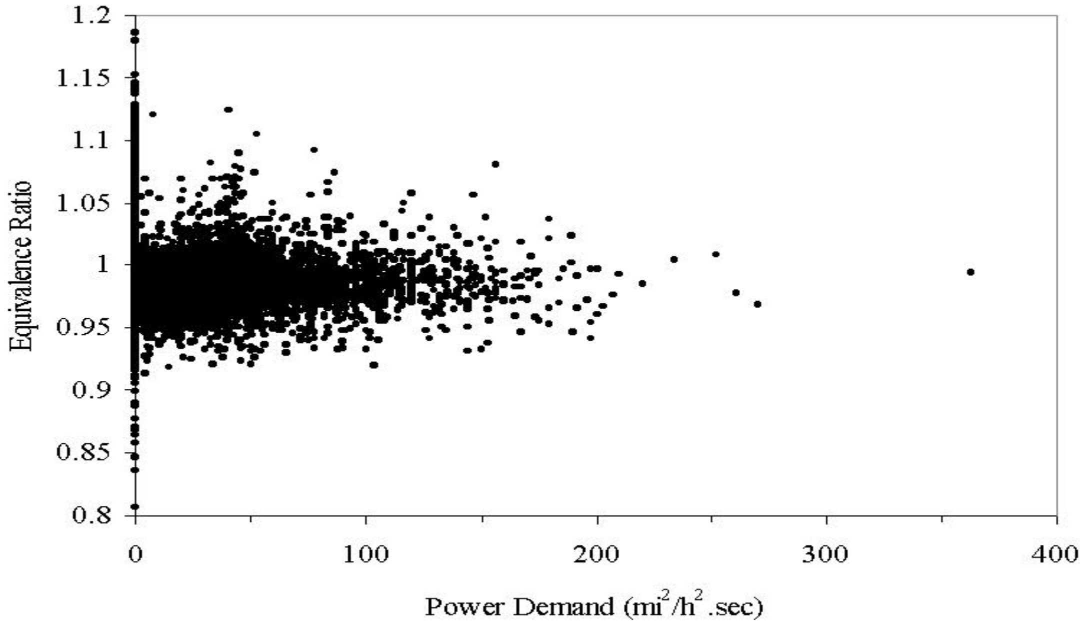


Figure 9-5. Relation Between Equivalence Ratio and Power Demand for 1999 Ford Taurus Driven on Chapel Hill Road

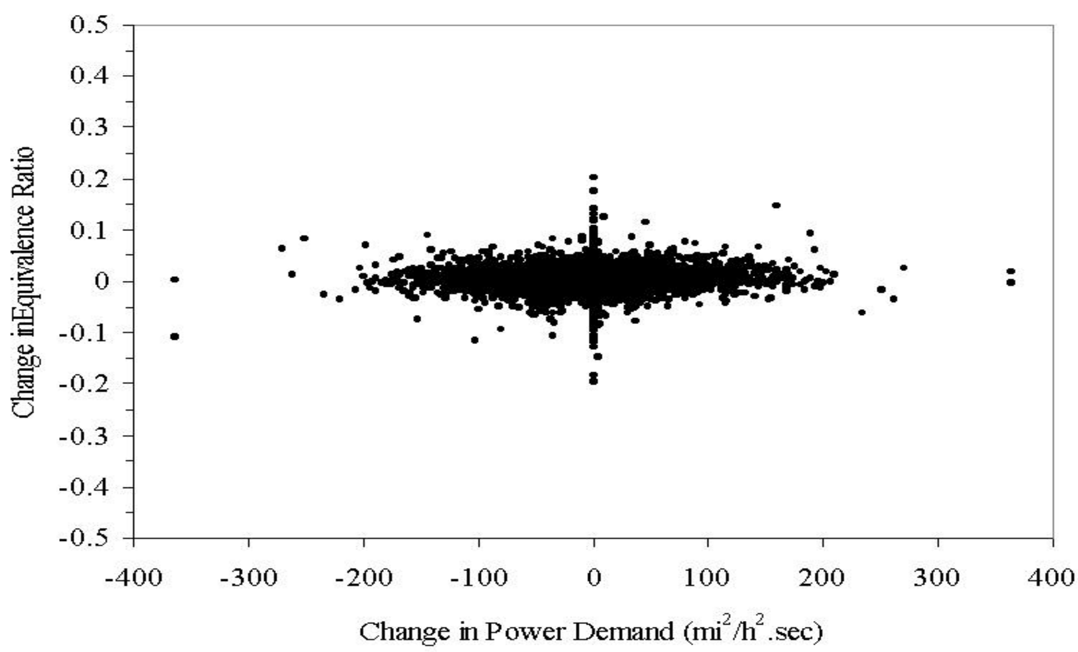


Figure 9-6. Relation Between Change in Equivalence Ratio and Change in Power Demand for 1999 Ford Taurus Driven on Chapel Hill Road

log-log scale plot, with CO emissions increasing as HC emissions increase. The range of variability in CO emissions for a given value of HC emissions appears to be approximately three orders-of-magnitude regardless of the value of HC emissions. For example, for HC emissions of 0.1 mg/sec, the CO emissions vary from 0.1 mg/sec to almost 100 mg/sec. For HC emissions of 1 mg/sec, CO emissions appear to vary from approximately 1 mg/sec to almost 1,000 mg/sec.

Intuitively, it seems reasonable that there is a more clearly defined relationship between CO and HC than for the other pairwise combinations. One mechanism in common for CO and HC emissions are situations associated with incomplete combustion. In contrast, NO emissions would tend to be low during some conditions associated with incomplete combustion, and can be high for some conditions associated with complete combustion. Therefore, a more complex and possibly nonlinear relationship is expected between either NO and HC emissions or NO and CO emissions.

Overall, the scatter plots suggest that CO, NO, and HC emissions are not independent of each other. However, at the same time, there is a substantial degree of variability in any of the pollutants even if the emission rate of one of the others is specified. While it is not the purpose of this project to develop simultaneous emission inventories of all three of these pollutants, it should be kept in mind for policy and management purposes that there is a positive relationship among the three pollutants. The implication is that if emission rate is high for one pollutant, they tend on average to be high for others as well.

9.5 Summary

CO emissions have a clear relationship with equivalence ratio. On average, CO emissions increase linearly as the equivalence ratio increases from one to higher values associated with fuel enrichment.

NO and HC emissions have at least a weak relationship with the fuel flow rate. Although emissions of either of these pollutants can be low at essentially any fuel flow rate, the highest emission rates occur only at high fuel flow rate. Thus, high fuel flow rate is a necessary but not sufficient condition for high emissions. When equivalence ratio is also accounted for, it appears that emissions are high at high fuel flow rate when the equivalence ratio indicated fuel enrichment.

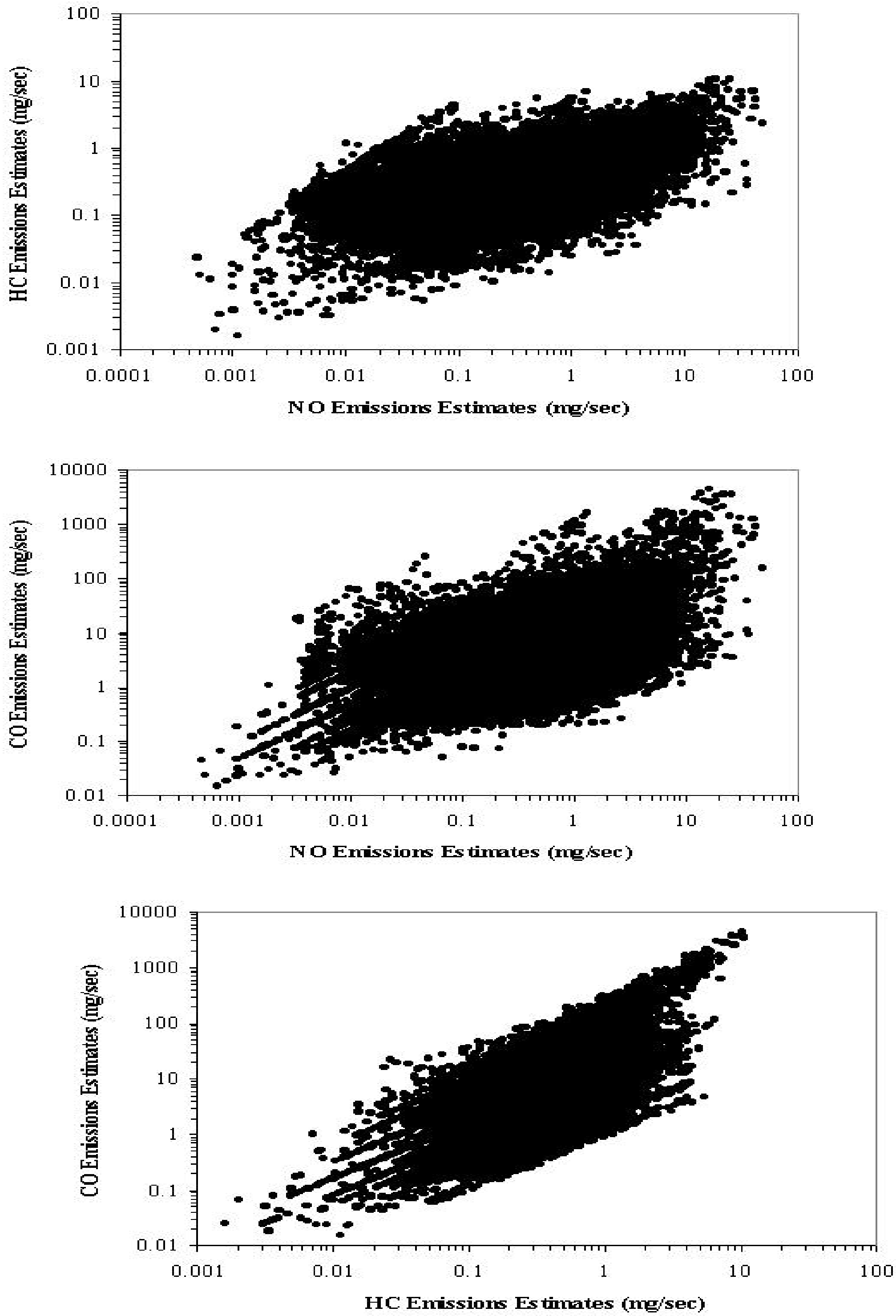


Figure 9-7. Relations Among Pollutants for 1999 Ford Taurus Driven on Chapel Hill Road

On a second-by-second basis, power demand does not have a clear relationship with emissions. The relation between equivalence ratio and power demand is also weak. There is too much variability in the data. Similar results were obtained for the analysis of the relation between change in power demand and change in equivalence ratio.

There is a positive statistical association between NO, HC, and CO emissions. This suggests that if emissions are high for any of these pollutants, they tend on average to be high for the other two pollutants. At the same time, however, there is also a large degree of variability in emissions of each of these pollutants that cannot be explained based upon the values of emissions for any of the other pollutants. For the purposes of this project, each pollutant is typically analyzed separately from the other two. However, for policy and management purposes, it may be necessary take into account in some situations the positive association in emission rates among these three pollutants.

10.0 EMPIRICAL STUDY OF THE EFFECT OF SIGNAL COORDINATION ON VEHICLE EMISSIONS: CHAPEL HILL ROAD CORRIDOR

An empirical study on Chapel Hill Road was performed to quantify the effect of signal timing and coordination on vehicle emissions for these corridors. The before-and-after study described in Chapter 5.0 set the framework for the analysis. The results represent a case study from only two study corridors and therefore should not be generalized to represent the effects of signal timing and coordination on vehicle emissions for all signalized arterials. Nevertheless, since the approach and results represent the first attempt of this kind, it can serve as a model for future studies.

In this chapter, a discussion of the effect of signal timing and coordination on vehicle emissions measured from Chapel Hill Road is given. First, modal emissions rates measured at this corridor are presented. Then, corridor-level comparisons of vehicle emissions between before and after signal timing and coordination is discussed for priority runs. Micro-scale analysis for priority runs are also given. Finally, discussion of non-priority runs is presented.

10.1 Factors Influencing Variability in Emissions

It has been established in Chapter 7 that corridor average vehicle emissions are dependent on a number of key factors: average speed; ambient temperature; ambient humidity; and time and direction of the trip. A before-and-after study must isolate or control the factors not being tested. The only factor that was intended to be different in the before and after cases was signal timing and coordination.

As discussed in Section 5.2, there could be various “threats to the validity of comparisons of before and after measurements. Each key potential threat was reviewed. Many of the threats can be and were addressed in the experimental design. For example, in the evaluation studies, the same vehicle/driver/instrument combinations were deployed in similar time periods with a similar number of runs in both the before and after cases. This design eliminates threats associated with changes in vehicle make and model, driver behavior, and general traffic patterns. With regard to the latter, a possible threat to validity could be associated with change in traffic volumes in comparing the before and

Table 10-1. Weather Conditions During Experiment on Chapel Hill Road

Test Arterial	Case	Month(s) Completed	Mean Temperature		Percent of Runs with A/C On	
			AM	PM	AM	PM
Chapel Hill Rd.	Before	Sept. 2000	72 °F	79 °F	59 %	77 %
	After	Oct. 2000	59 °F	78 °F	24 %	78 %

after data. However, since data were collected within a two month period, this potential threat was judged to be unimportant. The remaining possible threats to validity could be parameters that are uncontrollable but observable, such as ambient temperature and humidity, and also related use of AC. Table 10-1 shows the change in ambient temperature and air conditioner use on Chapel Hill Road. The temperature measurements were taken from a portable weather gauge attached to the outside of the test vehicles and recorded for each run.

As shown in Table 10-1, there was essentially no change in mean temperature and air conditioner use during the PM peak runs. During the AM peak runs, the mean temperature decreased 13 degrees (72°F to 59°F) and the air conditioner was used in 35 percentage point fewer runs (59% to 24%).

As reported in Section 7.2.3, ambient temperature was found to be a significant parameter for HC emissions for 1999 Ford Taurus both for the before and after cases. Based upon the detailed investigation of the relationship between HC emission and ambient temperature observed in the data set, it was determined, as described in Section 7.2.3, that ambient temperature is not an important factor. Air conditioner use is not a significant parameter as obtained from Section 7.2.3. In summary, the possible additional factors influencing vehicle emissions do not appear to be significant, especially during the PM peak.

10.2 Modal Emission Rates

Although the individual factors influencing vehicle emissions do not seem significant on Chapel Hill Road, it is difficult to ascertain whether the cumulative effects of these factors are significant and whether the before and after cases are truly controlled. One way to check the cumulative impacts of these factors is by comparing and evaluating the modal emission rates in the before and after cases. Changes in the signal timing and coordination was expected to predominantly affect the time spent in each mode, but not the modal emission rates themselves. However, if there are no other key factors that differ in the before and after cases, the modal emission rates in each case should be the same. Thus, an analysis was undertaken to verify whether modal emission rates are comparable as a means to verify the validity of subsequent before and after comparisons.

Figure 10-1 presents bar charts comparing the before and after modal emissions rates for both the 1999 Ford Taurus and the 1998 Chevrolet Venture. These two vehicles were used as the primary vehicles on the Chapel Hill Road corridor. The emission rates are shown for three pollutants, HC, NO, and CO, and for four driving modes: idle, acceleration, deceleration, and cruise. The model emission rates were estimated as described in Section 6.4.1.

Overall, there is good agreement between the before and after modal emission rates. For example, the average HC acceleration emission rate for the Ford Taurus is 0.82 mg/sec in the before data set and 0.79 mg/sec in the after data set. Although these averages differ by 4 percent, the difference is not statistically significant. The 95 percent confidence interval for the mean emission rate in the before case is 0.73 mg/sec to 0.91 mg/sec, and for the after case it is 0.71 mg/sec to 0.87 mg/sec. In this case, these two confidence intervals overlap, which is an indication of similarity in the two means. In addition, the means were compared using a t-test with a 0.05 significance level, and based upon this test there is no statistically significant difference in the means. Therefore, the HC acceleration mean emission rates are considered to be the same in both the before and after case. Thus, it appears that the vehicle is producing a similar emission rate for the same driving mode in both the before and after case. This indicates that there are not other factors causing differences in emissions between the before and after case, such as ambient temperature, humidity, or others.

T-tests were done to check whether emission rates are different among the four driving modes for each vehicles, in each of the before and after cases. There are six comparisons for the before case for each vehicle for each pollutant; idle-acceleration, idle-deceleration, idle-cruise, acceleration-deceleration, acceleration-cruise, and deceleration-cruise. Similarly, there are six comparisons for the after case for each vehicle, for each pollutant. Thus, there are 12 comparisons for each vehicle for each pollutant. There are two vehicles, three pollutants. Therefore, there are 72 comparisons. The t-tests results showed that except for 8 out of 72 cases, modal emission rates for a given vehicle and pollutant are statistically significant different from each other at a significance level of 0.05. Four of the cases where no difference occurred were a comparison between idle and deceleration modes for HC emissions. Three cases were for a comparison between idle and deceleration rates for CO emissions and one was for acceleration and cruise for CO emissions for Chevrolet Venture in the after case.

In almost all cases, there is not a statistically significant difference in mean modal emission rates for the before and after cases for both vehicles, for all three pollutants, and for all four driving modes, with only one exception. The mean NO idle before versus after emission rates for the Ford Taurus have a statistically significant difference. The t-test for the comparison of these two means resulted in a p-value of 0.03, which is less than the 0.05 criteria used here for statistical significance. However, although the average before case idle emission rate of 0.065 mg/sec differs from the average after case idle emission rate of 0.042 mg/sec, both rates are substantially lower than the emission rates for NO in any other driving mode. Thus, differences in the before and after idle emission rates are not expected to have any substantial impact on the estimate of trip-based mass emissions, since small differences in small emission rates comprising only one mode out of four would correspond to only small effects on the estimate of total mass emission rates.

In general, for both HC and NO, there is very good agreement between the before and after modal emissions rates. For CO, there appears to be a larger relative difference in the before and after comparison of the acceleration emission rate than appears to be true of other comparisons. Nonetheless, given the variability in the data, these differences are not statistically significant. The overall finding from the comparisons shown in Figure 10-1 is that the modal emission rates are similar when comparing the before and after cases. The similarity in modal emission rates provides evidence that there are not other influential factors that might threaten the validity of before and after comparisons. Thus, it is appropriate to compare the corridor-average emission rates in the before and after cases to determine what effect, if any, the change in traffic signal timing and coordination has on emissions.

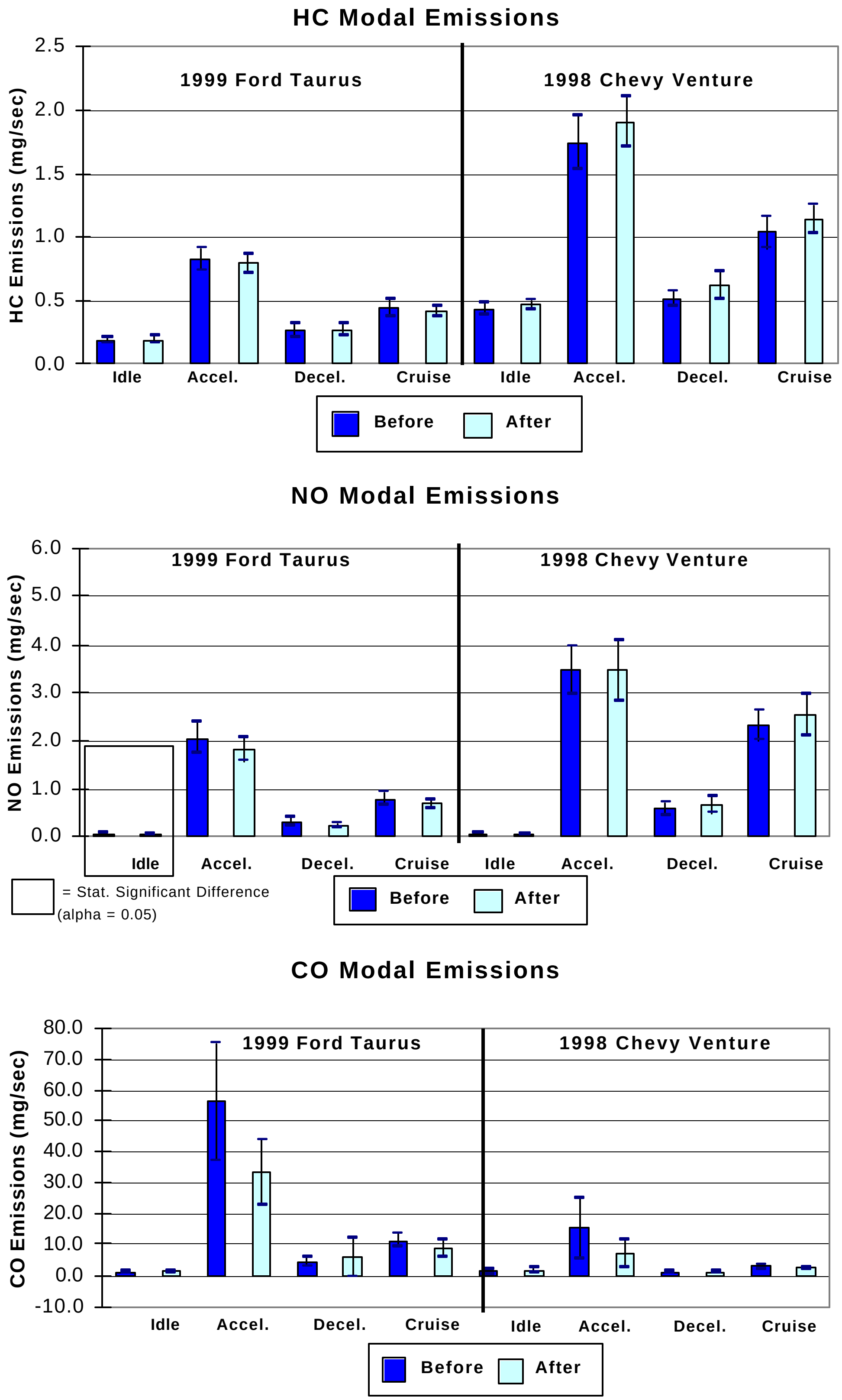


Figure 10-1. Comparison of Chapel Hill Road Before and After Mean Modal Emissions Rates [Error bars denote the 95 percent confidence interval of the mean]

10.3 Signal Coordination Improvements

NCDOT implemented a signal timing and coordination plan on Chapel Hill Road between Cary Parkway and Aviation Parkway in late September 2000. The data collection runs extended immediately south of Morrisville Parkway to immediately north of Airport Boulevard and took place between August 28, 2000 and October 26, 2000 as given in Section 5.0.

Figure 10-2 shows a summary of the signal timing changes associated with the signal coordination plan. The basic premise of signal coordination is to offset the green times at consecutive signalized intersections such that vehicles can travel through the signal system without stopping. The greenband, expressed in seconds, represents the 'window' where vehicles can enter the signal system and have a high likelihood of not stopping. Typically the greenbands are timed for vehicles traveling near the free-flow speed, and thus heavy congestion could render the greenband ineffective due to low speeds and long queues.

As shown in the figure, greenbands were introduced during both the AM and PM peaks. During the AM peak, fairly equal greenbands were provided in each direction. However, the AM northbound travel is so heavily congested (i.e. average speed around 15 mph) that the greenbands cannot be utilized due to the long queues and low travel speeds. During the PM peak, a greenband was provided only in the southbound direction. The majority of vehicles travel in the southbound direction, creating congestion between Airport Boulevard and Aviation Parkway. South of Aviation Parkway the congestion subsides and the greenband is thus well utilized.

Minor changes were also made to the proportion of green time given to the Chapel Hill Road through movements capacity (effective green over capacity ratio, g/C). At Aviation Parkway, the g/C ratio was decreased by 14 percent during both peak periods because the minor street movements were over capacity. At Weston Parkway, the minor street movements were not over capacity and thus extra green time was given to the major street through movements to aid in the signal coordination. At Morrisville Parkway, the g/C ratio was decreased slightly during the AM peak and increased slightly during the PM peak.

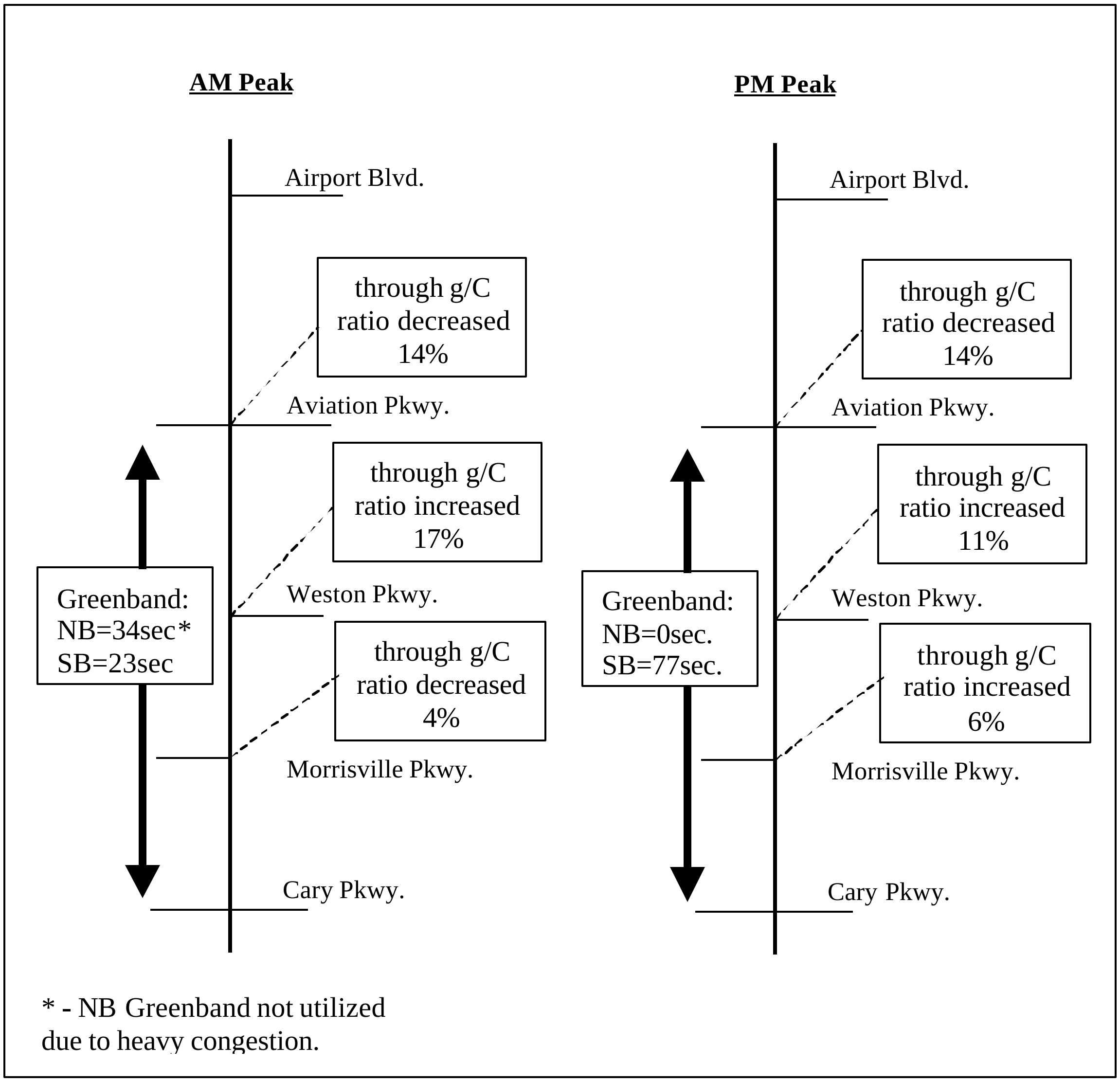


Figure 10-2. Signal Timing Changes on Chapel Hill Road

10.4 Corridor-Level Results

The changes in traffic parameters and vehicle emissions on a corridor-level due to signal coordination were examined for both the Ford Taurus and Chevrolet Venture runs. Vehicle, coordination, direction and time of trip were found to significantly effect emissions based upon ANOVA results as given in Section 7.2.3. Therefore, the corridor-level analysis will be based upon datasets segregated using these parameters.

Table 10-2. Number of Runs for Chapel Hill Road Before and After Study

Peak - Direction	Ford Taurus		Chevrolet Venture	
	Before	**After**	**Before**	**After**
AM North	21	18	23	15
AM South	24	20	22	15
PM North	13	18	16	14
PM South	14	18	14	14

Secondary vehicles tested on Chapel Hill Road were not included in this analysis due to the small number of runs collected (1-3 runs per peak and direction). Table 10-2 shows the number of runs collected for the before and after study.

Before giving the results of the before and after comparison, percent time spent in each driving modes are presented. Then, a section on the effect of change in percent of time spent in different driving modes as well as change in trip duration in the before and after runs on total emissions are investigated. Finally, comparison between the before and after cases are given.

10.4.1 Sensitivity Analysis of Emission Factors, Distribution of Time in Driving Modes, and Total Trip Duration

The purpose of this section is to understand the influence of selected factors with respect to their potential contribution to changes in emissions when comparing before and after cases. Specifically, can differences in emissions in the before versus after cases be attributable to: (1) differences in modal emission rates; (2) differences in the distribution of time spent in each driving mode; and/or (3) differences in the trip duration? Several comparisons were made to help isolate the role of these factors. Three comparisons are described in Table 10-3. Each of the three comparisons employs the specific time distribution of driving modes applicable to the before or after cases. Comparison Case A assumes that the average modal emission rates observed in the before case are also applicable to the after case. Conversely, Comparison Case B assumes that the average modal emission rates observed in the after case are applicable to the before case. The purpose of Cases A and B are to determine whether there is any significant difference in comparisons of total estimated before and after emissions that might be attributable to variation in modal emission rates. Case C focuses on the influence of trip duration. In comparison to both Cases A and B, which each assume the trip durations specific to the before and after cases, Case C assumes that the trip duration is the same in both the before and after cases. When the results of all three cases are compared and evaluated, it may be possible to determine whether modal emission rates, time distribution of modes, or trip duration either individually or in aggregate play an important role in potential differences between total emissions in the before and after cases. Insight obtained from these comparisons will be used to help explain the results of observed emissions differences, the latter of which are presented in the next section.

The key data needed for the three comparison cases include the modal emission rates, the time distribution of modes, and the trip duration. These data are given in Table 10-4 for modal emission rates and Table 10-5 for the time distribution and the trip duration. Table 10-4 illustrates that for each vehicle, direction, and time of day, there are differences in modal emission rates when comparing the before and after cases. For example, the NO emission rate during acceleration for the Ford Taurus in the AM North case is 1.10 mg/sec before and 1.06 mg/sec after the change in signal timing and coordination. In this particular example, the difference in the modal emission rates is relatively small and is insignificant. However, for the AM South case for the Ford Taurus, the acceleration emission rate is 2.71 mg/sec in the before case and 2.11 mg/sec in the after case. This difference appears to be more substantial than for the AM North case even though it may also be statistically insignificant. Thus, there is some variability in the observed modal emission rates when comparing the before and after cases. A key question is whether this variability may by itself be able to explain any observed differences in the total emissions when comparing the before and after cases.

Table 10-5 provides data regarding the average observed percentage of time spent in each driving mode, and the average observed trip duration, for each vehicle, time, and direction combination for both the before and after cases. These values may be important in helping to understand changes in total emissions that occurred when comparing the before and after cases. For example, there is a change in the percentage of idle time for the Chevrolet Venture minivan in the AM South study. In the before case, the idling comprised approximately 15 percent of the total trip time, whereas in the after case idling comprised approximately 15 percent of the total trip time. There was a decrease in the

Table 10-3. Study Design: Evaluation of Modal Emission Rates, Time Distribution of Modes, and Trip Duration With Respect to Before and After Comparisons

Comparison Case	Key Factors	Before Case Assumptions	After Case Assumptions
A: Before Modal Emissions	Modal Emission Rates	Before	Before
	Time Distribution of Modes	Before	After
	Trip Duration	Before	After
B: After Modal Emissions	Modal Emission Rates	After	After
	Time Distribution of Modes	Before	After
	Trip Duration	Before	After
C: Same Trip Duration	Modal Emission Rates	Before	Before
	Time Distribution of Modes	Before	After
	Trip Duration	Average[a]	Average[a]

[a]Average refers to an average of both the before and after trip durations.

Table 10-4. Observed Average Modal Emission Rates for NO Emissions in the Before and After Cases for Chapel Hill Road

Vehicle	Peak Time	Direction	Coord.	Idle (mg/sec)			Accel. (mg/sec)			Decel. (mg/sec)			Cruise (mg/sec)		
				NO	HC	CO	NO	HC	CO	NO	HC	CO	NO	HC	CO
Ford Taurus	AM	North	Before	0.04	0.15	0.88	1.10	0.53	20.59	0.13	0.19	2.30	0.36	0.29	5.82
			After	0.04	0.19	1.25	1.06	0.70	18.28	0.10	0.25	2.20	0.24	0.35	4.78
		South	Before	0.09	0.14	0.95	2.71	0.82	87.26	0.43	0.19	5.48	1.08	0.36	13.58
			After	0.03	0.09	0.37	2.11	0.84	28.93	0.28	0.30	2.52	0.95	0.48	8.10
	PM	North	Before	0.04	0.21	0.99	2.51	1.16	54.94	0.40	0.47	4.76	0.88	0.74	12.23
			After	0.03	0.19	1.41	1.91	0.88	24.37	0.19	0.30	2.54	0.68	0.46	6.71
		South	Before	0.06	0.26	1.91	1.90	0.95	58.01	0.28	0.32	5.91	0.84	0.54	14.85
			After	0.04	0.15	1.42	2.07	0.73	59.81	0.31	0.24	16.48	0.76	0.35	14.44
Chevy Venture	AM	North	Before	0.06	0.43	1.15	1.82	1.50	9.17	0.22	0.45	0.99	0.92	0.75	1.77
			After	0.05	0.37	0.67	1.12	1.15	2.86	0.20	0.40	0.75	0.92	0.62	1.29
		South	Before	0.05	0.33	2.04	4.73	1.95	8.74	1.05	0.62	1.32	3.38	1.31	3.10
			After	0.06	0.20	0.41	4.45	2.04	5.87	1.27	0.74	1.40	4.20	1.24	2.49
	PM	North	Before	0.07	0.33	0.72	4.82	2.00	38.88	0.54	0.55	1.23	2.66	1.08	3.41
			After	0.05	0.50	2.01	5.83	2.70	6.21	0.54	0.73	1.25	2.70	1.58	3.03
		South	Before	0.07	0.41	0.70	2.56	1.51	7.52	0.41	0.43	1.17	2.46	1.00	2.71
			After	0.04	0.53	2.52	2.53	1.77	13.57	0.63	0.61	1.61	2.37	1.14	2.37

Table 10-5. Percent of Time Spent in Different Driving Modes for Chapel Hill Road Data

Vehicle	Time/ Direction	Coord	Percent Time in Each Mode				Trip Duration (sec)	Change in Duration of Trip (%)
			Idle	Accel.	Decel.	Cruise		
Ford Taurus	AM North	Before	20.4	10.1	18.2	51.3	591	10
		After	22.4	8.8	16.8	52.0	651	
	AM South	Before	15.3	9.0	15.4	60.3	281	-5.9
		After	13.6	7.3	17.9	61.2	264	
	PM North	Before	17.2	12.8	13.3	56.8	257	7.8
		After	11.4	9.7	25.0	53.9	277	
	PM South	Before	24.5	12.1	19.6	43.8	519	-13
		After	24.3	8.1	24.2	43.4	449	
Chevrolet Venture	AM North	Before	15.7	23.2	11.5	49.7	584	40
		After	21.4	20.6	10.9	47.1	816	
	AM South	Before	14.7	13.5	9.0	62.7	270	-5.7
		After	11.8	12.0	8.2	68.0	255	
	PM North	Before	12.5	20.3	10.3	56.9	278	-3.5
		After	10.1	21.4	9.3	59.3	268	
	PM South	Before	15.5	24.5	13.4	46.6	479	-3.6
		After	15.6	21.3	14.0	49.0	462	

observed portion of total trip time spent in acceleration and deceleration modes, while there was an increase in the portion of time spent in cruise mode. However, the differences in the portion of time spent in each mode seem to be modest at best and the differences may not be substantial. Although there were only modest differences in the time distribution of driving modes, there appears to be more substantial differences in the observed average trip duration. In the before case, the average trip duration was 270 seconds, whereas in the after case it was 255 seconds, a decrease of 5.7 percent.

In order to evaluate the influence of modal emission rates, time distribution of modes, and changes in trip duration, a simple model was developed for purposes of estimating total emissions of an average trip under a variety of different assumptions. The total trip emissions of a pollutant is given by the product of the total trip duration and a weighted average emission factor in units of mass of pollutant emitted per unit time. The weighted average emission factor is calculated based upon the sum of the products of the fraction of time spent in each mode multiplied by the respective modal emission factor. A general equation for the estimated total trip emissions is:

$$TE = TD\left[\left(EF_{idle} \times PT_{idle}\right) + \left(EF_{accel} \times PT_{accel}\right) + \left(EF_{decel} \times PT_{decel}\right) + \left(EF_{cruise} \times PT_{cruise}\right)\right] \quad (10\text{-}1)$$

Where,

TE = Total emissions (mg)

TD = Average trip duration for peak time/direction combination (seconds)

EF_{idle} = Emission factor for individual driving mode (e.g., idle) in units of mg/sec or g/sec

PT_{idle} = Fraction of total time spent in a particular mode (fraction)

As an example, Equation (10-1) is applied to estimate the average total NO emissions for a before trip for the Ford Taurus traveling in the southbound direction in the morning. The modal emission factors are taken from Table 10-4 and the trip duration and fraction of total time in each driving mode are taken from Table 10-5 The total emissions are calculated as:

$$\mathrm{TE_{NO}}(\mathrm{mg}) = 281\,\mathrm{sec} \times \left[\left(0.09\,mg/\mathrm{sec} \times 0.153\right) + \left(2.71\,mg/\mathrm{sec} \times 0.090\right) + \left(0.43\,mg/\mathrm{sec} \times 0.154\right) + \left(1.08\,mg/\mathrm{sec} \times 0.603\right)\right]$$

$$\mathrm{TE_{NO}}(\mathrm{mg}) \approx 271$$

Comparisons of before and after emissions are estimated based upon each of the three cases described in Table 10-3.

10.4.1.1 Comparison Case A: Modal Emission Rates Held Constant at "Before" Values with Variation in Time Distribution of Modes, Total Travel Time

The results for Comparison Case A are given in Table 10-6. Table 10-6 presents the emissions estimated using the before modal rates for different peak time/direction and vehicle combinations for both the before and after cases. The table gives both the emission estimates in total milligrams and the percent differences between the before and after cases. The percent change in estimated emissions ranges from a 25 percent decrease to a 34 percent increase. The largest change occurred for the Chevrolet Venture for the AM North HC case with a 34 percent increase. Changes in estimated emissions between the before and after cases are due to changes in the percent of time spent in different driving modes and changes in the total duration of trips. It is typically the case that differences in the duration of trips in the before and after cases have an important effect

Table 10-6. Estimated Emissions for Chapel Hill Road based upon Before Modal Rates with Variation in Trip Duration and Time Distribution of Modes

Vehicle	Peak Time	Direction	Coord.	NO (mg)	Percent Change in NO (%)	HC (mg)	Percent Change in HC (%)	CO (mg)	Percent Change in CO (%)
Ford Taurus	AM	North	Before	194	6.0	157	8.3	3346	5.6
			After	206		170		3533	
		South	Before	273	-8.5	96	-8.2	4784	-13
			After	250		88		4176	
	PM	North	Before	226	0.9	171	5.6	3791	-3.2
			After	228		180		3671	
		South	Before	347	-22	250	-18	7859	-25
			After	271		204		5860	
Chevrolet Venture	AM	North	Before	534	29	492	34	1927	30.4
			After	690		657		2512	
		South	Before	773	-2.4	321	-3.6	958	-6.6
			After	755		309		894	
	PM	North	Before	710	0.6	311	-0.6	2787	1.1
			After	714		309		2819	
		South	Before	882	-4.6	459	-5.7	1615	-8.4
			After	841		433		1480	

on percent difference in emissions. For example, for the Chevrolet Venture for the AM North case, the before runs had a trip duration of 584 seconds on average whereas in the after case the duration was 816 seconds. Thus, there was approximately a 40 percent increase in the duration of the trip, as given in Table 10-5. The increase in emissions for this case, of 34 percent, is mainly due to the increase in trip duration.

10.4.1.2 Comparison Case B: Modal Emission Rates Held Constant at "After" Values with Variation in Time Distribution of Modes and in Total Travel Time

Since there is some difference in the modal emission rates when comparing the before and after values, it was deemed important to perform an analysis similar to Comparison Case A but using the "after" modal emission rates instead of the "before" emission rates. Thus, Table 10-7 presents the emissions estimated using the after modal rates for different peak time/direction and vehicle combinations. The table gives both the emission estimates in total milligrams units and also the percent differences between the before and after cases.

Table 10-7. Estimated Emissions for Chapel Hill Road based upon After Modal Rates with Variation in Trip Duration and Time Distribution of Modes

Vehicle	Peak Time	Direction	Coord.	NO (mg)	Percent Change in NO (%)	HC (mg)	Percent Change in HC (%)	CO (mg)	Percent Change in CO (%)
Ford Taurus	AM	North	Before	150	4.8	199	8.1	2926	5.6
			After	157		215		3091	
		South	Before	227	-8.3	119	-6.8	2228	-10.2
			After	208		111		2002	
	PM	North	Before	170	-1.4	115	3.8	1928	-2.4
			After	167		120		1882	
		South	Before	340	-23	170	-19	8892	-22
			After	262		138		6943	
Chevrolet Venture	AM	North	Before	436	30.3	395	34	872	33
			After	568		531		1160	
		South	Before	908	-1.6	311	-3.8	686	-4.9
			After	893		299		653	
	PM	North	Before	771	0.7	439	-0.6	934	-1.3
			After	777		437		922	
		South	Before	871	-4.7	541	-5.7	2415	-10.5
			After	830		510		2161	

The largest percent change in estimated emissions in Table 10-7 occurred for the Chevrolet Venture for the AM North HC case with a 34 percent increase. This result is very similar to that obtained when the “before” modal emission data were used as shown in Table 10-6. The percent change in emissions ranges from a 22 percent decrease to a 34 percent increase.

The percentage changes estimated in Table 10-7 are very similar to those estimated in Table 10-6, even though two different sets of modal emission factors were used. For example, for NO emissions in the AM North case for the Ford Taurus, the total estimated trip emissions increased by 6 percent when "before" emission factors were used and by 4.8 percent when "after" emission factors where used. In general, the estimates of percent changes were typically within two percentage points of each other for all but two cases. The largest difference between the two estimates of percentage change in emissions was 3.5 percentage points for the case of CO emissions for the PM south case for the Ford Taurus. However, in all cases except two, the direction of the change was estimated to be the same. Thus, if emissions were estimated to decrease when "before" emission factors were used, they were also estimated to decrease if "after" emission factors were used. Two cases where there are differences in the direction of the change are for the Ford Taurus PM North NO case and for the Chevrolet Venture PM North CO case. In these two cases, the percentage changes were very small.

Overall, the results of Comparison Cases A and B suggest that the differences among the observed average modal emission factors between the before and after cases are not substantial. Regardless of which set of emission factors are used, the same qualitative insights are obtained regarding whether total estimated emissions increase or decrease.

Comparison Cases A and B only evaluate whether relative differences among the model emission factors would influence a before and after comparison. It is clear that there is not much of an effect on estimates of the percentage change in emissions. However, the estimates of the absolute value of emissions do appear to differ when comparing estimates made in Table 10-6 using "before" emission factors with those in Table 10-7 using "after" emission factors. For example, for the AM north case for NO emissions for the Ford Taurus in the before case, the average estimated trip emissions are 194 mg using "before" emission factors and 150 mg using "after" emission factors. The differences in the absolute emission rates between the before and the after data can lead to more variation in estimates of changes in total emissions when comparing the empirically observed before and after cases.

10.4.1.3 Comparison Case C: Modal Emission Rates Held Constant at "Before" Values with Variation in Time Distribution of Modes and Travel Time Constant

In order to assess the potential importance of the distribution of driving modes with respect to before and after comparisons, Comparison Case C was developed in which both the emission factors and the total travel time were held constant and in which only the fraction of time spent in each mode was allowed to vary between the before and after cases. As revealed by Comparison Cases A and B, the results of relative comparisons of before and after are essentially the same regardless of whether only the "before" emission factors or the "after" emission factors are used throughout the analysis. Therefore, it is not important as to which set of emission factors are used and an arbitrary

Table 10-8. Results of Pollutant Estimates for Chapel Hill Road based upon Before Modal Rates and Trip Duration for the Before Case

Vehicle	**Peak Time**	**Direction**	**Coord.**	**NO (mg)**	**Percent Change in NO (%)**	**HC (mg)**	**Percent Change in HC (%)**	**CO (mg)**	**Percent Change in CO (%)**
Ford Taurus	AM	North	Before	194	-3.6	157	-1.6	3346	-4.0
			After	187		154		3212	
		South	Before	273	-2.8	96	-2.4	4784	-7.2
			After	266		94		4439	
	PM	North	Before	226	-6.4	171	-2.0	3791	-10.2
			After	211		167		3406	
		South	Before	347	-9.9	250	-5.3	7859	-13.8
			After	313		236		6772	
Chevrolet Venture	AM	North	Before	534	-7.5	492	-4.3	1927	-6.7
			After	494		470		1797	
		South	Before	773	3.4	321	2.2	958	-1.0
			After	800		328		948	
	PM	North	Before	710	4.2	311	3.0	2787	4.8
			After	740		320		2921	
		South	Before	882	-1.1	459	-2.2	1615	-5.0
			After	872		448		1535	

choice was made to use the "before" emission factors. The trip duration was held constant. The trip duration from the before case, as given in Table 10-5, was used to estimate both the before and after total emissions. The fraction of time spent in each mode was allowed to vary. The fraction of time spent in each mode in the before case is assumed to be the same as shown in Table 10-5 for the before case. Similarly, the after case time fractions in Table 10-5 were used to calculate the after emissions in Table 10-8.

The results in Table 10-8 are substantially different than the results in Table 10-6. There are differences in the estimated total emissions as well as in the percentage difference between the before and after cases. The percentage differences in between the before and after cases are less than plus or minus 10 percent in most cases, compared to much larger differences from Comparison Cases A and B. For example, only two of the 24 comparisons shown in Table 10-6 yield differences greater than plus or minus 10 percent, while 7 of the 24 comparisons in Table 10-5 exceed this range. Thus, because the only factor that varies between the before and after cases in Table 10-8 is the distribution of driving modes, and because the differences are relatively small, one key finding is that the differences in the fraction of time spent in each driving mode between the before and after cases by itself has only a modest effect on differences in total emissions.

In comparing Comparison Cases A and C, it is apparent that there are larger differences in estimated total emissions between the before and after cases for the former than for the latter. A second key finding is that the change in trip duration between the before and after cases is an important factor affecting comparisons. Since Comparison Cases A and C both use the same emission factor data and the same assumptions regarding changes in the fraction of time spent in each mode, the differences in results between the two can be attributable to differences in the assumptions regarding travel time.

10.4.1.4 Summary of Sensitivity Analysis Findings

The key findings from Comparison Cases A, B, and C are as follows:

- The relative differences among modal emission rates appear to be similar and similar comparative insights are obtained if emission factors are developed based upon only the "before" data or only upon the "after" data.
- There are differences in the absolute magnitude of emissions estimated from "before" emission factor data versus those estimated from "after" emission factor data, suggesting that differences in before and after emission rates, although not statistically significant on a mass per time basis, may substantially influence comparisons of total trip emissions.
- The fraction of time spent in each driving mode is similar in the before and after cases. The relatively modest differences in the fraction of time spent in each driving mode may account for only a small portion of the changes in before and after emissions.
- The duration of the trip may have a substantial influence on emissions when comparing the before and after cases.

With the key insights obtained from sensitivity analysis, the empirical results of the before and after measurements are presented and interpreted.

10.4.2 Empirical Comparison of Traffic and Emissions Before and After a Change in Signal Timing and Coordination

In this section, empirically observed values for traffic flow and emissions are summarized for the before and after measurements on Chapel Hill Road. These observed values differ from the previous section in that total emissions were measured, not calculated, based upon the OEM-2100^{TM} data collected in the field. The results are summarized in four tables which are as follows:

- Table 10-9 – AM Peak Chevrolet Venture Runs,
- Table 10-10 – AM Peak Ford Taurus Runs,
- Table 10-11 – PM Peak Chevrolet Venture Runs,
- Table 10-12 – PM Peak Ford Taurus Runs.

As shown in Table 10-9, all of the traffic parameters (speed, control delay, and total stops) worsened significantly after signal coordination for the northbound direction. There is no statistically significant change in pollutants for the northbound direction.

For HC emissions in the morning northbound direction, the average observed change is an increase of 16 percent in the after case compared to the before case. The average total emissions in the after case are 191 mg/mi versus 164 mg/mi in the before case. The difference is not statistically significant because the p-value is 0.219, which is much larger than the significance criterion of 0.05. The average speed of the trip decreased by 29 percent, and the trip duration (as shown in Table 10-5) increased by 40 percent. There is an increase in percent of time spent in idle, and a decrease in time spent in other modes. If the emission factors had not changed between the before and after cases, a substantial increase in emissions of 34 percent would have been expected, as suggested in the sensitivity analyses presented in Tables 10-6 and 10-7. In this case there is a decrease in the modal HC emission rates in the after case as shown in Table 10-4. However, the trip duration increased by 40 percent; thus, the observed increase in HC emissions is influenced by a substantial increase in trip duration, a change in the time distribution of driving modes, and a substantial decrease in emission rate for the acceleration mode. The actual increase likely would have been larger than observed in Table 10-9 if there was no change in modal emission rates between the before and after

Table 10-9. Chapel Hill Road AM Peak Before and After Coordination Results – Chevrolet Venture

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
AM NORTH				
Speed, mph	17.1 (0.910)	12.0 (0.631)	-29.6%	Yes (0.000)
Control Delay, sec/mi	83.6 (9.51)	128. (10.0)	+53.6%	Yes (0.003)
Total Stops, stops/mi	2.97 (0.268)	4.99 (0.423)	+68.1%	Yes (0.000)
HC, mg/mi	164. (15.2)	191. (14.6)	+16.0%	No (0.219)
NO, mg/mi	170. (15.8)	194.7 (20.5)	+14.3%	No (0.355)
CO, mg/mi	614. (105.5)	409.4 (23.7)	-33.3%	No (0.071)
AM SOUTH				
Speed, mph	36.9 (1.49)	39.0 (1.93)	+5.84%	No (0.384)
Control Delay, sec/mi	22.1 (3.91)	16.6 (4.12)	-24.8%	No (0.342)
Total Stops, stops/mi	0.521 (0.0807)	0.299 (0.0749)	-42.6%	No (0.051)
HC, mg/mi	117. (11.6)	110.5 (7.20)	-5.73%	No (0.626)
NO, mg/mi	273. (14.8)	321. (21.7)	+17.8%	No (0.075)
CO, mg/mi	328. (47.5)	234. (18.0)	-28.6%	No (0.076)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

cases. Thus, a robust finding in this case is that there is at least a modest increase in HC emissions.

For NO emissions in the northbound case of Table 10-9, the observed increase of 14.3 percent is statistically insignificant. If the emission factors had remained constant, the predicted increase would have been 29 to 30.3 percent per the estimates of Tables 10-6 and 10-7, respectively. From Table 10-4, it is apparent that the modal emission factors decreased substantially for the acceleration mode and decreased slightly for other modes in the after case. There is 40 percent increase in trip duration. Thus, a robust finding in this case is that NO emissions increased, and that the increase likely would have been more than was empirically observed if there had been no change in modal emission rates.

The northbound observed CO emissions shown in Table 10-9 decreased by 33 percent, compared to a predicted increase of 30.4 and 33 as indicated in Tables 10-6 and 10-7 respectively. There is a substantial decrease in modal emission rates for the after case as given Table 10-4. For example, there is approximately a 69 percent decrease in acceleration emission rate and a 27 percent decrease in cruise emission rate. If the emission rates had remained constant, CO emissions would have increased. Overall, an increase in CO emissions would be expected. In fact, for all three pollutants an increase in emissions of approximately 30 percent would be expected. Thus, even though the empirically observed changes were not statistically significant, it is reasonable to assume that emissions would have increased for the northbound case if the before and after data could have been collected under exactly the same ambient and vehicle conditions.

In the southbound cases of Table 10-9, there are no statistically significant observed changes in either traffic parameters or emissions of HC, NO, or CO. The predicted changes for all these pollutants are decreases of less than six percent. Thus, there is essentially no change in emissions. Furthermore, the sensitivity analysis results of Tables 10-6 and 10-7 also indicate essentially no change in emissions. Thus, a robust finding in this case is that there were no changes in emissions.

Table 10-10 shows the observed changes in traffic flow and emissions for the Ford Taurus during the AM peak period in both the north and south directions. Overall, there are no statistically significant improvements in traffic flow. The observed changes in emissions are not statistically significant except for one case in both the north and south directions.

For HC emissions in northbound case of Table 10-10, the observed increase of 69.3 percent is statistically significant. If the emission factors had remained constant, the predicted increase would have been only eight percent as shown in Tables 10-6 and 10-7. From Table 10-4, it is apparent that all four modal emission factors increased substantially in the after case, which accounts for the observed increase being larger than the predicted increase. Thus, a robust finding in this case is that HC emissions increased, but that the increase likely would have been less than what was observed if the before and

Table 10-10. Chapel Hill Road AM Peak Before and After Coordination Results – Ford Taurus

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
AM NORTH				
Speed, mph	15.6 (0.88)	14.8 (1.29)	-4.7%	No (0.643)
Control Delay, sec/mi	99.1 (9.63)	101. (13.7)	+2.09%	No (0.902)
Total Stops, stops/mi	3.36 (0.292)	3.68 (0.440)	+9.40%	No (0.555)
HC, mg/mi	68.9 (6.93)	116.8 (16.5)	+69.3%	Yes (0.014)
NO, mg/mi	93.2 (12.0)	89.1 (13.9)	-4.4%	No (0.824)
CO, mg/mi	1619. (149.8)	1867. (283.6)	+15.3%	No (0.446)
AM SOUTH				
Speed, mph	32.1 (1.11)	34.8 (1.66)	+8.51%	No (0.180)
Control Delay, sec/mi	24.0 (3.60)	20.0 (4.61)	-16.6%	No (0.500)
Total Stops, stops/mi	0.683 (0.0803)	0.430 (0.105)	-37.0%	No (0.063)
HC, mg/mi	43.0 (3.64)	49.0 (4.15)	+13.6%	No (0.293)
NO, mg/mi	123. (14.0)	97.6 (9.82)	-20.6%	No (0.146)
CO, mg/mi	2542. (633.3)	989.8 (113.5)	-61.1%	Yes (0.024)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

after measurements could have been taken instantaneously, without any changes in vehicle or environmental conditions.

For NO emissions in northbound case of Table 10-10, the observed decrease of 4.4 percent is statistically insignificant. If the emission factors had remained constant, the predicted increase would have been 6.0 to 4.8 percent per the estimates of Tables 10-6 and 10-7, respectively. From Table 10-4, it is apparent that the modal emission factors decreased substantially for deceleration and cruise modes and decreased slightly for the acceleration mode in the after case. Overall, the empirically observed decrease in Table

10-10 and the predicted increase of Tables 10-6 and 10-7 are small. Therefore, a robust finding is that there was essentially no change in NO emissions.

Similar to NO emissions, the change in average CO emissions in the northbound case was not statistically significant. There would have been an increase of approximately five percent if there was no change in modal emission rates as given in Tables 10-6 and 10-7. The finding in this case is that there was no significant change in CO, whether empirically observed or predicted.

In the southbound cases of Table 10-10, there are no statistically significant observed changes in traffic parameters or in emissions of HC and NO. However, there is a statistically significant decrease of 61 percent for CO emissions. The predicted decrease in CO emissions would have been only 13 and 10.2 percent if the emission factors had remained constant as indicated in Tables 10-6 and 10-7, respectively. There is a 5.9 percent decrease in trip duration that contributes to the decrease in total CO emissions. The reason for the difference between the observed and predicted decrease in CO emissions is the substantial decrease in modal emission rates as shown in Table 10-4. Thus, a robust finding in this case is that CO emissions decreased, but that the increase likely would have been less than what was observed.

The results for the afternoon measurements with the Chevrolet Venture are shown in Table 10-11. Overall, there is slight improvement in traffic flow in both the northbound and southbound directions. However, these improvements are not statistically significant.

There is a statistically significant increase of 43.9 in HC emissions in the northbound runs. The observed increase in HC is explained by an observed increase in the modal emission rates, given in Table 10-4. Thus, if the modal emission rates had remained constant, there would have been an observed slight decrease of 0.6 percent, as indicated in Tables 10-6 and 10-7.

For NO, the emissions were predicted to be approximately the same with a change of only 0.6 percent versus an observed increase of 11 percent. The acceleration modal emissions rates for NO increased substantially which explains the observed difference. For CO, the expected change would be between a 1.1 percent increase and a 1.3 percent

Table 10-11. Chapel Hill Road PM Peak Before and After Coordination Results – Chevrolet Venture

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
PM NORTH				
Speed, mph	35.4 (1.55)	36.2 (1.20)	+2.28%	No (0.684)
Control Delay, sec/mi	21.6 (3.96)	18.0 (3.51)	-16.8%	No (0.497)
Total Stops, stops/mi	0.612 (0.114)	0.621 (0.0857)	+1.48%	No (0.950)
HC, mg/mi	110.6 (11.9)	159. (8.76)	+43.9%	Yes (0.003)
NO, mg/mi	249.4 (19.0)	276.9 (33.6)	+11.0%	No (0.484)
CO, mg/mi	933. (382.5)	339.9 (45.0)	-63.6%	No (0.144)
PM SOUTH				
Speed, mph	22.7 (2.02)	23.3 (2.12)	+2.53%	No (0.846)
Control Delay, sec/mi	56.7 (12.6)	44.6 (8.87)	-21.3%	No (0.441)
Total Stops, stops/mi	2.28 (0.400)	2.09 (0.429)	-8.03%	No (0.758)
HC, mg/mi	142.6 (7.27)	176. (12.7)	+23.2%	Yes (0.034)
NO, mg/mi	263. (22.4)	267. (19.2)	+1.63%	No (0.886)
CO, mg/mi	532.4 (154.9)	756.6 (387.)	+42.1%	No (0.598)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

decrease versus an observed decrease of 63.6 percent. The observed decrease is mainly due to a substantial decrease in the acceleration modal emission rate.

For the southbound direction, the expected changes in emissions are decreases of approximately five percent for both HC and NO and approximately ten percent for CO per Tables 10-6 and 10-7. The observed increase in HC and CO can be attributed to differences in the modal emission factors between the before and after cases.

The expected changes in emissions based upon Tables 10-6 and 10-7 were typically less than five percent, except for a predicted change of as much as 10 percent

Table 10-12. Chapel Hill Road PM Peak Before and After Coordination Results – Ford Taurus

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
PM NORTH				
Speed, mph	34.4 (1.05)	32.5 (1.33)	-5.40%	No (0.282)
Control Delay, sec/mi	19.5 (2.65)	26.0 (4.59)	+33.2%	No (0.232)
Total Stops, stops/mi	0.618 (0.139)	0.594 (0.106)	-3.87%	No (0.892)
HC, mg/mi	77.6 (10.6)	54.6 (6.51)	-29.6%	No (0.079)
NO, mg/mi	103.7 (14.9)	80.6 (10.9)	-22.3%	No (0.225)
CO, mg/mi	1764. (388.6)	928. (179.6)	-47.4%	No (0.067)
PM SOUTH				
Speed, mph	18.6 (1.78)	22.2 (2.03)	+19.1%	No (0.199)
Control Delay, sec/mi	83.2 (15.2)	58.0 (9.44)	-30.2%	No (0.175)
Total Stops, stops/mi	2.76 (0.531)	2.00 (0.347)	-27.7%	No (0.242)
HC, mg/mi	116. (18.6)	66.7 (10.4)	-42.6%	Yes (0.030)
NO, mg/mi	163. (27.0)	139.7 (18.1)	-14.2%	No (0.484)
CO, mg/mi	4091. (876.9)	3123.8 (874.8)	-23.7%	No (0.441)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

for CO in the southbound case. These expected changes are very small. The two statistically significant observed changes are because of artifacts associated with changes in the modal emission factors. Thus, overall, there was no substantial change in emissions.

As in the case for the Chevrolet Venture PM runs, there are no statistically significant changes for traffic parameters for the Ford Taurus PM peak runs as shown in Table 10-12. For the northbound direction this resulted in statistically insignificant changes in emissions of all pollutants. Observed changes are higher than the predicted changes, which are reported in Tables 10-6 and 10-7. This is explained by the fact that there is substantial difference in the modal emission rates between the before and after cases. For nearly all modes, and for all pollutants, there were decreases in the observed after modal emission rates. The decreases in emission rates account for most of the observed decrease in emissions. If emission rates had remained constant, the emissions of each of the three pollutants would have changed less than approximately five percent. Thus, in the northbound case, there is no substantial change in emissions either predicted or observed.

For the southbound case, the observed changes in traffic flow were not statistically significant. However, all three traffic measures indicate improvement in traffic flow. The observed changes in emissions were statistically significant in the case of HC but not for the other two pollutants. However, the emissions of all three indicated at least some decrease. The predicted change in emissions, if emission rates had remained constant, would have been a decrease of approximately 20 percent for each of the three pollutants. Thus, a robust finding in this case is that there was a modest improvement in traffic flow and a modest improvement in emissions.

10.5 Micro-Level Results for Hotspots

The previous section focused on the corridor-level changes in traffic parameters and vehicle emissions. As reported, the majority of the vehicle emissions changes were minor and statistically insignificant. While the corridor-level averages often did not change significantly, smaller areas within the corridor may have experienced statistically significant changes. For example, a significant decrease in delays and stops at a particular intersection may result in a significant change in emissions at that location.

The micro-level results were investigated through a spatial analysis of vehicle speed and emissions data. The spatial analysis allows an evaluation of how vehicle speeds and emissions fluctuate throughout the corridor. To evaluate the data spatially, the second-by-second speed and emissions data for each run were first grouped into bins of one-tenth of a mile. Thus, there would be 26 bins for a 2.6-mile corridor. The second-by-second data within each bin were then averaged to determine the average speed or vehicle emissions for each bin.

The runs were then separated into different data sets by vehicle make and model, peak period, and direction of travel. For example, one data set would represent all runs with a Ford Taurus made during the AM peak in the northbound direction. These divisions were made to help isolate auxiliary variables so that the only difference in the before and after runs is signal timing and coordination. As shown previously in the ANOVA testing, vehicle make and model, peak period, and direction of travel are all variables that have a significant impact on vehicle emissions.

Table 10-2 shows the sample sizes for each of these data sets. Figure 10-3 shows a graphical output of the spatial analysis for runs with the Ford Taurus during the AM peak. Figure 10-4 shows a similar graphical output for runs with the Chevrolet Venture during the AM peak. Appendix V shows similar graphs for the PM peak runs with the Ford Taurus and Chevrolet Venture.

These graphs confirm the earlier finding that corridor-level vehicle speeds were lower in the AM north than the AM south runs. However, these graphs provide additional insight that the average speeds are low only for a portion of the corridor. For example, in the AM north runs, average vehicle speeds are around 20 mph until passing the traffic signal at 1.25 miles (Aviation Parkway), indicating that this signal is the bottleneck and free-flow conditions resume once vehicles pass the signal. Also, the graphs indicate that the signal at 2.3 miles (Airport Boulevard) caused more delay, and thus lower speeds, in the north direction after the signal coordination plan had been implemented.

Figure 10-3 and Figure 10-4 provide insight into the basic relationships between vehicle speed and emissions. The spikes in HC emissions occur for the most part when vehicles accelerate from low to high speeds. For example, in Figure 10-3, the peak HC emissions occur at the 1.25-mile point in the north runs which corresponds to an acceleration event for the after cases. The second largest HC peak occurs at approximately the 0.25-mile point for the after case. At this point the speed trace suggest that there is cruising at a speed of 20 mph. For the before case, HC emissions are around 50 mg/mi except from 0.5 to 1.3 miles where the average HC emissions are 80 mg/mi. This part of the trip has deceleration from 20 mph to 14 mph, from 0.5 to 0.8 miles, and then acceleration from 14 mph to 35 mph, from 0.8 to 1.3 miles. Therefore, high HC

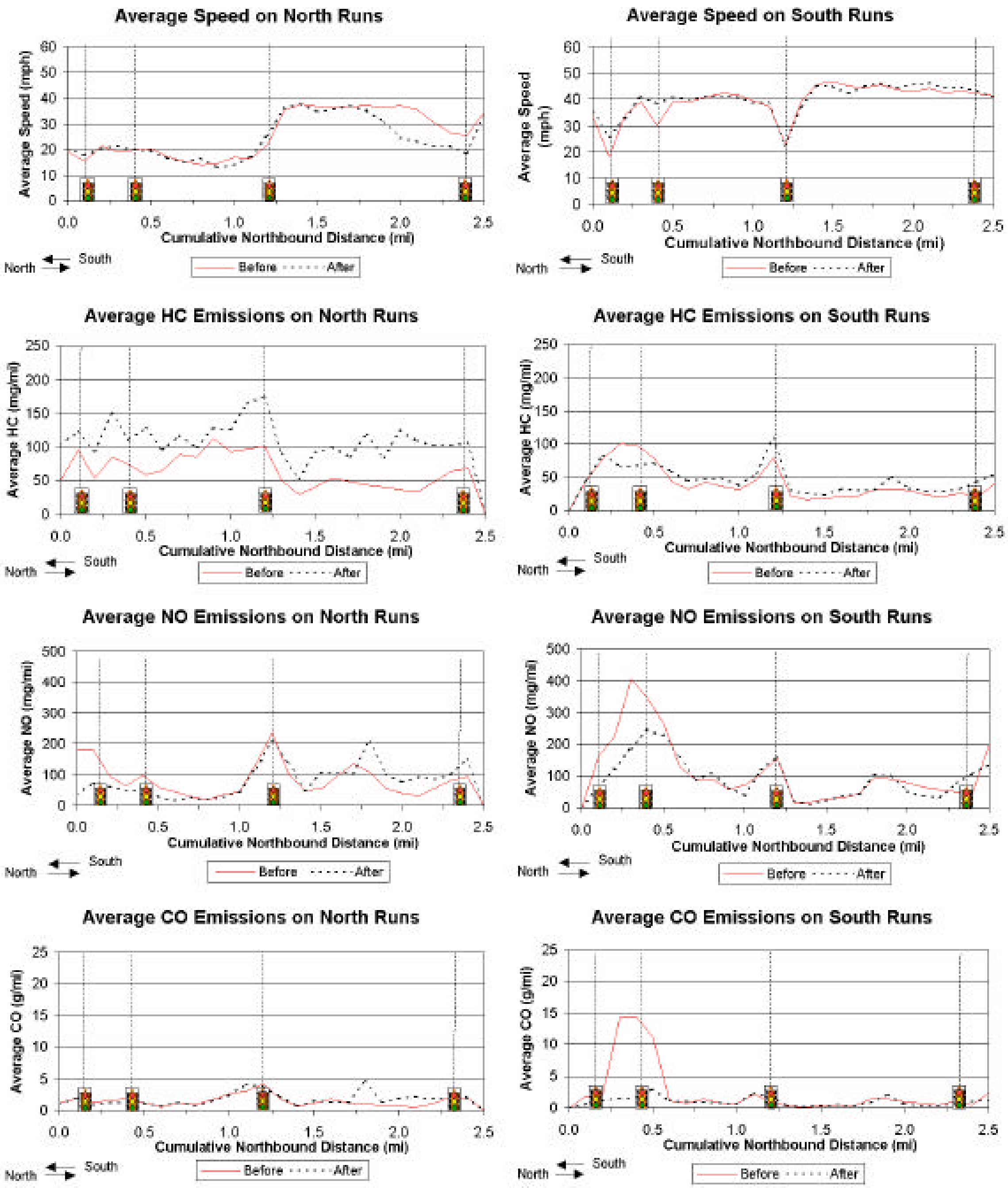


Figure 10-3. Spatial Analysis of Ford Taurus AM Peak Runs on Chapel Hill Road

emissions in the before case is a combination of deceleration and acceleration events. The peak HC occurs at around 0.8-mile point corresponds to a slight acceleration event.

For south runs in the before case, slight deceleration and then sharp acceleration that occurred between 0.1 and 0.6 miles of the runs caused HC emissions higher than the average emissions of the total trip. For this case the HC peak, 100 mg/mi, occurs at the 0.3-mile point, where there is acceleration from 17 mph to 37 mph. For the after case, average HC emissions are 45 mg/mi. For part of the trip, from 0.2 to 0.6 miles, emissions are higher than the average value of 70 mg/mi. This part of the trip includes an acceleration event, where average speed increased from 24 mph to 40 mph, and then cruising. Overall, peak HC emissions tend to occur at locations where there is an indication of an acceleration event. However, other modes such as cruising and even deceleration could cause high HC emissions. Therefore, there is a complex relation between the HC emissions and change in average speed.

NO emissions have a peak at 1.25-mile point for northbound runs both in before and after cases. In both of the cases this point corresponds to an increase in average speed from lower to higher speeds. For the after case there are two other spikes that are caused by the acceleration events. For the southbound runs peak NO emissions occur at 0.3-mile point with NO emission value of 400 mg/mi for the before case. For the after case peak NO emissions occur at 0.4-mile point with a emission value of 240 mg/mi. All these points correspond to events where average speed increased from low to higher values.

CO emissions are highest at 1.25-mile point both for before and after cases for the northbound runs. A second peak occurs for the after case at 1.8-mile point. At this point average speed increased from low to higher speeds, an indication of acceleration events. For the after case there is another peak at 1.8-mile point. At this point there is a slight decrease in average speed from 33 mph to 31 mph. For southbound runs the largest CO peak occurs between 0.3 and 0.5 miles. At this part of the trip average CO emissions is 13 mg/mi whereas the overall average CO emissions is approximately 2 mg/mi. This is due to the fact that at this part of the trip there is increase in average speed from 17 mph to 38 mph.

Similar results are obtained from the Chevrolet Venture, as given in Figure 10-4. Although the locations and magnitudes of peak emissions might differ, an increase in average speed tends to cause an increase in emissions. For example, for the northbound runs, peak HC emissions occur at the 1.25-mile point where there is an indication of an acceleration event for the after case. For the before case, peak HC emissions occur at the 0.1-mile point with an increase in average speed from low to higher values. However, in the southbound runs, the peak HC emissions occur at the 1.25-mile point where average speeds show a decrease from 40 mph to 25 mph in both before and after cases. This is the same as the finding for the Ford Taurus case, which indicates that there is a complex relation between HC emissions and change in average speed.

Peak NO emissions occur from 1.2 to 2 miles for the northbound before case, which corresponds to acceleration and cruising events as indicated in the speed trace. For the southbound runs peak NO emissions occur between 0.3 and 0.8 miles of the trip in the before case which is mainly cruising at high average speed, averaging approximately 43 mph for this part of the trip. For the after case peak NO emissions occur at the same location as the before case which is due to high speed cruising, approximately 45 mph over this part of the trip.

For CO emissions three different peaks occur for the northbound before case. The highest of these peaks are associated with increase in average speed at the 1.25-mile point. The other two peaks are associated with moderate speed cruising at 0.3 and 0.5-mile points. For the after case, peak CO emissions occurred at the 1.25-mile point due to a sudden increase in average speed. For the southbound runs, peak CO emissions occur at the 1.25-mile point for both the before and after cases.

In general, the highest emissions for all of the pollutants occur at locations where there is an increase in average speed that is an indication of acceleration events. However, there are other locations where peak in emissions occur due to steady average speed or decrease in average speed. It should be noted that speeds and emissions data for this analysis are averaged over mileage driven. During this averaging period different driving modes can be observed. An acceleration event that occurred in one second might have a high effect on emissions although its effect on speed might be negligible. Therefore, the findings observed in this study cannot be used directly for comparison to driving mode analysis. Some of the emissions peaks occur at the same location for both the Ford Taurus and Chevrolet Venture. However, there are other cases where a peak

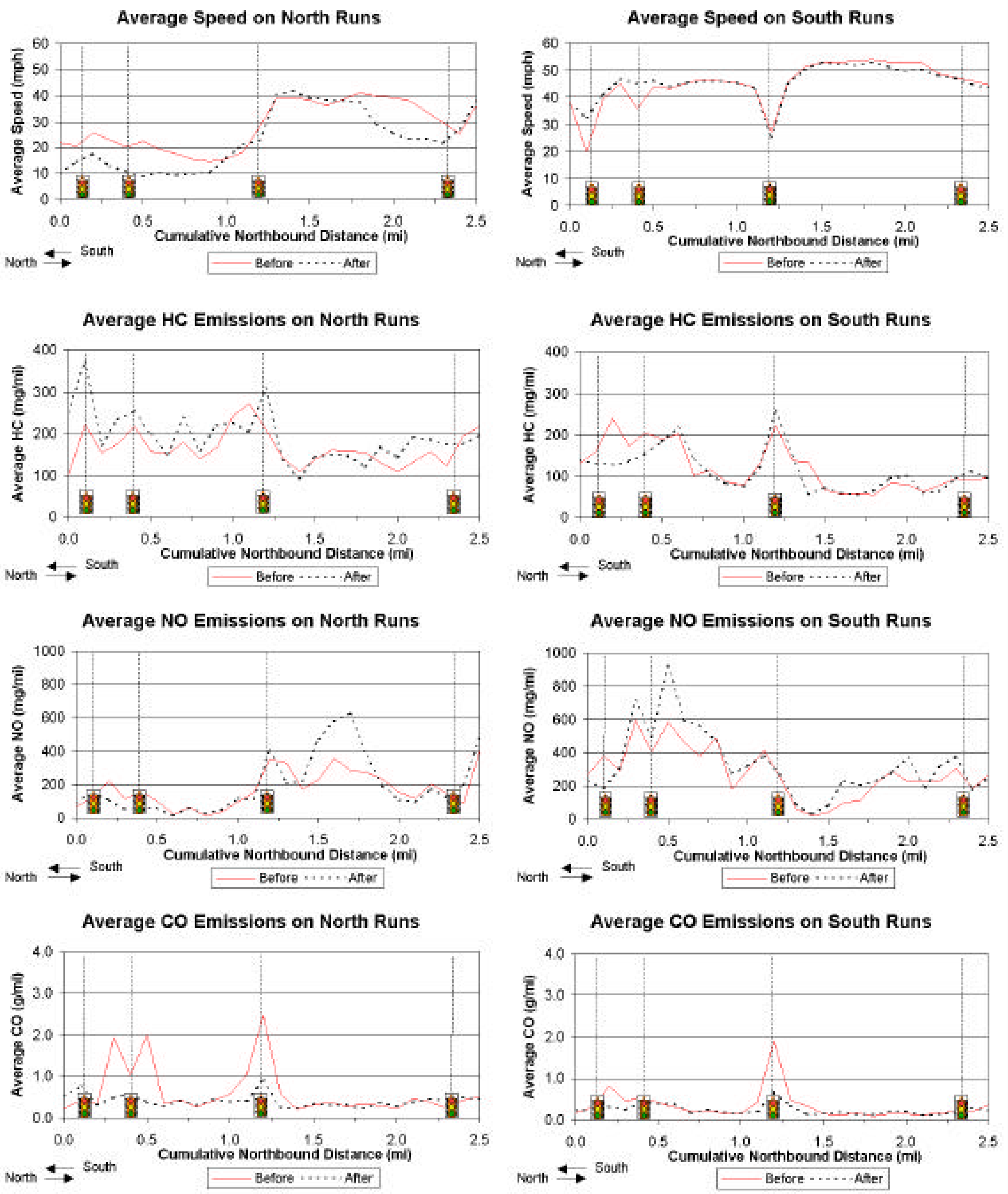


Figure 10-4. Spatial Analysis of Chevrolet Venture AM Peak Runs on Chapel Hill Road

occurs for Ford Taurus but not for Chevrolet Venture. For example, the peak at the 1.75-mile point for NO emission for the Chevrolet Venture for the northbound after case did not occur for the Ford Taurus.

An important application of the spatial analysis is to identify points along the corridor where signal coordination has a significant effect on vehicle emissions. This was done by performing Student's-t tests on individual bins (each bin is 0.1 mile) or groups of bins where the before and after emissions data differed on the spatial graphs. Figure 10-5 displays the same spatial graphs of Ford Taurus runs with the sections highlighted that show a statistically significant difference between the before and after runs. Appendix V displays similar graphs for all combinations of vehicle make and model, peak hour, and direction of travel.

As shown in Figure 10-5, a number of sections show statistically significant differences in the before and after runs even when the corridor-level averages are not statistically different. This shows that the effects of signal coordination for Chapel Hill Road are not large overall, but the coordination does have some local effect on small portions of the corridor. Table 10-13 shows a summary of all statistically significant differences on Chapel Hill Road on both a corridor-level and micro-level. The micro-level analysis was not performed when the corridor-level showed a statistically significant change in emissions because the purpose was to identify micro-level statistical changes when the corridor-level change was not significant.

As shown in Table 10-13, there are a number of micro-level sections that experience statistically significant changes in emissions while the corridor-level average does not change significantly. Two locations have a statistically significant difference for HC emissions. Four locations have a statistically significant difference for NO emissions and only one location has a statistically significant difference for CO emissions. In all cases, the direction of change in emissions (positive or negative) is the same for both the corridor-level and micro-level. For example, the Venture AM peak north runs experienced a 16 percent increase in HC emissions, and between 0.0 and 0.1 miles, the HC emissions increased 66.6 percent.

There are a number of large changes in micro-level CO emissions that are not statistically significant. The largest, a 122 percent increase in CO emissions, was not

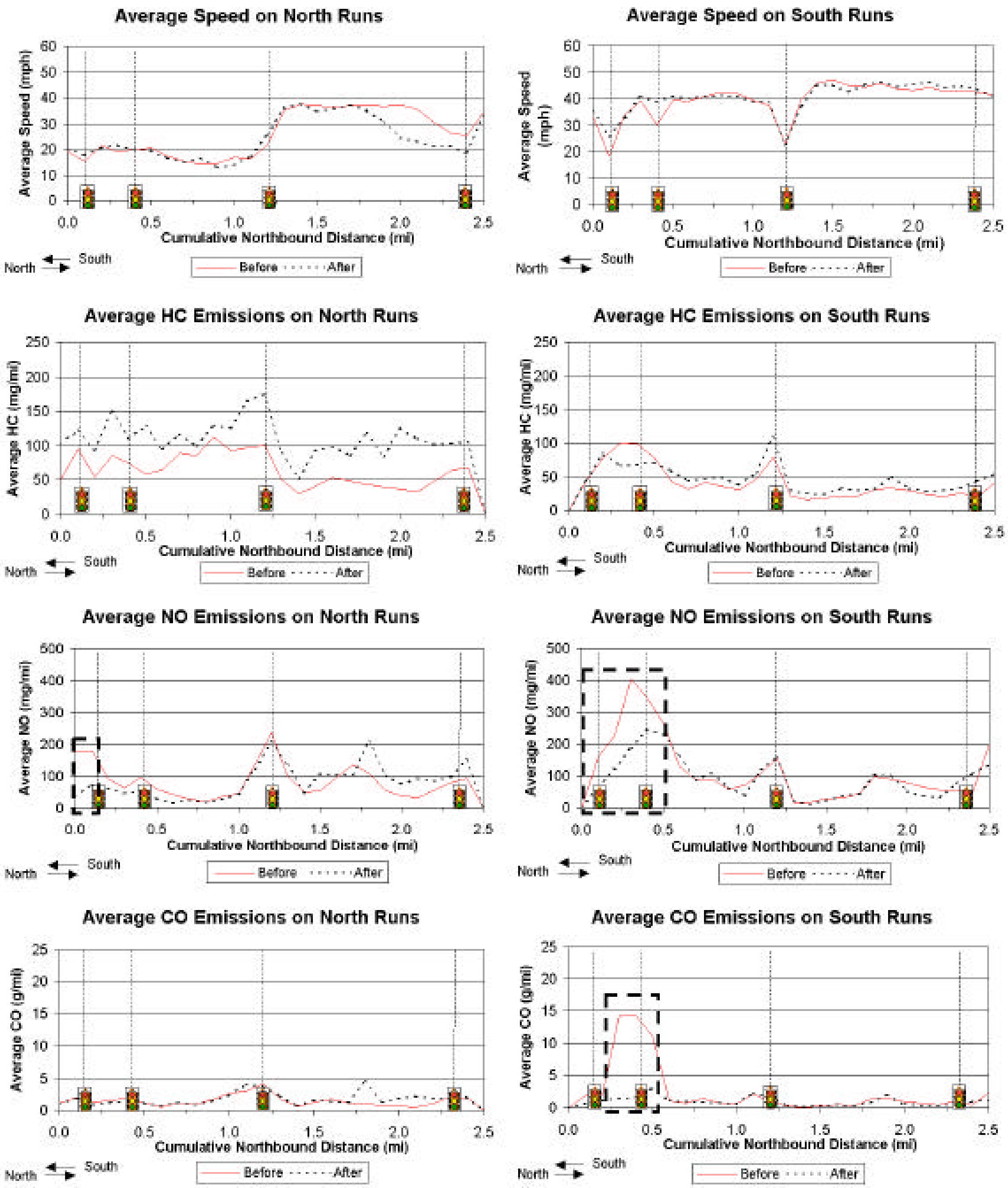


Figure 10-5. Spatial Analysis of Ford Taurus AM Peak Runs on Chapel Hill Road with Statistically Different Sections Highlighted

Table 10-13. Summary of Changes in Emissions Before and After Signal Coordination on Chapel Hill Road

Vehicle: Peak & Direction	Corridor-Level % Change (Stat. Signif.?)[1]	Micro-Level		
		Location[2]	% Change[3]	Stat. Signif.?[4] (P-Value)
HC Emissions				
Taurus: AM North	+69.3% (Yes)	N/A	N/A	N/A
Taurus: AM South	+13.6% (No)	None	-	-
Taurus: PM North	-29.6% (No)	None	-	-
Taurus: PM South	-42.6% (Yes)	N/A	N/A	N/A
Venture: AM North	+16.0% (No)	0.1-0.2	+66.6%	Yes (0.007)
Venture: AM South	-5.73% (No)	0.1-0.5	-20.9%	Yes (0.002)
Venture: PM North	+43.9% (Yes)	N/A	N/A	N/A
Venture: PM South	+23.2% (Yes)	N/A	N/A	N/A
NO Emissions				
Taurus: AM North	-4.4% (No)	0.0-0.1	-62.8%	Yes (0.024)
Taurus: AM South	-20.6% (No)	0.0-0.3	-39.8%	Yes (0.001)
Taurus: PM North	-22.3% (No)	None	-	-
Taurus: PM South	-14.2% (No)	None	-	-
Venture: AM North	+14.3% (No)	1.4-1.8	+73.0%	Yes (0.002)
Venture: AM South	+17.8% (No)	0.3-0.8	27.0%	Yes (0.018)
Venture: PM North	+11.0% (No)	None	-	-
Venture: PM South	+1.6% (No)	None	-	-
CO Emissions				
Taurus: AM North	+15.3% (No)	None	-	-
Taurus: AM South	-61.1% (Yes)	0.3-0.5	-90.7%	Yes (0.001)
Taurus: PM North	-47.4% (No)	None		
Taurus: PM South	-23.7% (No)	0.3	-8.0%	No (0.87)
Venture: AM North	-33.3% (No)	0.2-0.6 1.1-1.3	-66.5% -58.2%	No (0.13) No (0.12)
Venture: AM South	-28.6% (No)	1.2	-65.2%	No(0.234)
Venture: PM North	-63.6% (No)	0.2-0.4 0.9 2.0	-91.5% -70.3% -72.2%	No (0.16) No (0.36) No (0.35)
Venture: PM South	+42.1% (No)	0.5-0.6	+122.%	No (0.53)

Notes: N/A = No analysis was performed because the corridor-level average change was statistically significant.

1. More detailed corridor-level results shown in Table 10-9 through Table 10-12.
2. In miles from beginning of south end of corridor.
3. Calculated as (After value – Before value)/Before value.
4. Statistically significant at 95% confidence level ($\alpha = 0.05$).

statistically significant. To better understand why such a large difference could not be statistically significant, a cumulative distribution function (CDF) for both the before and after emissions at this location is examined. Figure 10-6 shows a spatial graph of the before and after Chevrolet Venture PM peak south runs and a comparison of the before and after CDFs of the CO emissions between the 0.5 and 0.6 mile points.

As shown in Figure 10-6, it is clear that the after runs have a higher average than the before runs due to an outlying run producing CO emissions greater than 100 grams/mile. The remainder of the runs produce very similar CO emissions during the before and after cases. Thus, the two distributions are very similar. The single highest emission rate data point in the after case not only increases the mean emission rate, but also increases the standard deviation.

In turn, the standard error of the mean is increased, leading to overlap of the confidence intervals of the mean when comparing the before and after cases. Thus, even though the percentage change in average emissions appears to be large, it is not statistically significant.

In Figure 10-7 another case is given where statistically significant difference is observed. In this case, the CDFs for the before and after cases are substantially different from each other. The CDF for the after case generally have larger values of emissions for a given percentile than for the before case. Appendix V shows CDF graphs of all micro-level differences listed in Table 10-13.

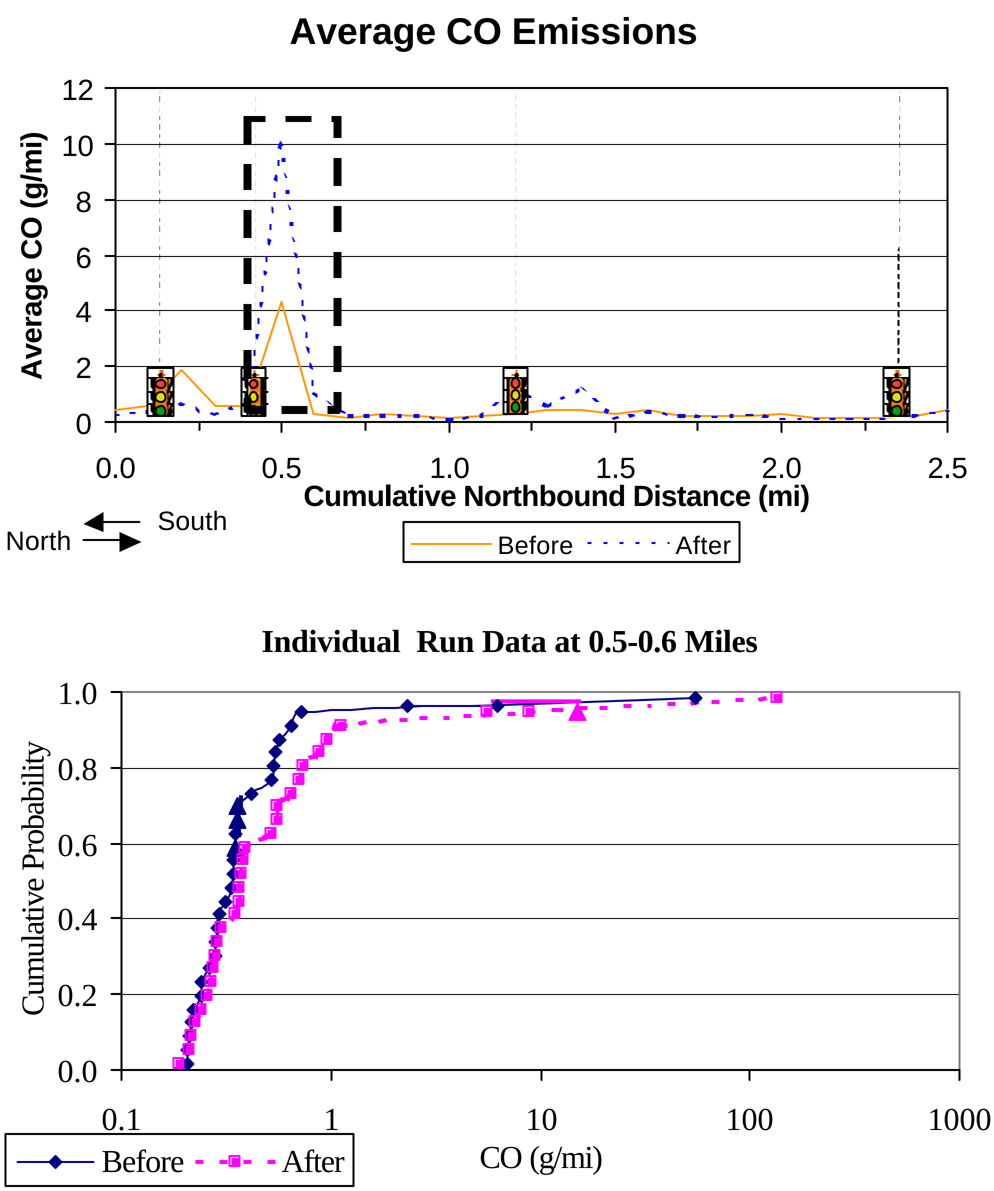
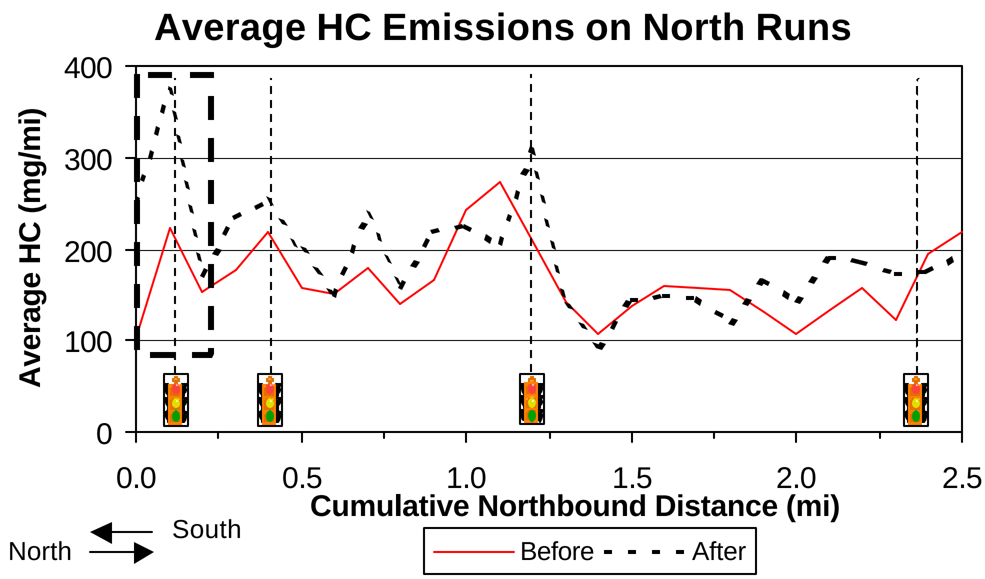


Figure 10-6. Spatial and CDF Graphs of Chevrolet Venture PM South Runs on Chapel Hill Road



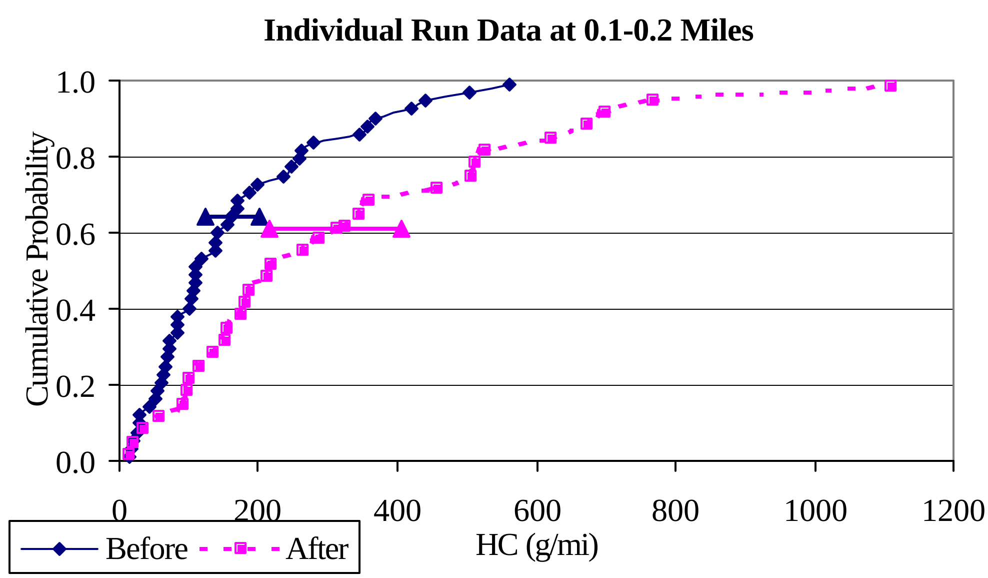


Figure 10-7. Spatial and CDF Graphs of Chevrolet Venture AM North Runs on Chapel Hill Road

10.6 Non-Priority Movement Results

Often a signal coordination plan will improve the main through movements of a corridor but worsen the non-priority movements (side street and turning movements). Thus, it is important to evaluate both the priority and non-priority movements to understand the overall impact of signal coordination on vehicle emissions. Fewer runs were completed with the non-priority runs compared to the priority runs. Table 10-14 shows the number of non-priority runs completed on Chapel Hill Road. A non-priority run is defined where a vehicle enters corridor from a side street and exits the corridor to another side street at the next intersection. Figure 10-8 shows the non-priority movements tested on Chapel Hill Road.

The number of non-priority runs given in Table 10-14 is a combination of different side street runs. For example, 7 runs were completed with the 1999 Ford Taurus on Chapel Hill for AM North. This number is the sum of N1, N2, and N3 runs collected in AM peak time with this particular vehicle.

Approximately the same number of S1, S2, and S3 (see Figure 10-8) runs were completed for each vehicle. For example, a total of 14 runs were completed for the Ford Taurus PM south runs after coordination was implemented, of which five were S1 runs, five were S2 runs, and four were S3 runs. A total of 11 runs were completed for the Ford Taurus PM north runs after coordination was implemented, of which two were N1 runs, four were N2 runs, and five were N3 runs.

A total of eight Ford Taurus AM runs were completed after coordination was implemented (four north and four south), but these runs produced a high proportion of negative NO values and were thus eliminated from the database during the file screening process (refer to Section 6.0, Data Reduction and Screening). As a result, an evaluation is not possible for the Ford Taurus AM runs.

Because of the low number of runs, for each before and after comparison confidence intervals are generally large and most of the time this causes statistical insignificance. Table 10-15 through Table 10-17 show the before and after results of the non-priority runs for the Chevrolet Venture AM peak, Chevrolet Venture PM peak, and Ford Taurus PM peak, respectively. As shown in Table 10-15, the average speeds decreased in both the north and south directions. The emission rates changed between

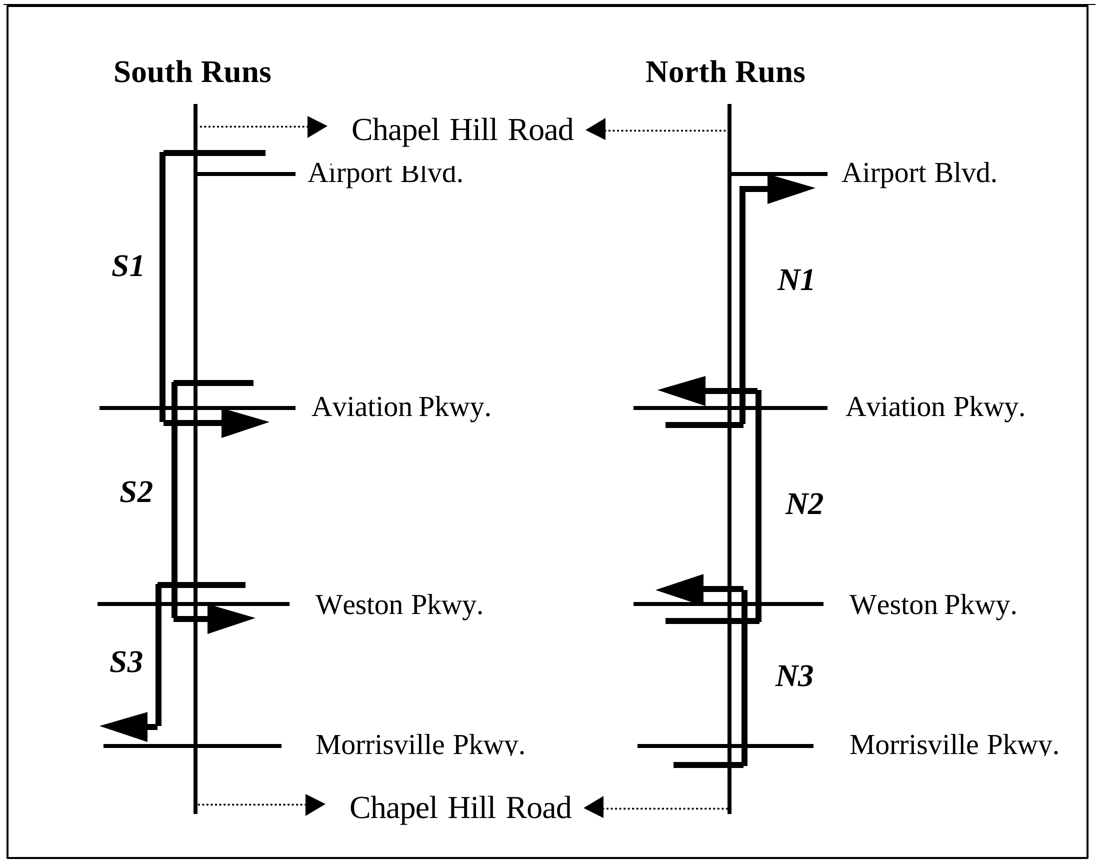


Figure 10-8. Non-priority Runs on Chapel Hill Road

Table 10-14. Number of Non-Priority Runs on Chapel Hill Road.

Peak – Direction	**Ford Taurus**		**Chevrolet Venture**	
	Before	**After**	**Before**	**After**
AM North	7	0	6	5
AM South	9	0	6	9
PM North	8	11	9	3
PM South	6	14	9	3

-19 and +28 percent. All of the p-values of the t-tests showed that none of the changes in emission rates are statistically significant.

As shown in Table 10-16, the before and after average speeds were practically equal. The emission rates varied between –26 and +94 percent. There was no statistically significant difference in mean emissions except two cases. The t-test showed a statistical significance for the PM north HC and CO emissions indicating that the before and after rates are different. However, there are only three after runs. This is not enough to draw any firm conclusions.

Table 10-15. Chapel Hill Road AM Peak Non-Priority Runs – Chevrolet Venture

Quantity	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat, Signif.? (P-Value)
AM NORTH				
Speed, mph	12.6 (2.14)	10.7 (1.29)	-15.1%	No (0.469)
HC, mg/mi	217. (12.8)	231. (16.8)	+6.7%	No (0.511)
NO, mg/mi	190. (52.5)	243. (125.5)	+28.2%	No (0.709)
CO, mg/mi	459. (50.6)	408. (34.6)	-11.2%	No (0.424)
AM SOUTH				
Speed, mph	27.1 (2.66)	22.5 (2.55)	-18.5%	No (0.199)
HC, mg/mi	189. (29.2)	236. (39.2)	+24.9%	No (0.353)
NO, mg/mi	328. (54)	398. (68)	+21.5%	No (0.432)
CO, mg/mi	539. (195.3)	436. (82.4)	-19.1%	No (0.648)

Table 10-16. Chapel Hill Road PM Peak Non-Priority Runs – Chevrolet Venture

Quantity	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat, Signif.? (P-Value)
PM NORTH				
Speed, mph	17.4 (2.66)	17.5 (2.01)	+0.3%	No (0.988)
HC, mg/mi	195. (13.0)	346. (5.3)	+77.5%	Yes (0)
NO, mg/mi	236. (33.5)	308. (93.5)	+30.7%	No (0.528)
CO, mg/mi	323. (30.0)	627. (52.9)	+94.%	Yes (0.011)
PM SOUTH				
Speed, mph	24.0 (2.38)	22.8 (4.59)	-4.7%	No (0.840)
HC, mg/mi	200. (21.0)	298. (45.9)	+49.3%	No (0.150)
NO, mg/mi	411. (87.7)	305. (72.7)	-25.8%	No (0.379)
CO, mg/mi	667. (316.)	593. (88.4)	-11.2%	No (0.825)

Table 10-17. Chapel Hill Road PM Peak Non-Priority Runs – Ford Taurus

Quantity	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat, Signif.? (P-Value)
PM NORTH				
Speed, mph	17.7 (2.19)	13.9 (1.71)	-21.5%	No (0.193)
HC, mg/mi	50.6 (10.1)	68.1 (4.35)	+34.6%	No (0.145)
NO, mg/mi	125.8 (38.9)	61.4 (8.29)	-51.2%	No (0.146)
CO, mg/mi	4443. (2465.)	1267. (161.)	-71.5%	No (0.239)
PM SOUTH				
Speed, mph	24.2 (2.16)	18.9 (1.49)	-21.8%	No (0.073)
HC, mg/mi	75.1 (10.6)	69.5 (4.05)	-7.5%	No (0.634)
NO, mg/mi	195. (38.1)	87.9 (10.8)	-55.0%	Yes (0.036)
CO, mg/mi	6281. (2009.)	1225. (155.)	-80.5%	No (0.053)

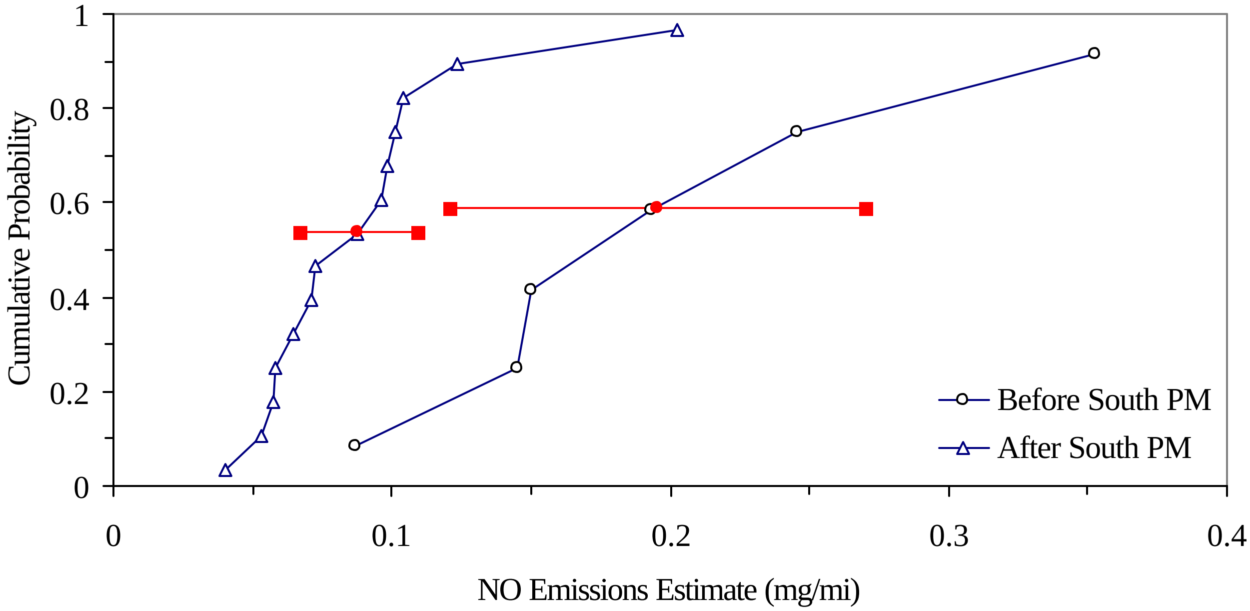


Figure 10-9. Comparison of Cumulative Distribution Functions for Before and After NO Emissions for 1999 Ford Taurus Driven on Chapel Hill Road for PM South Non-Priority Runs

As shown in Table 10-17, the vehicle speeds decreased by approximately 20 percent in both the PM north and PM south runs for Ford Taurus. In comparison, the PM runs with the Chevrolet Venture (refer to Table 10-16) experienced approximately equal vehicle speeds in the before and after runs. The emission rates for the Ford Taurus changed between –80 and +35 percent. There was no statistically significant difference in mean emissions except in one case. NO emissions for PM South runs decreased significantly. To examine the reason for this significance CDFs are plotted for before and after cases for NO emissions in Figure 10-9. The CDF for the before case generally has larger values of emissions for a given percentile than for the after case. However, excluding the highest NO emission data for before case yields a statistically insignificant comparison. This indicates that the results are sensitive to only one data point and, therefore, may not be robust. Overall, both the traffic parameters and emission rates generally did not significantly change for the non-priority runs after signal coordination was implemented.

10.7 Effect of Traffic Congestion on Vehicle Emissions

Because Chapel Hill Road is primarily a commuter route, traffic volume and congestion are highly directional. The overwhelming majority of vehicles travel northbound during the AM peak and southbound during the PM peak. This allows a comparison of vehicle emissions in light traffic versus heavy congestion. Effectively, this comparison simulates a very effective signal improvement plan on Chapel Hill Road, where conditions change from very congested to uncongested.

The analysis compared the AM north runs, representing congested conditions, to the PM north runs, representing uncongested conditions in the same direction of travel on the same corridor. Also, the AM south runs, representing uncongested conditions, were compared to the PM south runs, representing congested conditions. This comparison controls for roadway geometry (i.e. grade, horizontal curves, add/drop lanes), but it does not control for differences in temperature and air conditioner use between the two peak periods. The ANOVA found ambient temperature as a significant variable, but further analysis showed that there is no clear relation between emissions and ambient temperature, as shown in Section 7.2.3.

10.7.1 Sensitivity Analysis of Emission Factors, Distribution of Time in Driving Modes, and Total Trip Duration

In order to understand the influence of selected factors with respect to their potential contribution to changes in emissions when comparing congested and uncongested cases, a sensitivity analysis was conducted. This section specifically focuses on the effects of: (1) differences in modal emission rates; (2) differences in the distribution of time spent in each driving mode; and (3) differences in the trip duration. The methodology described in Section 10.4.1 was utilized for this purpose.

Three comparisons are described in Table 10-18. Each of the three comparisons employs the specific time distribution of driving modes applicable to the uncongested or congested cases. Comparison Case A assumes that the average modal emission rates observed in the uncongested case are also applicable to the congested case. Conversely, Comparison Case B assumes that the average modal emission rates observed in the congested case are applicable to the uncongested case. The purpose of Cases A and B are to determine whether there is any significant difference in comparisons of total estimated uncongested and congested emissions that might be attributable to variation in modal emission rates. Case C focuses on the influence of trip duration. In comparison to both Cases A and B, which each assume the trip durations specific to the uncongested and congested cases, Case C assumes that the trip duration is the same in both the uncongested and congested cases. When the results of all three cases are compared and evaluated, it may be possible to determine whether modal emission rates, time distribution of modes, or trip duration either individually or in aggregate play an important role in potential differences between total emissions in the uncongested and congested cases. Insight obtained from these comparisons will be used to help explain the results of observed emissions differences presented in the Section 10.4.2.

The key data needed for the sensitivity analysis include the modal emission rates, the time distribution of modes, and the trip duration. These data are given in Table 10-19 for modal emission rates and Table 10-20 for the time distribution and the trip duration. Table 10-19 illustrates that for each vehicle and direction there are differences in modal emission rates when comparing the uncongested and congested cases. For example, the CO emission rate during acceleration for the Ford Taurus in the uncongested North case is 19.63 mg/sec and 37.19 mg/sec for the congested case. In this particular example, the difference in the modal emission rates is substantial. Thus, there is some variability in the observed modal emission rates when comparing the uncongested and congested cases. A key question is whether this variability may by itself be able to explain any observed differences in the total emissions when comparing the uncongested and congested cases.

Table 10-20 provides data regarding the average observed percentage of time spent in each driving mode, and the average observed trip duration, for each vehicle and direction combination for both the uncongested and congested cases. These values may be important in helping to understand changes in total emissions that occurred when comparing the uncongested and congested cases.

For example, there is what appears to be a change in modal time rates for the Ford Taurus driven in the North direction. In the uncongested case idling comprised approximately 14 percent of the total trip time, whereas in the congested case idling comprised approximately 21 percent of the total trip time. There was a decrease in the

Table 10-18. Study Design: Evaluation of Modal Emission Rates, Time Distribution of Modes, and Trip Duration With Respect to Uncongested and Congested Comparisons for Chapel Hill Road.

Comparison Case	Key Factors	Before Case Assumptions	After Case Assumptions
A: Uncongested Modal Emissions	Modal Emission Rates	Uncongested	Uncongested
	Time Distribution of Modes	Uncongested	Congested
	Trip Duration	Uncongested	Congested
B: Congested Modal Emissions	Modal Emission Rates	Congested	Congested
	Time Distribution of Modes	Uncongested	Congested
	Trip Duration	Uncongested	Congested
C: Same Trip Duration	Modal Emission Rates	Uncongested	Uncongested
	Time Distribution of Modes	Uncongested	Congested
	Trip Duration	Uncongested	Uncongested

Table 10-19. Modal Emission Rates in the Congested and Uncongested Cases for Chapel Hill Road.

Vehicle	Direction	Traffic Condition	Idle (mg/sec)			Accel. (mg/sec)			Decel. (mg/sec)			Cruise (mg/sec)		
			NO	HC	CO	NO	HC	CO	NO	HC	CO	NO	HC	CO
Ford Taurus	North	Uncongested	0.03	0.20	1.23	2.16	1.00	37.19	0.27	0.37	3.47	0.76	0.58	9.03
		Congested	0.04	0.17	1.03	1.08	0.60	19.63	0.12	0.21	2.26	0.31	0.32	5.39
	South	Uncongested	0.06	0.11	0.69	2.44	0.83	60.75	0.36	0.24	4.13	1.02	0.41	11.09
		Congested	0.05	0.20	1.63	1.99	0.82	59.02	0.30	0.28	11.85	0.80	0.44	14.62
Chevrolet Venture	North	Uncongested	0.06	0.41	1.32	5.29	2.32	23.64	0.54	0.63	1.24	2.68	1.31	3.23
		Congested	0.05	0.40	0.96	1.54	1.36	6.68	0.21	0.43	0.90	0.92	0.70	1.58
	South	Uncongested	0.06	0.28	1.40	4.62	1.98	7.61	1.14	0.67	1.35	3.70	1.28	2.86
		Congested	0.06	0.47	1.58	2.54	1.63	10.44	0.52	0.51	1.38	2.42	1.07	2.55

observed portion of total trip time spent in the rest of the modes, acceleration, deceleration, and cruise modes. There appears to be substantial differences in the observed average trip duration. In the uncongested case, the average trip duration was 269 seconds, whereas in the congested case it was 616 seconds, an increase of 56 percent.

In order to evaluate the influence of modal emission rates, time distribution of modes, and changes in trip duration, the model developed in Section 10.4 is utilized. In this simple model the total trip emissions of a pollutant is given by the product of the total trip duration and a weighted average emission factor in units of mass of pollutant

Table 10-20. Percent of Time Spent in Different Driving Modes for Congested and Uncongested Cases for Chapel Hill Data

Vehicle	Direction	Traffic Condition	Percent Time in Each Mode: Idle	Accel.	Decel.	Cruise	Trip Duration (sec)	Change in Duration of Trip (%)
Ford Taurus	North	Uncongested	13.8	11.0	20.0	55.1	269	56.3
		Congested	21.3	9.5	17.6	51.6	616	
	South	Uncongested	14.5	8.2	16.5	60.7	274	42.8
		Congested	24.4	9.9	22.1	43.6	478	
Chevrolet Venture	North	Uncongested	11.4	20.8	9.8	58.0	273	59.6
		Congested	18.4	21.9	11.2	48.5	676	
	South	Uncongested	13.6	12.9	8.7	64.7	264	43.9
		Congested	15.5	23.0	13.7	47.7	471	

emitted per unit time. The weighted average emission factor is calculated based upon the sum of the products of the fraction of time spent in each mode multiplied by the respective modal emission factor. Comparisons of uncongested and congested emissions are estimated based upon each of the three cases described in Table 10-18.

10.7.1.1 Comparison Case A: Modal Emission Rates Held Constant at "Uncongested" Values with Variation in Time Distribution of Modes and in Total Travel Time

The results for Comparison Case A are given in Table 10-21. Table 10-21 presents the emissions estimated using the uncongested modal rates for different direction and vehicle combinations for both the uncongested and congested cases. The table gives both the emission estimates in total milligrams and percent differences between the before and after cases. The percent change in emissions ranges from a 35 percent decrease to a 57 percent decrease. The largest change occurred for CO emissions for the Chevrolet Venture for the North case with a 60 percent decrease as shown in Table 10-21. In Table 10-21, changes in emissions between the congested and uncongested cases are due to change in the percent time spent in different driving modes and change in the total duration of trips since modal rates were the same in estimating emissions for both the uncongested and congested cases. For both vehicles, both travel directions, and all three pollutants, substantial decreases in emissions are expected if conditions change from congested to uncongested, if modal emission rates remain constant.

Table 10-21. Results of Pollutant Estimates for Walnut Street based upon Uncongested Modal Rates

Vehicle	Direction	Traffic Condition	NO (mg)	% Difference (U-C)/C	HC (mg)	% Difference (U-C)/C	CO (mg)	% Difference (U-C)/C
Ford Taurus	North	Uncongested	193	-52	143	-54	2674	-52
		Congested	403		309		5587	
	South	Uncongested	242	-35	103	-37	3421	-40
		Congested	373		164		5705	
Chevrolet Venture	North	Uncongested	741	-57	370	-58	1928	-60
		Congested	1709		873		4819	
	South	Uncongested	820	-42	312	-45	830	-50
		Congested	1411		566		1656	

10.7.1.2 Comparison Case B: Modal Emission Rates Held Constant at "Congested" Values with Variation in Time Distribution of Modes and in Total Travel Time

Since there is some difference in the modal emission rates when comparing the uncongested and congested values, it was deemed important to perform an analysis similar to Comparison Case A but using the "congested" modal emission rates instead of the "uncongested" emission rates. Thus, Table 10-22 presents the emissions estimated using the uncongested modal rates for different direction and vehicle combinations. The table gives both the emission estimates in total milligrams units and percent differences between the uncongested and congested cases. The largest percent change in emissions occurred for the Chevrolet Venture for the North case with a 60 percent decrease as shown in Table 10-22. The percent change in emissions ranges from a 35 percent decrease to a 60 percent decrease.

The percentage changes estimated in Table 10-21 are similar to and in most cases identical to those estimated in Table 10-22, although two different sets of modal emission factors were used. For example, for NO emissions in the South case for the Ford Taurus, total estimated trip emissions decreased by 35 percent when both the "uncongested" and "congested" emission factors were used. In general, the estimates of percent changes were typically within two percentage points of each other for all but one case. The largest difference between the two estimates of percentage change in emissions was four percentage points for the case of CO emissions for the South case for the Chevrolet Venture. However, in all cases, the direction of the change was estimated to be the same.

Table 10-22. Results of Pollutant Estimates for Walnut Street based upon Congested Modal Rates

Vehicle	Direction	Traffic Condition	NO (mg)	% Difference (U-C)/C	HC (mg)	% Difference (U-C)/C	CO (mg)	% Difference (U-C)/C
Ford Taurus	North	Uncongested	86	-52	82	-54	1541	-52
		Congested	180		180		3244	
	South	Uncongested	193	-35	112	-39	4355	-40
		Congested	298		183		7286	
Chevrolet Venture	North	Uncongested	241	-56	212	-59	683	-60
		Congested	553		514		1695	
	South	Uncongested	515	-40	267	-45	881	-54
		Congested	857		484		1907	

Thus, if emissions were estimated to decrease when "uncongested" emission factors were used, they were also estimated to decrease if "congested" emission factors were used.

Overall, the results of Comparison Cases A and B suggest that there are substantial similarities in the estimates of relative changes in uncongested versus congested trip average emissions regardless of which set of modal emission factors are used. This suggests that the relative differences among the modes are similar in the congested case when compared to the uncongested case, even though the absolute value of the modal emission rates may differ. For example, consider the comparison of uncongested and congested emissions for HC emissions from the Ford Taurus in the northbound direction. In Comparison Cases A and B, the difference was found to be -35 percent. Thus, the same relative difference in emissions was estimated. However, the absolute value of the trip emissions was different in the two cases. For Comparison Case A, the total uncongested emissions were estimated to be 143 mg versus 82 mg for Comparison Case B. Thus, it appears possible to obtain robust estimates of relative differences in emissions even though the absolute value of emissions may differ substantially.

10.7.1.3 Comparison Case C: Modal Emission Rates Constant at "Uncongested" Values with Variation in Time Distribution of Modes and with Travel Time Constant

In order to assess the potential importance of the distribution of driving modes with respect to uncongested and congested comparisons, Comparison Case C was developed in which both the emission factors and the total travel time were held constant and in which only the fraction of time spent in each mode was allowed to vary between the uncongested and congested cases. As revealed by Comparison Cases A and B, there are some differences in the modal emissions factors for uncongested and congested cases. Therefore, this analysis was applied twice using each of the uncongested and congested emission factors. Trip durations for each direction vehicle combination for the uncongested case were used for estimating total emissions in Table 10-23, and trip durations for each direction peak time combination for the after case were used for estimating total emissions in Table 10-24. The trip durations and uncongested and congested modal time fractions were obtained from Table 10-20. The results of the comparison are shown in Table 10-23 and Table 10-24, using the uncongested modal emission rates and the congested modal emission rates, respectively.

The results in Table 10-23 are substantially different than the results in Table 10-21. There are differences in the estimated in the percentage difference between the congested and uncongested cases. For example, there is 10 percent increase in NO emissions for the Ford Taurus in the northbound direction as given in Table 10-23, whereas there is a decrease of 52 percent as reported in Table 10-21. There is a difference of 62 percentage points between these two results. The percentage differences in between the uncongested and congested cases are less than plus or minus 10 percent in most cases, compared to much larger differences from Comparison Cases A and B. For example, ten of the 12 comparisons shown in Table 10-23 yield differences less than or equal to plus or minus 10 percent with similar findings in Table 10-24. Overall, as shown in both Tables 10-23 and 10-24, if travel time remains constant, the estimated changes in emissions are small from a practical perspective. These comparisons imply that the differences in the fraction of time spent in each driving mode between the before and after cases by itself has only a modest effect on differences in total emissions, as in the case of Chapel Hill Road.

Another key finding is that the change in trip duration between the before and after cases is an important factor affecting comparisons. Since Comparison Cases A and C, as well as Cases B and C both use the same emission factor data and the same assumptions regarding changes in the fraction of time spent in each mode, the differences

Table 10-23. Results of Pollutant Estimates for Chapel Hill Road based upon Uncongested Modal Rates and Trip Duration for the Uncongested Case

Vehicle	Direction	Traffic Condition	NO (mg)	% Difference (U-C)/C	HC (mg)	% Difference (U-C)/C	CO (mg)	% Difference (U-C)/C
Ford Taurus	North	Uncongested	193	10	143	6	2674	10
		Congested	176		135		2440	
	South	Uncongested	242	14	103	9	3421	5
		Congested	213		94		3264	
Chevrolet Venture	North	Uncongested	741	7	370	5	1928	-1
		Congested	691		353		1948	
	South	Uncongested	820	4	312	-2	830	-11
		Congested	791		318		929	

Table 10-24. Results of Pollutant Estimates for Chapel Hill Road based upon Congested Modal Rates and Trip Duration for the Congested Case

Vehicle	Direction	Traffic Condition	NO (mg)	% Difference (U-C)/C	HC (mg)	% Difference (U-C)/C	CO (mg)	% Difference (U-C)/C
Ford Taurus	North	Uncongested	196	9	188	4	3529	9
		Congested	180		180		3244	
	South	Uncongested	337	13	195	7	7614	4
		Congested	298		183		7286	
Chevrolet Venture	North	Uncongested	596	8	526	2	1691	0
		Congested	553		514		1695	
	South	Uncongested	917	7	476	-2	1570	-18
		Congested	857		484		1907	

in results between the two can be attributable to differences in the assumptions regarding travel time.

10.7.1.4 Summary of Sensitivity Analysis Findings

The key findings from Comparison Cases A, B, and C are as follows:

- There are differences in the absolute magnitude of emissions estimated from "uncongested" emission factor data versus those estimated from "congested" emission factor data, suggesting that differences in the observed uncongested and congested emission rates may substantially influence comparisons of total trip emissions.

- In general, the fraction of time spent in each driving mode differs between the uncongested and congested cases. The differences in the fraction of time spent in each driving mode may account for only a small portion of the changes in uncongested and congested emissions. However, there are exceptions to this, as in the cases for the Ford Taurus and Oldsmobile Cutlass northbound runs in the afternoon.
- The duration of the trip may have a substantial influence on emissions when comparing the uncongested and congested cases.

With the key insights obtained from sensitivity analysis, the empirical results of the uncongested and congested measurements are presented and interpreted.

10.7.2 Empirical Comparison of Traffic and Emissions for Uncongested and Congested Traffic Conditions

In this section, empirically observed values for traffic flow and emissions are summarized for the uncongested and congested cases on Chapel Hill Road. These observed values differ from the previous section in that total emissions were measured, not calculated, based upon the OEM-2100™ data collected in the field. The results are summarized in two tables which are as follows:

- ♦ Table 10-25 – North Runs,
- ♦ Table 10-26 – South Runs,

Table 10-25 shows a comparison of the northbound runs, with the AM and PM peaks representing uncongested and congested conditions, respectively. All of the traffic parameters (speed, control delay, and total stops) improved significantly in the uncongested case for both the Ford Taurus and the Chevrolet Venture.

For HC emissions for the Ford Taurus, the average observed change is a decrease of 29.4 percent in the uncongested case compared to the congested case. The average total emissions in the congested case are 91 mg/mi versus 64.3 mg/mi in the uncongested case. The difference is statistically significant because the p-value is 0.018, which is much smaller than the significance criterion of 0.05. The average speed of the trip increased by 118 percent, and the trip duration (as shown in Table 10-20) decreased by 56 percent. There is an decrease in percent of time spent in idle, and a increase in time

Table 10-25. Chapel Hill Road Traffic Congestion Comparison – North Runs

Quantity	Uncongested[1]: Average (Std. Error)	Congested[2]: Average (Std. Error)	% Difference (U-C)/C	Stat. Significant Difference?[3] (P-Value)
FORD TAURUS				
Speed, mph	33.3 (0.903)	15.3 (0.736)	+118%	Yes (0.000)
Control Delay, sec/mi	23.4 (2.97)	99.9 (7.89)	-76.5%	Yes (0.000)
Total Stops, stops/mi	0.603 (0.0831)	3.50 (0.248)	-82.7%	Yes (0.000)
HC, mg/mi	64.3 (6.10)	91.0 (9.21)	-29.4%	Yes (0.018)
NO, mg/mi	90.3 (9.0)	91.3 (9.0)	-1.18%	No (0.933)
CO, mg/mi	1279. (204.)	1734. (152.9)	-26.2%	No (0.080)
CHEVROLET VENTURE				
Speed, mph	35.7 (0.984)	15.1 (0.721)	+137%	Yes (0.000)
Control Delay, sec/mi	19.9 (2.65)	101.2 (7.78)	-80.3%	Yes (0.000)
Total Stops, stops/mi	0.616 (0.0714)	3.77 (0.281)	-83.6%	Yes (0.000)
HC, mg/mi	133. (8.67)	175. (10.9)	-23.7%	Yes (0.004)
NO, mg/mi	262. (18.5)	180. (12.5)	+45.8%	Yes (0.001)
CO, mg/mi	656. (209.)	533. (66.)	+23.08%	No (0.579)

Notes: 1. PM North before and after runs combined.
2. AM North before and after runs combined.
3. Statistically significant at 95% confidence level ($\alpha = 0.05$).

spent in other modes. If the emission factors had not changed between the before and after cases, a larger decrease of 54 percent would have been expected, as suggested in the sensitivity analyses presented in Tables 10-21 and 10-22. Thus, a robust finding in this case is that there is at least a significant decrease in HC emissions.

For NO emissions for the Ford Taurus, the observed decrease of 1.18 percent is statistically insignificant. If the emission factors had remained constant, the predicted decrease would have been 54 percent as given in Tables 10-21 and 10-22. From Table

10-20, it is apparent that the modal emission factors decreased substantially for the acceleration, deceleration, and cruise modes and increased slightly for idle mode in the congested case. There is 56 percent decrease in trip duration. Thus, a robust finding in this case is that NO emissions decreased, and that the increase likely would have been more than was empirically observed if there had been no change in modal emission rates.

The observed CO emissions for the Ford Taurus runs shown in Table 10-25 decreased by 26.2 percent, compared to a predicted decrease of 52 percent as indicated in Tables 10-21 and 10-22. The empirically observed change is not statistically significant. However, the results of the sensitivity analysis imply that the empirically observed decrease in CO emissions for the uncongested case compared to the congested case is expected.

There is a substantial decrease in modal emission rates for the after case as given Table 10-19. For example, there is approximately a 90 percent decrease in acceleration emission rate and a 67 percent decrease in cruise emission rate. Thus, the substantial decrease in modal emission rates are outweighed the substantial increase in trip duration. There was also a change in time spent in each driving mode. If the emission rates had remained constant, CO emissions would have increased. Overall, an increase in CO emissions would be expected. Thus, even though the empirically observed changes were not statistically significant, it is reasonable to assume that emissions would have increased for the Ford Taurus case if the uncongested and congested data could have been collected under the same ambient and vehicle conditions.

For the Chevrolet Venture runs of Table 10-25, all of the traffic parameters (speed, control delay, and total stops) worsened significantly in the congested case. For HC emissions for the Chevrolet Venture, the average observed change is a statistically significant increase of 23.7 percent in the congested case compared to the uncongested case. The average total emissions in the congested case are 175 mg/mi versus 133 mg/mi in the uncongested case. The average speed of the trip decreased by 137 percent, and the trip duration (as shown in Table 10-20) increased by 43 percent. There is an increase in percent of time spent in idle, and a slight increase in acceleration and deceleration modes, and a decrease in time spent in cruise mode. If the emission factors had not changed between the before and after cases, a larger increase of 58 percent would have been expected, as suggested in the sensitivity analyses presented in Tables 10-21 and 10-22. Thus, a robust finding in this case is that there is at least a significant increase in HC emissions.

For NO emissions for the Ford Taurus, the observed decrease of 45.8 percent is statistically significant. If the emission factors had remained constant, the predicted increase would have been 57 and 56 percent as given in Tables 10-21 and 10-22 respectively. From Table 10-20, it is apparent that the modal emission factors decreased substantially for the acceleration, deceleration, and cruise modes and decreased slightly for idle mode in the congested case. It is expected in this case that NO emissions would have increased if there had been no change in modal emission rates. The fact that a statistically significant result was observed to the contrary is not unexpected. There can be “false positive” results on occasion when using statistical methods.

The observed CO for the Chevrolet Venture emissions shown in Table 10-25 decreased by 23 percent, compared to a predicted increase of 60 percent as indicated in Tables 10-21 and 10-22. There is a substantial decrease in observed modal emission rates for the after case as given Table 10-20. Thus, the substantial decrease in modal emission rates are outweighed the substantial increase in trip duration. There was also a change in time spent in each driving mode. If the emission rates had remained constant, CO emissions would have increased. Overall, an increase in CO emissions would be expected. Thus, even though the empirically observed changes were not statistically significant, it is reasonable to assume that emissions would have increased for the northbound case if the before and after data could have been collected under exactly the same conditions.

Overall, there is statistically significant change in the traffic parameters for the northbound runs with both the Ford Taurus and Chevrolet Venture. The emission rates of all three pollutants for both vehicles would be expected to increase substantially if modal emission rates had remained constant. Changes in emission rates could be because of different environmental conditions between the congested and uncongested cases, or between the AM and PM runs.

Table 10-26 shows a comparison of the southbound runs, with the PM and AM time periods representing congested and uncongested conditions, respectively. As shown

Table 10-26. Chapel Hill Road Traffic Congestion Comparison – South Runs

Quantity	Uncongested[1]: Average (Std. Error)	Congested[2]: Average (Std. Error)	% Difference (U-C)/C	Stat. Significant Difference?[1] (P-Value)
FORD TAURUS				
Speed, mph	33.3 (0.976)	20.7 (1.42)	+60.9%	Yes (0.000)
Control Delay, sec/mi	22.2 (2.85)	68.4 (8.53)	-67.6%	Yes (0.000)
Total Stops, stops/mi	0.568 (0.0667)	2.31 (0.302)	-75.4%	Yes (0.000)
HC, mg/mi	45.8 (2.74)	88.4 (10.8)	-48.1%	Yes (0.001)
NO, mg/mi	111. (8.9)	150. (15.5)	-25.6%	Yes (0.037)
CO, mg/mi	1836. (365.4)	3547. (620.)	-48.2%	Yes (0.021)
CHEVROLET VENTURE				
Speed, mph	37.7 (1.17)	23.0 (1.44)	+63.8%	Yes (0.000)
Control Delay, sec/mi	19.9 (2.87)	50.9 (7.74)	-60.9%	Yes (0.000)
Total Stops, stops/mi	0.434 (0.0591)	2.19 (0.288)	-80.2%	Yes (0.000)
HC, mg/mi	114. (7.42)	159. (7.85)	-28.1%	Yes (0.000)
NO, mg/mi	292. (12.9)	265. (14.5)	+10.3%	No (0.164)
CO, mg/mi	290. (29.9)	537. (115)	-55.0%	Yes (0.047)

Notes: 1. AM South before and after runs combined.
2. PM South before and after runs combined.
3. Statistically significant at 95% confidence level ($\alpha = 0.05$).

in Table 10-26 traffic conditions worsened significantly in the congested case for the Ford Taurus. This caused a statistically significant increase in emissions in the congested case. For HC emissions for the Ford Taurus, the average observed change is a statistically significant increase of 48.1 percent in the congested case compared to the uncongested case. The average speed of the trip decreased by 63.8 percent, and the trip duration (as shown in Table 10-20) increased by 60 percent. There is an increase in percent of time spent in idle, a slight increase in acceleration and deceleration modes, and a decrease in cruise mode. Thus, a robust finding in this case is that there is a significant increase in HC emissions. Similar to HC emissions there are statistically significant increases in NO and CO emissions for the Ford Taurus in the southbound runs as expected from the change in traffic conditions.

For the Chevrolet Venture runs traffic conditions worsened significantly in the southbound runs. These changes caused a statistically significant increase of 28.1 percent in HC emissions in the congested case. The average speed of the trip decreased by 118 percent, and the trip duration (as shown in Table 10-20) increased by 44 percent. There is slight increase in percent of time spent in idle, acceleration, and deceleration modes, and a decrease in time spent in cruise mode. If the emission factors had not changed between the before and after cases, a larger increase of 45 percent would have been expected, as suggested in the sensitivity analyses presented in Tables 10-21 and 10-22.

For NO emissions in the southbound runs with the Chevrolet Venture there is an observed decrease of 10.3 percent in the congested case which is not statistically significant. If the emission factors had remained constant, the predicted increase would have been 42 and 40 percent as given in Tables 10-21 and 10-22 respectively. From Table 10-20, it is apparent that the modal emission factors decreased substantially for the acceleration, deceleration, and cruise modes and increased slightly for idle mode in the congested case. Thus, a robust finding in this case is that NO emissions would have increased if there had been no change in modal emission rates.

For CO emissions in the south runs with the Chevrolet Venture a statistically significant increase of 55 percent is observed, as shown in Figure 10-26. The predicted increase of 50 to 54 percent is nearly the same as the observed increase.

Overall, there is statistically significant change in the traffic parameters for the southbound runs with both the Ford Taurus and Chevrolet Venture. Emissions of all three pollutants are predicted to increase substantially. In some cases, the observed increases were not as large as predicted, and some decreases were observed. However, the observations are influenced by differences in modal emission rates that might be attributable to differences in ambient conditions or vehicle conditions. Overall, the key finding is that emissions of all three pollutants are likely to increase substantially when comparing uncongested and congested conditions.

10.8 Summary

This section presented an empirical before and after study of the effects of signal coordination and traffic congestion on vehicle emissions for one study corridor. There are a number of factors that can influence vehicle emissions if they change appreciably from the before to after runs. These factors were successfully controlled for the majority of pollutants, as the overall average modal emission rates were similar in the before and after cases for all pollutants for the Chevrolet Venture runs and for the Ford Taurus runs. However, when the data are subdivided by travel direction and time of day, there is more variability in the average modal emission rates, which makes comparison more complex.

The signal coordination plan for Chapel Hill Road did not statistically change the traffic measures (speed, delay, and stops) in the after runs, with the exception of degradation in traffic flow for the AM north runs. This resulted in generally insignificant changes in emissions. However, there were cases where changes in observed emission were statistically significant but in which there was no significant change in traffic conditions. For example, HC emissions decreased statistically significantly in the after case for the Ford Taurus PM South runs. In order to explain these cases a sensitivity analysis was conducted, which revealed that changes in modal emission rates and trip duration between the before and after cases are the main reasons for observing significant changes in emissions where there is no significant change in traffic condition. When the comparison is done using the same modal emissions for both the before and after cases, the predicted changes in emissions are typically less than 10 percent in magnitude, which is statistically insignificant. Overall, the key findings with respect to the change in signal timing and coordination on Chapel Hill Road are:

- there was not a significant improvement in traffic flow
- there was not a significant change in emissions

These findings suggest that Chapel Hill road is at capacity regardless of what signal timing and coordination plan is in place. The fact that there is not a significant change in emissions is expected if there is not a significant change in traffic flow.

Spatial analyses were conducted to observe changes in emissions spatially and at smaller areas within the corridor. It was found that emissions tend to increase with acceleration events. However, there were peak emissions that resulted from cruising or even deceleration events. The reason for this is the fact that average values were used for emissions and sometimes a small number runs might have a significant influence on the average. For example, it is possible that even though on average most vehicles were decelerating at a particular location, there may be a run in which a vehicle accelerates at that location and produces an emission rate much larger than for other measurements at that location. The key findings from the spatial analysis are:

- In the AM north direction, there is a bottleneck at Aviation Park way as revealed by an average speed much lower for vehicles before passing through this intersection compared to after they pass through the intersection.
- The signal at Airport Boulevard cased more delay after the signal coordination plan had been implemented.
- High average HC emissions occur at locations typically where vehicles accelerate from low to high speeds, such as at the 1.25 mile point in the study corridor.
- NO emissions have a peak at the 1.25 mile mark in the northbound direction both before and after the change in signal timing and coordination, corresponding to an increase from low average speed to high average speed at this bottleneck location.
- Average NO emissions also show peak near the 0.4 mile point in the southbound directions in both the before and after cases, corresponding to accelerations at this location.
- Average CO emissions are highest at the 1.25 mile point, similar to the case for NO emissions. This and many other average CO emission peaks are associated with increases in average speed at specific locations.
- In general, most peaks in emissions for all three pollutants occur at locations where accelerations take place. However, there are some locations where peaks in average emissions occur associated with no change or a decrease in average speed. Such situations may be influenced by short term accelerations that are averaged out over the 0.1 mile bins used in the analysis.
- Even though there may not be a statistically significant change in average emissions over the entire length of the corridor, there can be statistically

significant changes in average emissions at specific locations along the corridor.

Data for nonpriority runs were investigated to find the effect of traffic signal timing and coordination. There were only three statistically significant changes in emissions out of 18 cases considered. The main reason for not observing significant changes in the emissions and traffic conditions is due to the fact that there were a comparatively small number of data collected for nonpriority runs and because of the substantial run-to-run variability in emissions. No clear conclusion can be drawn regarding the effect of the change in signal timing and coordination on non-priority movements for this particular corridor. The fact that there was not a statistically significant change in average speed for nonpriority movements suggests that no significant change in nonpriority emissions is expected. The lack of statistically significant differences in emissions is consistent with this expectation.

Arranging the data into groups of congested and uncongested runs allowed a direct comparison of the effects of traffic congestion on vehicle emissions. When comparing uncongested traffic movement with congested traffic flow for the same travel direction, there were statistically significant changes in traffic parameters. The change in traffic flow was associated with significant changes in emissions of HC in all of the cases, and for NO and CO in most of the cases. Sensitivity analysis for these data revealed that changes in modal emission rates and trip duration between the uncongested and congested cases have a significant effect on the total emissions observed. Therefore, generally the observed changes in emissions that were insignificant were because of the changes in modal emission rates. In general, it is expected that emissions would have increased substantially for both vehicles, both travel directions, and all three pollutants if ambient and vehicle conditions could have been controlled. Thus, the key findings for the analysis of traffic congestion are:

- the average speed for uncongested traffic movement was approximately twice as high as the average speed for congested traffic movement.
- Control delay was 60 to 80 percent less for uncongested than congested traffic flow.

- The total number of stops per mile was approximately 75 to 80 percent less for uncongested than congested traffic flow.
- Emissions are predicted to decrease approximately 35 to 57 percent for NO, 37 to 58 percent for CO, and 40 to 60 percent for HC, if modal emission rates were constant.
- The observed variation in modal emissions between the congested and uncongested cases may be the result of some factors that are uncontrollable in an observational study such as this.
- Even when changes in emissions are compared based upon direct empirical observations that include differences in average modal emissions between the congested and uncongested cases, most of the comparisons show a statistically significant decrease in emissions for the uncongested case.

Overall, the results of the study of the Chapel Hill corridor show that this particular corridor did not benefit from the change in signal timing and coordination. The corridor has a bottleneck at Aviation Parkway. However, it was possible to observe differences in emissions at specific locations along the corridor. Furthermore, it was possible to compare the effect of congested and uncongested traffic flow in the same travel direction. In the latter case, there were significant differences in both traffic flow and emissions. The comparison of uncongested and congested traffic flow suggest the potential reduction in emission rates that could occur if measures could be implemented on this corridor to increase capacity and improve traffic flow. For example, a reduction in emissions of approximately 50 percent for each of NO, CO, and HC could be achieved if traffic flow could be improved from congested to uncongested. However, it is clear that traffic signal timing and coordination alone cannot achieve such an improvement during peak time periods on this particular corridor.

11.0 EMPIRICAL STUDY OF THE EFFECT OF SIGNAL COORDINATION ON VEHICLE EMISSIONS: WALNUT STREET CORRIDOR

This chapter is similar to Chapter 10, but focuses on a different corridor. Chapter 10 focused on a detailed presentation of the evaluation study done for the Chapel Hill Road corridor. This chapter focuses on a detailed presentation of the evaluation study done on the Walnut Street corridor. Both evaluation studies had the central objective of empirically evaluating the effects of changes in signal timing and coordination with respect to vehicle emissions. The emissions measurement methodology is addressed in Chapter 3. The data collection methodology is presented in Chapter 4. The experimental design is given in Chapter 5. Data reduction and screening is described in Chapter 6.

The Walnut Street corridor differs in significant ways from the Chapel Hill Road corridor. The Walnut Street corridor is not at capacity. The Walnut Street corridor has more traffic signals per mile and more high-intensity adjacent land uses (i.e., regional shopping mall, major retail stores) than the Chapel Hill Road corridor. Overall, Walnut Street is more suburban in nature than the more rural Chapel Hill corridor.

11.1 Factors Influencing Variability in Emissions

Section 7.0 identifies a number of factors that influence the variability in emissions. It is important in a before and after study to control as much as possible the factors not being specifically tested. For uncontrollable factors, such as ambient temperature, measurements were made.

On Walnut Street, the same four vehicles (Ford Taurus, Oldsmobile Cutlass, Toyota Camry, and Dodge Caravan) were driven in both the before and after cases, virtually eliminating any variability due to vehicle make and model.

Two additional factors that can affect vehicle emissions are ambient temperature and air conditioning use. Table 11-1 displays the change in these factors from the before to after runs. The ambient temperature decreased in the after runs, with mean decreases of eight degrees in the AM peak and 15 degrees in the PM peak. Results of ANOVA, in Section 7.2.3, indicated that ambient temperature is a significant parameter that affects vehicle emissions. However, air conditioner in use was not significant according to results given in Section 7.2.3.

Table 11-1. Weather Conditions on Walnut Street

Test Arterial	**Coordination**	**Experiment Dates**	**Mean Temperature**		**Percent of Runs with A/C On**	
			AM	**PM**	**AM**	**PM**
Walnut Street	Before	10/31/00-11/10/00	47°F	61°F	4.6%	33.3%
	After	11/30/00-12/13/00	39°F	46°F	0.0%	9.0%

11.2 Modal Emission Rates

The before and after modal emission rates help verify the comparability of the before and after emissions. Figure 11-1 compares the modal emission rates for the Ford Taurus and Oldsmobile Cutlass tested on Walnut Street. Figure 11-1 presents bar charts comparing the before and after modal emissions rates for both the 1999 Ford Taurus and the 1996 Oldsmobile Cutlass. These two vehicles were used as the primary vehicles on the Chapel Hill Road corridor. The emission rates are shown for three pollutants, HC, NO, and CO, and for four driving modes: idle, acceleration, deceleration, and cruise. The model emission rates were estimated as described in Section 6.4.1. The emission rates for each driving mode in the before and after cases, the percent difference between them and the result of a t-test of the means, including p-value, are reported in Table 11-2.

Overall, there is good agreement between the before and after modal emission rates. For example, the average HC deceleration emission rate for the Ford Taurus is 0.34 mg/sec in the before data set and 0.40 mg/sec in the after data set as given in Table 11-2. Although these averages differ by 18 percent, the difference is not statistically significant. The 95 percent confidence interval for the mean emission rate in the before case is 0.29 mg/sec to 0.38 mg/sec, and for the after case it is 0.34 mg/sec to 0.46 mg/sec. In this case, these two confidence intervals overlap, which is an indication of similarity in the two means. In addition, the means were compared using a t-test with a 0.05 significance level, and based upon this test there is no statistically significant difference in the means, where the p-value was found to be 0.10 as given in Table 11-2. Therefore, the HC deceleration mean emission rates are considered to be the same in both the before and after case. Thus, it appears that the vehicle is producing a similar emission rate for

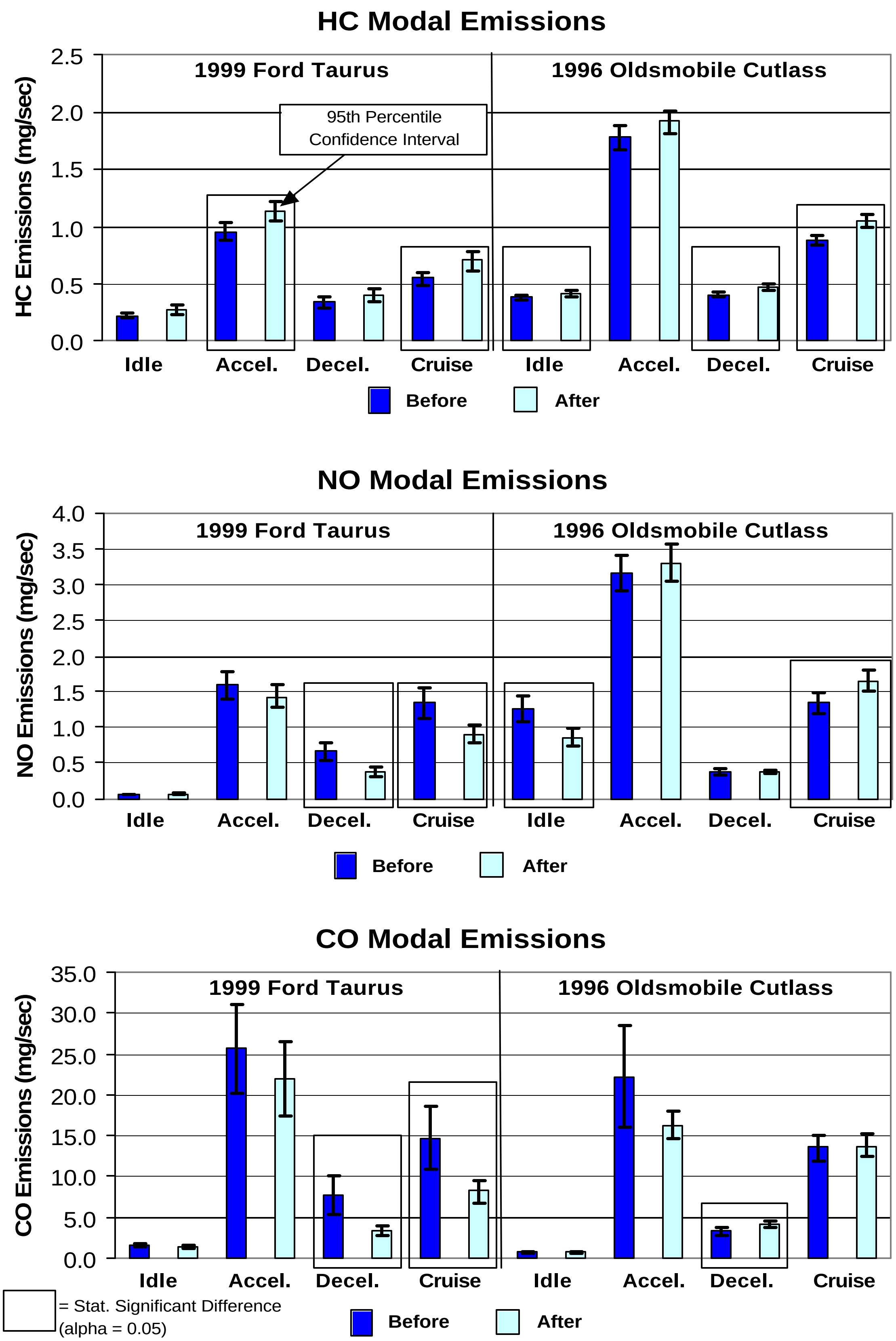


Figure 11-1. Walnut Street Modal Emission Rate

Table 11-2. Results of Before and After Modal Rates Comparison for Walnut Street

Vehicle	Driving Mode	Coord.	HC (mg/sec)	% Diff.	Stat. Sig. (p-value)	NO (mg/sec)	% Diff.	Stat. Sig. (p-value)	CO (mg/sec)	% Diff.	Stat. Sig. (p-value)
Ford Taurus	Idle	Before	0.22	23	No (0.06)	0.06	0	No (0.76)	1.6	-13	No (0.27)
		After	0.27			0.06			1.4		
	Accel.	Before	0.95	16	Yes (0.00)	1.6	-13	No (0.23)	26	-15	No (0.33)
		After	1.1			1.4			22		
	Decel.	Before	0.34	18	No (0.10)	0.66	-44	Yes (0.00)	7.1	-48	Yes (0.00)
		After	0.40			0.37			3.7		
	Cruise	Before	0.57	23	Yes (0.00)	1.3	-32	Yes (0.00)	15	-40	Yes (0.00)
		After	0.70			0.89			9		
Oldsmobile Cutlass	Idle	Before	0.38	11	Yes (0.02)	1.26	-32	Yes (0.00)	0.69	-6	No (0.49)
		After	0.42			0.86			0.65		
	Accel.	Before	1.8	6	No (0.07)	3.2	3	No (0.49)	22	-27	No (0.08)
		After	1.9			3.3			16		
	Decel.	Before	0.41	15	Yes (0.00)	0.38	0	No (0.99)	3.4	21	Yes (0.04)
		After	0.47			0.38			4.1		
	Cruise	Before	0.88	19	Yes (0.00)	1.3	23	Yes (0.00)	14	0	No (0.81)
		After	1.05			1.6			14		

the same driving mode in both the before and after case. Similar condition occurs for idle emissions where there is not statistically significant difference in before and after HC emissions. Overall, there was no significant difference in mean before modal emissions versus after modal emissions for 12 of the 24 comparisons shown in Figure 11-1 and Table 11-2.

There are some cases, shown in Figure 11-1 and Table 11-2, where there is statistical significance between before and after emissions rates. For example, the difference in mean HC emission rates for the acceleration mode for the 1999 Ford Taurus is statistically significant. In the before case average HC emission rate is 0.95 mg/sec, whereas it is 1.1 mg/sec in the after case. The 95 percent confidence interval for the mean emission rate in the before case is 0.88 mg/sec to 1.03 mg/sec, and for the after case it is 1.04 mg/sec to 1.22 mg/sec. There is a slight difference between the confidence intervals for the means. The percent difference between the average HC emission rates is 16 percent as given in Table 11-2. Although statistically significant, for practical purpose this is not a large difference. For four of the comparisons that had a statistically significant difference in the means, the difference was less than 20 percent. These include HC acceleration emissions for the Taurus, and HC idle, acceleration, and cruise emissions for the Cutlass. As a practical matter, these differences are not considered substantial.

There are some differences in before and after modal emissions that are statistically significant and that may also be substantial from a practical perspective. There are eight cases in Table 11-2 where there are absolute differences of 21 to 48 percent. Of the 12 cases where differences were not statistically significant, two have absolute differences of greater than 20 percent, including one with a difference of minus 27 percent for CO emissions during acceleration for the Cutlass. Therefore, it is plausible that differences of approximately 20 to 30 percent, even though statistically significant, may not be substantial from a practical perspective. Thus, when combining the number of cases for which there was not a statistically significant difference in emissions with those for which the differences were statistically significant but less than an absolute value of approximately 30 percent, there are 19 out of the 24 comparisons that do not appear to be either significantly and/or substantially different.

There are five differences which were found to be statistically significant and for which the absolute percentage difference exceeded 30 percent. These include deceleration and cruise emissions of both NO and CO for the Ford Taurus, and idle NO emissions for the Oldsmobile Cutlass. In all five of these cases, the "after" emission rates were lower than the before emission rates by as much as 32 to 48 percent. In some of these cases, the confidence intervals for the mean emission rates are relatively large. For example, for the NO cruise emission rate for the Taurus, the 95 percent confidence interval for the before case is from 1.1 mg/sec to 1.5 mg/sec, and in the after case it is from 0.8 mg/sec to 1.0 mg/sec. These confidence intervals do not overlap, which is consistent with the finding that these two means are statistically significantly different from each other. However, the intervals are not very far apart. The low end of the before interval is separated from the high end of the after interval by an increment of only 0.1 mg/sec. Thus, although the mean difference is 32 percent, the difference may be as low as 11 percent.

For the five cases where the differences in mean emissions exceeded an absolute difference of 30 percent, it is not possible to conclude that the observed differences are not substantial. It may be the case that there are real differences in some of the modal emission rates of the after case when compared to the before case. The specific cause of such differences cannot be precisely determined. It is possible that such differences may be because of differences in the condition of the vehicle at the time of the after study compared to the time of the before study. The vehicles were obtained from a motor pool, and the investigators did not have direct control over vehicle operation, maintenance and repair during the intervening time between the before and after studies. It is also possible that some complex combination of differences in ambient conditions could lead to differences in emission rates.

Overall, when comparing the before and after modal emissions for the two primary vehicles used in the before and after study on Walnut Street, it is clear that in half of the comparisons of mean modal emissions there is not a statistically significant difference and that for 19 of the 24 comparisons there is not a practically substantial difference. In five of the 24 cases, there does appear to be a substantial difference. Because this was an observational study, it was not possible to control every single possible factor that may affect vehicle emissions. Although it is hypothesized that modal emissions should be similar in the before and after studies, differences may arise because of factors not under the direct control of the investigators.

In order to understand the implications of differences in before and after mean modal emission rates with respect to evaluation of the efficacy of changes in traffic signal timing and coordination, a detailed sensitivity analysis was performed as described later in Section 11.4.1. The purpose of the sensitivity analysis was to determine what differences in total emissions would be expected if the modal emissions were the same in both the before and after cases. Furthermore, the sensitivity analysis helps provide insight into which of the following key factors has the most influence with respect to comparison of total emissions: (1) modal emission rates; (2) fraction of time spent in each mode; and (3) trip duration. Thus, although it is not possible to completely control the modal emission rates so that they are same in the observed data set, it is possible to perform calculations and sensitivity analysis to understand whether the observed changes in modal emissions lead to different conclusions than would have been obtained if the modal emissions had remained constant.

11.3 Signal Coordination Improvements

The NCDOT implemented a signal coordination plan on Walnut Street between Dillard Drive and Cary Towne Boulevard in mid-November 2000. As described previously, the progression of vehicles through a signal system can be improved through introducing a greenband and by increasing the proportion of green time given to the primary movements. Because a high number of signals (nine) were being coordinated together, it was not practical to implement a system-wide greenband (where vehicles can progress through the entire system without stopping). Rather, a series of local greenbands were introduced that allowed vehicles to progress through a portion of the corridor without stopping but not the entire corridor. The green times for the primary movements were increased at the majority of intersections. Figure 11-2 shows the change in green times at each intersection after the signal coordination plan was implemented. Overall, the green times increased 11 percent in the northbound direction of the AM peak, eight percent in the northbound PM peak runs, 14 percent in the southbound AM peak runs, and 20 percent in the southbound PM peak runs.

11.4 Corridor-Level Results

The changes in traffic parameters and vehicle emissions on a corridor-level due to signal coordination were examined for both the Ford Taurus and Oldsmobile Cutlass on Walnut Street. The Toyota Camry and Dodge Caravan were not included in this analysis due to the small number of runs collected. Table 11-3 shows the total runs collected for each vehicle on Walnut Street.

This section is divided into two major subsections. Section 11.4.1 features a detailed sensitivity analysis of the before and after comparison. The sensitivity analysis is based on three key sets of data: (1) modal emission rates for each vehicle, time of day, and direction of travel for both the before and after cases; (2) the fraction of total trip time spent in each of the driving modes for each vehicle, time of day, and direction of travel; and (3) the trip duration for each vehicle, time of day, and direction of travel. These three sets of data were analyzed to determine which of the three most significantly affect estimates of total trip emissions and comparisons of the before and after emissions. The key insights obtained from sensitivity analysis are summarized. Subsequently, in

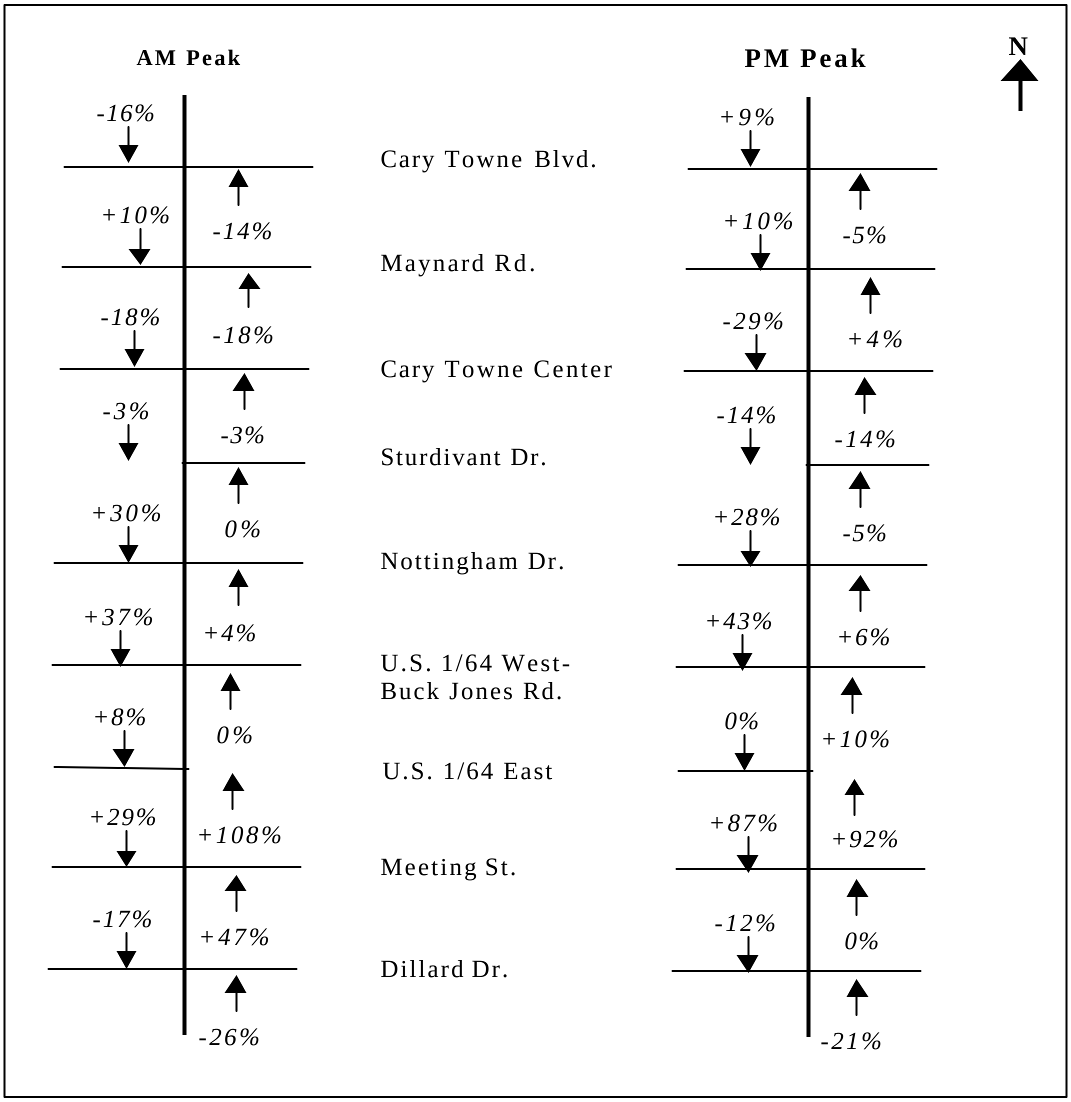


Figure 11-2. Change in Percentage of Green Time with Signal Coordination Plan on Walnut Street

Section 11.4.2, the results of the empirically observed traffic flow and emissions measurements for both the before and after cases are presented. These results are interpreted based upon the insights obtained from the sensitivity analysis presented in Section 11.4.1.

Table 11-3. Number of Runs on Walnut Street

Vehicle	Coordination	AM Peak		PM Peak	
		North	South	North	South
Ford Taurus	Before	24	24	22	24
	After	24	25	16	19
Oldsmobile Cutlass	Before	25	25	21	22
	After	23	23	22	23
Toyota Camry	Before	0	0	4	3
	After	0	0	4	5
Dodge Caravan	Before	5	5	0	0
	After	5	5	0	0

11.4.1 Sensitivity Analysis of Emission Factors, Distribution of Time in Driving Modes, and Total Trip Duration

The purpose of this section is to understand the influence of selected factors with respect to their potential contribution to changes in emissions when comparing before and after cases, as previously shown for Chapel Hill Road. Specifically, can differences in emissions in the before versus after cases be attributable to: (1) differences in modal emission rates; (2) differences in the distribution of time spent in each driving mode; and/or (3) differences in the trip duration? The analysis methodology described in Section 10.4.1 is utilized in this section to answer these questions.

Three comparisons are described in Table 11-4. Each of the three comparisons employs the specific time distribution of driving modes applicable to the before or after cases. Comparison Case A assumes that the average modal emission rates observed in the before case are also applicable to the after case. Conversely, Comparison Case B assumes that the average modal emission rates observed in the after case are applicable to the before case. The purpose of Cases A and B are to determine whether there is any significant difference in comparisons of total estimated before and after emissions that might be attributable to variation in modal emission rates. Case C focuses on the influence of trip duration. In comparison to both Cases A and B, which each assume the trip durations specific to the before and after cases, Case C assumes that the trip duration is the same in both the before and after cases. When the results of all three cases are compared and evaluated, it may be possible to determine whether modal emission rates, time distribution of modes, or trip duration either individually or in aggregate play an

Table 11-4. Study Design: Evaluation of Modal Emission Rates, Time Distribution of Modes, and Trip Duration With Respect to Before and After Comparisons for Walnut Street

Comparison Case	**Key Factors**	**Before Case Assumptions**	**After Case Assumptions**
A: Before Modal Emissions	Modal Emission Rates	Before	Before
	Time Distribution of Modes	Before	After
	Trip Duration	Before	After
B: After Modal Emissions	Modal Emission Rates	After	After
	Time Distribution of Modes	Before	After
	Trip Duration	Before	After
C: Same Trip Duration	Modal Emission Rates	Before	Before
	Time Distribution of Modes	Before	After
	Trip Duration	Average[a]	Average[a]

[a]Average refers to an average of both the before and after trip durations.

important role in potential differences between total emissions in the before and after cases. Insight obtained from these comparisons will be used to help explain the results of observed emissions differences presented in the Section 11.4.2.

The key data needed for the three comparison cases include the modal emission rates, the time distribution of modes, and the trip duration. These data are given in Table 11-5 for modal emission rates and Table 11-6 for the time distribution and the trip duration. Table 11-5 illustrates that for each vehicle, direction, and time of day, there are differences in modal emission rates when comparing the before and after cases. For example, the CO emission rate during acceleration for the Ford Taurus in the PM South case is 19 mg/sec before and 20 mg/sec after the change in signal timing and coordination. In this particular example, the difference in the modal emission rates is relatively small and is insignificant. However, for the AM North case for the Ford Taurus, the acceleration emission rate is 27 mg/sec in the before case and 16 mg/sec in the after case. This difference appears to be more substantial than for the idle case even though it may also be statistically insignificant. Thus, there is some variability in the observed modal emission rates when comparing the before and after cases. A key

Table 11-5. Modal Emission Rates for Emissions in the Before and After Cases for Walnut Street

Vehicle	Peak Time	Direc.	Coord.	Idle (mg/sec)			Accel. (mg/sec)			Decel. (mg/sec)			Cruise (mg/sec)		
				NO	HC	CO	NO	HC	CO	NO	HC	CO	NO	HC	CO
Ford Taurus	AM	North	Before	0.08	0.20	1.60	1.4	0.88	27	0.58	0.31	11	1.0	0.49	13
			After	0.07	0.29	1.50	1.2	1.05	16	0.31	0.39	2.4	0.64	0.64	6.5
		South	Before	0.06	0.17	1.2	1.8	0.87	33	0.69	0.28	5.8	1.6	0.48	16
			After	0.05	0.17	0.79	1.9	1.1	28	0.45	0.39	4.3	1.1	0.72	10
	PM	North	Before	0.07	0.30	1.8	1.4	1.2	23	0.75	0.42	8.0	1.6	0.69	18
			After	0.08	0.32	1.6	1.4	1.3	26	0.47	0.50	4.6	1.0	0.88	9.3
		South	Before	0.04	0.22	1.7	1.7	0.92	19	0.64	0.35	5.7	1.2	0.55	11
			After	0.04	0.24	1.20	1.3	1.1	20	0.24	0.36	2.4	0.85	0.67	7.4
Olds. Cutlass	AM	North	Before	1.1	0.37	0.67	3.5	1.8	18	0.34	0.39	3.9	1.6	0.91	16
			After	0.77	0.46	0.75	2.9	2.07	17	0.39	0.52	5.1	1.9	1.2	16
		South	Before	0.96	0.31	0.55	3.2	1.6	28	0.37	0.37	3.6	1.5	0.87	13
			After	0.74	0.36	0.71	3.4	2.0	18	0.38	0.46	4.0	2.0	1.1	14
	PM	North	Before	1.6	0.45	0.86	3.3	2.03	28	0.42	0.47	3.6	1.2	0.90	14
			After	0.85	0.46	0.66	2.9	1.9	19	0.37	0.50	5.1	1.5	1.02	15
		South	Before	1.5	0.40	0.70	2.7	1.6	15	0.40	0.40	2.3	1.1	0.83	10
			After	0.95	0.41	0.51	3.8	1.8	12	0.36	0.42	2.7	1.4	0.91	11

question is whether this variability may by itself be able to explain any observed differences in the total emissions when comparing the before and after cases.

Table 11-6 provides data regarding the average observed percentage of time spent in each driving mode, and the average observed trip duration, for each vehicle, time, and direction combination for both the before and after cases. These values may be important in helping to understand changes in total emissions that occurred when comparing the before and after cases.

For example, there is what appears to be a large change in modal time rates for the Ford Taurus driven in the PM peak time in the North direction. In the before case idling comprised approximately 36 percent of the total trip time, whereas in the after case idling comprised approximately 16 percent of the total trip time. There was an increase in the observed portion of total trip time spent in the rest of the modes, acceleration, deceleration, and cruise modes. The differences in the portion of time spent in idle and cruise modes seem substantial. There appears to be substantial differences in the

Table 11-6. Percent of Time Spent in Different Driving Modes for Walnut Street Data

Vehicle	Time/ Direction	Coord	Percent Time in Each Mode				Trip Duration (sec)	Change in Duration of Trip (%)
			Idle	Accel.	Decel.	Cruise		
Ford Taurus	AM North	Before	24.6	26.1	18.2	31.1	336	-14
		After	15.5	22.0	16.5	46.0	288	
	AM South	Before	21.5	25.6	19.1	33.9	300	-24
		After	8.6	21.1	15.7	54.6	227	
	PM North	Before	35.7	22.4	17.2	24.6	433	-23
		After	16.1	25.6	18.5	39.8	332	
	PM South	Before	29.3	22.1	18.1	30.5	365	0.3
		After	29.2	22.5	17.2	31.1	366	
Oldsmobile Cutlass	AM North	Before	23.8	27.4	21.4	27.4	359	-16
		After	15.2	25.0	19.7	40.2	302	
	AM South	Before	15.3	25.5	20.3	38.9	292	-17
		After	7.2	24.4	18.6	49.8	243	
	PM North	Before	32.4	23.0	19.6	25.0	456	-21
		After	13.8	25.4	21.4	39.4	359	
	PM South	Before	25.2	22.9	20.3	31.6	387	-0.9
		After	25.4	22.3	19.9	32.5	383	

observed average trip duration. In the before case, the average trip duration was 433 seconds, whereas in the after case it was 332 seconds, a decrease of 23 percent.

In order to evaluate the influence of modal emission rates, time distribution of modes, and changes in trip duration, the model developed in Section 10.4 is utilized. In this simple model the total trip emissions of a pollutant is given by the product of the total trip duration and a weighted average emission factor in units of mass of pollutant emitted per unit time. The weighted average emission factor is calculated based upon the sum of the products of the fraction of time spent in each mode multiplied by the respective modal emission factor. Comparisons of before and after emissions are estimated based upon each of the three cases described in Table 11-4.

11.4.1.1 Comparison Case A: Modal Emissions Held Constant at "Before" Values with Variation in Time Distribution of Modes and in Total Travel Time

The results for Comparison Case A are given in Table 11-7. Table 11-7 presents the emissions estimated using the before modal rates for different peak time/direction and vehicle combinations for both the before and after cases.

Table 11-7 gives both the emission estimates in total milligrams and percent differences between the before and after cases. The percent change in emissions ranges from 23 percent decrease to 2 percent increase. The largest change occurred for NO emissions for the Oldsmobile Cutlass for PM North case with a 23 percent decrease as shown in Table 11-7. In Table 11-7, change in emissions between the before and after cases are due to change in percent time spent in different driving modes and change in total duration of trips since modal rates were the same in estimating emissions for both the before and after cases.

11.4.1.2 Comparison Case B: Modal Emissions Held Constant at "After" Values with Variation in Time Distribution of Modes and in Total Travel Time

Since there is some difference in the modal emission rates when comparing the before and after values, it was deemed important to perform an analysis similar to Comparison Case A but using the "after" modal emission rates instead of the "before" emission rates. Thus, Table 11-8 presents the emissions estimated using the after modal rates for different peak time/direction and vehicle combinations.

Table 11-8 gives both the emission estimates in total milligrams units and also percent differences between the before and after cases. The largest percent change in emissions occurred for the Ford Taurus for AM South case with a 20.2 percent decrease as shown in Table 11-8. The percent change in emissions ranges from 20.2 percent decrease to 2 percent increase.

The percentage changes estimated in Table 11-7 are different from those estimated in Table 11-8, since two different sets of modal emission factors were used. For example, for HC emissions in the AM South case for the Ford Taurus, total estimated trip emissions decreased by 20 percent when "before" emission factors were used and by 17 percent when "after" emission factors where used. In general, the estimates of percent changes were typically within four percentage points of each other for all but three cases. The largest difference between the two estimates of percentage change in emissions was nine percentage points for the case of NO emissions for the PM north case for the

Table 11-7. Results of Pollutant Estimates for Walnut Street based upon Before Modal Rates

Vehicle	Peak Time	Direction	Coord.	NO (mg)	Percent Change in NO	HC (mg)	Percent Change in HC	CO (mg)	Percent Change in CO
Ford Taurus	AM	North	Before	274	-6.5	164	-12	4510	-11
			After	256		144		4008	
		South	Before	341	-10	142	-20	4591	-17
			After	307		114		3820	
	PM	North	Before	375	1.9	264	-12	5111	-1.9
			After	382		231		5013	
		South	Before	319	1.2	183	1.0	3337	1.2
			After	323		185		3378	
Oldsmobile Cutlass	AM	North	Before	619	-15	330	-13	3750	-3.9
			After	524		288		3604	
		South	Before	467	-15	258	-13	3828	-10.2
			After	397		226		3436	
	PM	North	Before	748	-23	424	-12	4944	-2.6
			After	575		371		4816	
		South	Before	547		319		2845	
			After	540	-1.3	315	-1.4	2814	-1.1

Table 11-8. Results of Pollutant Estimates for Walnut Street based upon After Modal Rates

Vehicle	Peak Time	Direction	Coord.	NO (mg)	Percent Change in NO	HC (mg)	Percent Change in HC	CO (mg)	Percent Change in CO
Ford Taurus	AM	North	Before	196	-9.0	207	-12	2381	-13
			After	178		183		2079	
		South	Before	287	-14.0	194	-17	3448	-20.2
			After	247		161		2753	
	PM	North	Before	288	-2.0	307	-10.6	4117	-7.5
			After	282		275		3810	
		South	Before	217	1.6	217	1.1	2765	1.6
			After	220		219		2810	
Oldsmobile Cutlass	AM	North	Before	565	-10.8	397	-12	3732	-3.8
			After	504		348		3589	
		South	Before	537	-12	319	-12	3179	-7.7
			After	474		281		2933	
	PM	North	Before	634	-14	433	-11	4279	0.6
			After	546		384		4303	
		South	Before	629	-1.6	341	-1.4	2728	-0.8
			After	619		336		2706	

Oldsmobile Cutlass. However, in all cases, the direction of the change was estimated to be the same, except two cases. Thus, if emissions were estimated to decrease when "before" emission factors were used, they were also estimated to decrease if "after" emission factors were used. Two cases where there were differences in the direction of change were NO emissions for PM North runs for the Ford Taurus and CO emissions for the Oldsmobile Cutlass in PM North runs. However, in these two cases, the estimated differences were less than an absolute value of three percent, which indicates no substantial change. Thus, the change in sign of these comparisons is not a substantial concern.

Overall, the results of Comparison Cases A and B suggest that there are substantial similarities in the estimates of relative changes in after versus before trip average emissions regardless of which set of modal emission factors are used. This suggests that the relative differences among the modes are similar in the after case when compared to the before case, even though the absolute value of the modal emission rates may differ. For example, consider the comparison of before and after emissions for HC emissions from the Ford Taurus in the morning peak period and the northbound direction. In Comparison Cases A and B, the difference was found to be -12 percent. Thus, the same relative difference in emissions was estimated. However, the absolute value of the trip emissions was different in the two cases. For Comparison Case A, the total before emissions were estimated to be 164 mg versus 207 mg for Comparison Case B. Thus, it appears possible to obtain robust estimates of relative differences in emissions even though the absolute value of emissions may differ substantially.

11.4.1.3 Comparison Case C: Modal Emissions Held Constant at "Before" Values with Variation in Time Distribution of Modes and with Total Travel Time Constant

In order to assess the potential importance of the distribution of driving modes with respect to before and after comparisons, Comparison Case C was developed in which both the emission factors and the total travel time were held constant and in which only the fraction of time spent in each mode was allowed to vary between the before and after cases. As revealed by Comparison Cases A and B, there are some differences in the modal emissions factors for the before and after cases. Therefore, this analysis was applied using both the before and after emission factors. Trip durations for each direction and peak time combination for the before case were used for estimating total emissions in Table 11-7, and trip durations for each direction and peak time combination for the after case were used for estimating total emissions in Table 11-8. The trip durations and before and after modal time fractions were obtained from Table 11-6. The results of the comparison are shown in Table 11-7 and Table 11-8, using the before modal emission rates and the after emission rates, respectively.

The results in Table 11-9 are substantially different than the results in Table 11-7. There are differences in the estimated in the percentage difference between the before and after cases. For example, there is 8.9 percent increase in NO emissions for the Ford Taurus in the morning northbound direction as given in Table 11-9, whereas there is a decrease of 6.5 percent as reported in Table 11-7. There is a difference of 15.4 percentage points between these two results. The percentage differences in between the before and after cases are less than plus or minus 10 percent in most cases, compared to much larger differences from Comparison Cases A and B. For example, six of the 24 comparisons shown in Table 11-9 yield differences greater than plus or minus 10 percent, while 13 of the 24 comparisons in Table 11-7 exceed this range. Comparison of Table 11-10 to Table 11-8 also reveals the same finding. Eight of the 24 comparisons shown in Table 11-10 yield differences greater than plus or minus 10 percent, while 12 of the 24 comparisons in Table 11-8 exceed this range. The relatively small differences in before and after emissions predicted when only the fraction of time spent in each mode is allowed to vary between the before and after cases suggests that the comparisons of before and after are not strongly sensitive to the time distribution of the modes.

A second key finding is that the change in trip duration between the before and after cases is an important factor affecting comparisons. Since Comparison Cases A and C, as well as Cases B and C both use the same emission factor data and the same assumptions regarding changes in the fraction of time spent in each mode, the differences in results between the two can be attributable to differences in the assumptions regarding travel time.

Table 11-9. Results of Pollutant Estimates for Walnut Street based upon Before Modal Rates and Trip Duration for the Before Case

Vehicle	Peak Time	Direction	Coord.	NO (mg)	Change in NO (%)	HC (mg)	Change in HC (%)	CO (mg)	Change in CO (%)
Ford Taurus	AM	North	Before	274	8.9	164	2.7	4510	3.6
			After	299		168		4671	
		South	Before	341	19	142	6.2	4591	9.9
			After	405		150		5044	
	PM	North	Before	375	33	264	14	5111	28
			After	498		302		6543	
		South	Before	319	0.9	183	0.7	3337	0.95
			After	322		184		3369	
Oldsmobile Cutlass	AM	North	Before	619	0.8	330	3.6	3750	14
			After	624		342		4290	
		South	Before	467	2.4	258	5.2	3828	8.06
			After	478		271		4136	
	PM	North	Before	748	-2.4	424	11	4944	24
			After	730		471		6113	
		South	Before	547	-0.4	319	-0.5	2845	-0.21
			After	545		318		2839	

Table 11-10. Results of Pollutant Estimates for Walnut Street based upon After Modal Rates and Trip Duration for the After Case

Vehicle	Peak Time	Direction	Coord.	NO (mg)	Change in NO (%)	HC (mg)	Change in HC (%)	CO (mg)	Change in CO (%)
Ford Taurus	AM	North	Before	168	6.0	178	3.0	2043	1.7
			After	178		183		2079	
		South	Before	217	13.6	147	9.9	2611	5.4
			After	247		161		2753	
	PM	North	Before	221	27.9	235	16.7	3154	20.8
			After	282		275		3810	
		South	Before	217	1.3	217	0.8	2773	1.4
			After	220		219		2810	
Oldsmobile Cutlass	AM	North	Before	475	6.2	333	4.4	3136	14.4
			After	504		348		3589	
		South	Before	446	6.2	265	6.0	2641	11.1
			After	474		281		2933	
	PM	North	Before	499	9.4	341	12.4	3371	27.7
			After	546		384		4303	
		South	Before	623	-0.7	338	-0.5	2705	0.1
			After	619		336		2706	

11.4.1.4 Summary of Sensitivity Analysis Findings

The key findings from Comparison Cases A, B, and C are as follows:

- There are differences in the absolute magnitude of emissions estimated from "before" emission factor data versus those estimated from "after" emission factor data, suggesting that differences in before and after emission rates, although not statistically significant on a mass per time basis, may substantially influence comparisons of total trip emissions.
- In general, the fraction of time spent in each driving mode is similar in the before and after cases. The relatively modest differences in the fraction of time spent in each driving mode may account for only a small portion of the changes in before and after emissions. However, there are exceptions to this, as in the cases for the Ford Taurus and Oldsmobile Cutlass northbound runs in the afternoon.
- The duration of the trip may have a substantial influence on emissions when comparing the before and after cases.

With the key insights obtained from sensitivity analysis, the empirical results of the before and after measurements are presented and interpreted.

11.4.2 Empirical Comparison of Traffic and Emissions Before and After a Change in Signal Timing and Coordination

In this section, empirically observed values for traffic flow and emissions are summarized for the before and after measurements on Walnut Street. These observed values differ from the previous section in that total emissions were measured, not calculated, based upon the OEM-2100^{TM} data collected in the field. The results are summarized in four tables which are as follows:

- Table 11-11 – AM Peak Ford Taurus Runs,
- Table 11-12 – AM Peak Oldsmobile Cutlass Runs,
- Table 11-13 – PM Peak Ford Taurus Runs,
- Table 11-14 – PM Peak Oldsmobile Cutlass Runs.

Table 11-11. Walnut Street AM Peak Before and After Coordination Results – Ford Taurus

Quantity	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
AM NORTH				
Speed, mph	23.9 (0.952)	27.2 (0.268)	+13.9%	Yes (0.002)
Control Delay, sec/mi	55.6 (4.95)	33.7 (1.33)	-39.4%	Yes (0.000)
Total Stops, stops/mi	1.83 (0.161)	1.29 (0.0488)	-29.7%	Yes (0.003)
HC, mg/mi	73.5 (5.15)	81.0 (6.43)	+10.3%	No (0.365)
NO, mg/mi	121.9 (9.5)	78.5 (8.62)	-35.6%	Yes (0.002)
CO, mg/mi	1936. (339.)	918. (131.)	-52.6%	Yes (0.009)
AM SOUTH				
Speed, mph	26.6 (0.890)	35.1 (0.982)	+31.6%	Yes (0.000)
Control Delay, sec/mi	43.9 (4.01)	16.1 (2.76)	-63.3%	Yes (0.000)
Total Stops, stops/mi	1.49 (0.104)	0.591 (0.103)	-60.2%	Yes (0.000)
HC, mg/mi	63.7 (5.89)	71.8 (5.88)	+12.7%	No (0.138)
NO, mg/mi	147. (21.5)	110. (10.8)	-24.9%	No (0.336)
CO, mg/mi	2034. (468.)	1247. (167.)	-38.7%	No (0.124)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

As shown in Table 11-1, all of the traffic parameters (speed, control delay, and total stops) improved significantly after signal coordination. This indicates the signal coordination plan worked effectively in progressing vehicles through the corridor. There is statistically significant decrease in NO and CO emissions in the northbound direction. However, the change in HC emissions is not statistically significant, and there were no statistically significant changes in emissions in the southbound case.

For HC emissions in the morning northbound direction, the observed change is an increase of 10.3 percent in the after case compared to the before case. The total emissions in the after case are 81.0 mg/mi versus 73.5 mg/mi in the before case. The difference is not statistically significant because the p-value is 0.365, which is much larger than the significance criterion of 0.05. The average speed of the trip increased by 14 percent, and the trip duration (as shown in Table 11-6) decreased by 14 percent. The distribution of time spent in each driving mode shifted from less idling to more cruising, with some increases also in the time spent in acceleration and idling. If the emission factors had not changed between the before and after cases, a slight decrease in emissions would have been expected, as suggested in the sensitivity analyses presented in Tables 11-7 and 11-8. However, in this case, the average modal emission rates for all four modes were larger in the after case than in the before case. Thus, the observed increase in HC emissions can be attributed to an observed increase in the modal emission rates. The observed increase of 10.3 percent is not statistically significant. The predicted decrease of 12 percent from Tables 11-7 and 11-8 is similarly modest and not substantial. Thus, a robust finding in this case is that there is not a substantial change in HC emissions, either positive or negative.

For NO emissions in the northbound case of Table 11-11, the observed decrease of 35.6 percent is statistically significant. If the emission factors had remained constant, the predicted decrease would have been only 6.5 to 9.0 percent per the estimates of Tables 11-7 and 11-8, respectively. From Table 11-5, it is apparent that the modal emission factors decreased substantially in the after case, which accounts for the observed decrease being larger than the predicted decrease. Thus, a robust finding in this case is that NO emissions decreased, but that the decrease likely would have been less than what was observed if the before and after measurements could have been taken instantaneously, without any changes in vehicle or environmental conditions.

The northbound observed CO emissions shown in Table 11-11 decreased by 53 percent, compared to a predicted decrease of only 11 to 13 percent as indicated in Tables 11-7 and 11-8, respectively. The observed modal emission rates for CO were substantially lower in the after case compared to the before case, as indicated in Table 11-5. Thus, most of the observed decrease in CO emissions is attributable to a change in the modal emission rates.

In the southbound cases of Table 11-11, there are no statistically significant observed changes in emissions of HC, NO, or CO. From Tables 11-7 and 11-8, these three pollutants are predicted to decrease by approximately 12 percent, 18 percent, and 18 percent, respectively. The observed decreases in NO and CO are larger than the predicted decreases. For NO, there seems to be a modest decrease in the average observed emission factor, whereas for CO the decrease is more pronounced and accounts for the larger observed decrease in trip emissions. For HC, the observed emissions increased even though the predicted emissions would decrease. For HC, the acceleration, deceleration, and cruise emission factors were found to be larger in the after case than in the before case. Overall, the expected change in emissions for these three pollutants is modest. Although the observed changes in emissions are not statistically significant, a modest decrease in emissions would be expected based upon the results shown in Tables 11-7 and 11-8.

Overall, the results of Table 11-11, when interpreted based upon the sensitivity analyses in Tables 11-7 and 11-8 and the modal emission rate data in Table 11-5, suggest that modest decreases in emissions of all three pollutants are expected in both the northbound and southbound directions. In all cases, there are large enough differences in the modal emission rates of the before and after cases that the observed differences in trip emissions are potentially misleading if not properly interpreted. In general, there is an improvement in traffic flow accompanied by modest (e.g., 10 to 20 percent) reductions in pollutant emissions. The reduction in pollutant emissions can also be attributed to changes in trip duration when comparing the before and after cases. In general, the travel time is less because the average speed has increased.

Table 11-12. Walnut Street AM Peak Before and After Coordination Results–Oldsmobile Cutlass

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
AM NORTH				
Speed, mph	23.9 (0.771)	28.2 (0.584)	+17.6%	Yes (0.000)
Control Delay, sec/mi	62.8 (5.48)	39.1 (2.27)	-37.7%	Yes (0.000)
Total Stops, stops/mi	1.90 (0.148)	1.34 (0.0769)	-29.2%	Yes (0.002)
HC, mg/mi	144. (7.81)	152. (8.40)	+5.6%	No (0.49)
NO, mg/mi	266. (20.5)	220. (10.7)	-17.3%	No (0.054)
CO, mg/mi	1630. (163.)	1560. (139.)	-4.4%	No (0.74)
AM SOUTH				
Speed, mph	29.2 (0.837)	35.0 (0.874)	+19.8%	Yes (0.000)
Control Delay, sec/mi	36.4 (3.33)	18.2 (2.33)	-49.9%	Yes (0.000)
Total Stops, stops/mi	1.11 (0.112)	0.605 (0.0853)	-45.7%	Yes (0.001)
HC, mg/mi	113. (5.01)	123. (8.27)	+9.6%	No (0.27)
NO, mg/mi	200. (11.1)	211. (12.9)	+5.7%	No (0.51)
CO, mg/mi	1590. (236.)	1260. (107.)	-20.6%	No (0.22)

Notes: 1. Statistically significant at 95% confidence level (a = 0.05).

Table 11-12 shows the observed changes in traffic flow and emissions for the Oldsmobile Cutlass during the AM peak period in both the north and south directions. Overall, there are statistically significant improvements in traffic flow. The observed changes in emissions are not statistically significant. For four of the observed changes in emissions, the absolute difference between the before and after case is less than 10 percent. Although in some cases the observed differences in emissions suggest an increase, the predicted changes in all six emissions cases are for modest decreases, based upon the sensitivity analyses reported in Tables 11-7 and 11-8. For example, HC emissions in the northbound case are observed to increase 5.6 percent. However, the predicted change is a 12 to 13 percent decrease if the modal emission factors had remained constant. The observed modal emission factors increased somewhat for all four driving modes. Thus, the difference between the observed change and the predicted change can be attributed to a change in the modal emission factors. Overall, the predicted changes are a decrease of approximately 10 to 15 percent in the emissions of all three pollutants for both directions, with the exception of CO in the northbound case. This latter one is predicted to decrease only approximately 4 percent, which is consistent with the observed change. Overall, there is an improvement in traffic flow and a modest improvement expected in emissions for all three pollutants if the modal emission rates remained constant.

The results for the afternoon measurements with the Ford Taurus are shown in Table 11-13. Overall, there is an improvement in traffic flow only in the northbound direction. There is barely any change in traffic flow in the southbound direction. In all cases, there is no statistically significant change in emissions observed for any of the three pollutants. The observed changes in emissions range from a decrease of as much as 30 percent to an increase of as much as 24 percent. In contrast, the predicted changes based upon Tables 11-7 and 11-8 are for decreases of as much as 11 percent to increases of as much as 2 percent. For the northbound case, a decrease of approximately 12 percent was predicted for HC. The observed increase in HC is explained by an observed increase in the modal emission rates. Thus, if the modal emission rates had remained constant, there would have been an observed decrease. For NO, the emissions were predicted to be approximately the same (a change of between -2 percent and 2 percent) versus an observed decrease of 25 percent. The deceleration and cruise modal emissions rates for NO decreased substantially which explains the observed difference. For CO, the expected decrease would be approximately 5 percent versus an observed decrease of 23 percent. Even though the acceleration modal emission rate for CO increased by approximately 10 percent, the other three modal emission rates decreased substantially leading to the observed difference. For the southbound direction, the expected changes in emissions are in the range of one to two percent increases, which are

Table 11-13. Walnut Street PM Peak Before and After Coordination Results – Ford Taurus

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
PM NORTH				
Speed, mph	18.4 (0.551)	23.7 (0.487)	+28.7%	Yes (0.000)
Control Delay, sec/mi	87.2 (5.34)	39.0 (3.97)	-55.2%	Yes (0.000)
Total Stops, stops/mi	2.23 (0.122)	1.58 (0.104)	-29.4%	Yes (0.000)
HC, mg/mi	117. (12.7)	121. (17.6)	+3.4%	No (0.854)
NO, mg/mi	165. (18.1)	124. (14.8)	-25.0%	No (0.086)
CO, mg/mi	2201. (424.)	1684. (418.)	-23.0%	No (0.401)
PM SOUTH				
Speed, mph	22.0 (0.788)	21.6 (0.748)	-1.8%	No (0.71)
Control Delay, sec/mi	65.6 (6.08)	62.6 (5.00)	-4.6%	No (0.70)
Total Stops, stops/mi	1.52 (0.143)	1.49 (0.134)	-2.3%	No (0.86)
HC, mg/mi	80.7 (7.97)	100.4 (11.4)	+24.4%	No (0.167)
NO, mg/mi	143. (18.3)	100.0 (11.4)	-30.2%	No (0.052)
CO, mg/mi	1483. (261.)	1278. (209.)	-13.8%	No (0.543)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

very small. The observed changes are much larger than the predicted changes, but can be attributable to differences in modal emission rates.

Overall, the improvements in traffic flow observed with the Ford Taurus n the northbound direction during the afternoon are expected to result in either no change in emissions, as in the case of NO, or very modest 5 to 10 percent decreases in emissions in the case of CO and HC, respectively. For the southbound direction, essentially no change in emissions is expected.

Table 11-14. Walnut Street PM Peak Before and After Coordination Results – Oldsmobile Cutlass

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat. Significant Difference?[1] (P-Value)
PM NORTH				
Speed, mph	18.8 (0.474)	24.3 (0.823)	+29.2%	Yes (0.000)
Control Delay, sec/mi	95.7 (6.07)	42.6 (3.60)	-55.5%	Yes (0.000)
Total Stops, stops/mi	2.34 (0.114)	1.66 (0.168)	-29.0%	Yes (0.002)
HC, mg/mi	187. (13.0)	165. (6.74)	-12.0%	No (0.14)
NO, mg/mi	330. (28.7)	239. (21.4)	-27.4%	Yes (0.016)
CO, mg/mi	2150. (422.)	1830. (138.)	-14.9%	No (0.48)
PM SOUTH				
Speed, mph	22.8 (0.719)	22.4 (0.766)	-1.8%	No (0.70)
Control Delay, sec/mi	61.2 (4.92)	66.4 (4.58)	+8.5%	No (0.44)
Total Stops, stops/mi	1.68 (0.108)	1.49 (0.125)	-11.1%	No (0.27)
HC, mg/mi	139. (8.36)	147. (7.02)	+5.7%	No (0.47)
NO, mg/mi	229. (20.8)	266. (22.3)	+16.0%	No (0.24)
CO, mg/mi	1230. (149.)	1190. (124.)	-3.8%	No (0.81)

Notes: 1. Statistically significant at 95% confidence level ($\alpha = 0.05$).

For the Oldsmobile Cutlass, the observed traffic flow improved in the northbound direction during the afternoon peak but did not change significantly in the southbound direction, as shown in Table 11-14. The findings are qualitatively similar to those for the Ford Taurus. There was only one observed change in emissions that was statistically significant, which was a 27 percent decrease in CO for the northbound direction. The observed decrease is approximately consistent with the predicted decreases of 23 percent and 14 percent, from Tables 11-7 and 11-8, respectively. The observed CO modal emission rates changed only modestly between the before and after cases, with slight increases in idle and acceleration and decreases in deceleration and cruise.

The observed change in HC emissions in the northbound direction, although not statistically significant, is the same as the predicted change of approximately a 12 percent decrease. For HC, it is concluded that there is a very modest decrease. The observed change in NO emissions is not significant. The very high p-value of 0.48 suggests that the expected absolute change could be much closer to zero than the observed 15 percent decrease in emissions. The predicted change is from a decrease of 3 percent to an increase of almost one percent. Thus, for NO, it is concluded that there is essentially no change.

For the southbound direction, the observed changes in HC and CO emissions are very small and are associated with very high p-values of 0.47 and 0.81, respectively. Furthermore, the predicted changes for these two pollutants are decreases of only approximately one percent. Thus, there is essentially no change in HC and CO emissions. For NO emissions, the observed increase of 16 percent has a p-value of 0.24. by comparison, the predicted change is a decrease of one percent. Here, again, the observed change is consistent with a finding of no real change in emissions.

Overall, the Cutlass experienced a modest decrease in HC and CO emissions in the northbound direction, and no change in emissions in the southbound direction.

In summary, both vehicles reveal the same patterns with respect to traffic flow and emissions. In the morning, there are significant improvements in traffic flow in both directions. In the afternoon, traffic flow improved in the northbound direction. There was no change in traffic flow in the southbound direction. Emissions generally tended to decrease when traffic flow improved, although there are some examples in which emissions essentially remain unchanged even when there was an improvement in traffic flow. When traffic flow did not improve, there was no substantial change in emissions.

11.5 Micro-Level Results

A micro-level spatial analysis of the Walnut Street runs was performed using the same methodology explained for the Chapel Hill Road spatial analysis. The spatial analysis allows a closer look at changes occurring in vehicle emissions along the corridor due to signal coordination.

Figure 11-3 shows spatial analysis graphs of Ford Taurus AM peak runs on Walnut Street both before and after signal coordination. Figure 11-4 shows spatial graphs of Oldsmobile Cutlass PM peak runs.

Trends in emissions were, in general, similar to the findings for Chapel Hill Road. CO emissions are affected mainly from the acceleration events, and peak CO emissions occur at locations where sharp acceleration occurs for both the Ford Taurus and he Oldsmobile Cutlass runs.

Although, NO emissions are affected by acceleration events, there are cases where peaks occur at locations where a decrease in average speed occurs, especially for the Oldsmobile Cutlass runs. For example, at the 0.3-mile point for the northbound before case there is a peak in NO emissions that corresponds to a decrease in average speed, as shown in Figure 11-4. Similar results are observed for the after runs in the north runs, and both before and after runs in the south direction for the Oldsmobile Cutlass runs.

HC emissions are affected by acceleration and deceleration events; however, peak HC emissions mainly occur at locations where there is a deceleration event as in the case for Chapel Hill Road. Data for this analysis are averaged over mileage driven. Over the averaging distance of 0.1 mile multiple driving modes can occur. An acceleration event that occurred in one second might have a high effect on emissions although its effect on speed might be negligible. Therefore, the findings observed in this study cannot be used directly for comparison to driving mode analysis.

An important application of the spatial analysis is to identify points along the corridor where signal coordination has a significant effect on vehicle emissions. This was done by performing Student's-t tests on individual bins (each bin is 0.1 mile) or groups of bins where the before and after emissions data differed on the spatial graphs. Figure 11-5 displays the same spatial graphs of Oldsmobile Cutlass runs as shown in Figure 11-4, with the sections highlighted that show a statistically significant difference between the before and after runs. Appendix V displays similar graphs for all combinations of vehicle make and model, peak hour, and direction of travel.

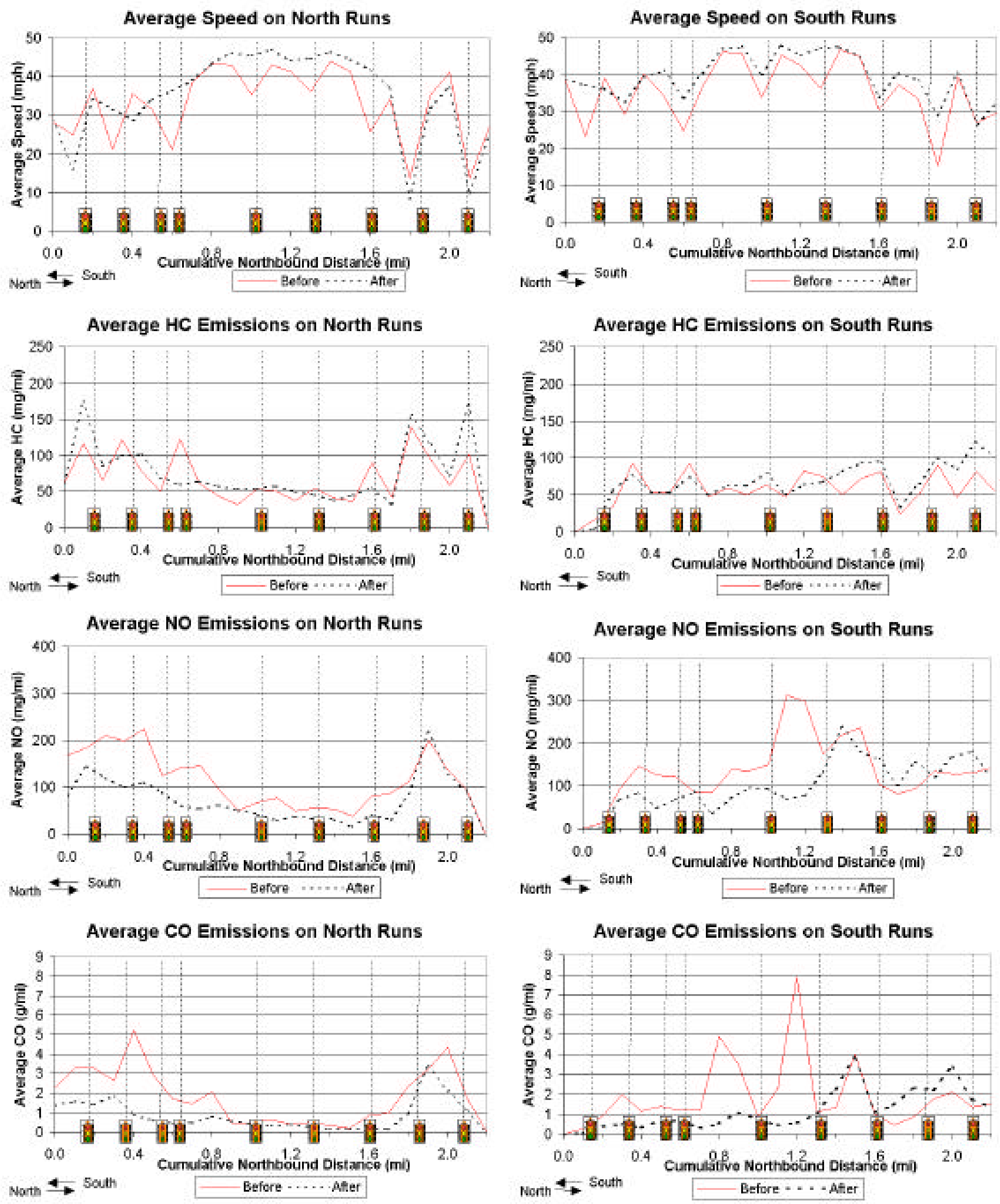


Figure 11-3. Spatial Analysis of Ford Taurus AM Peak Runs on Walnut Street

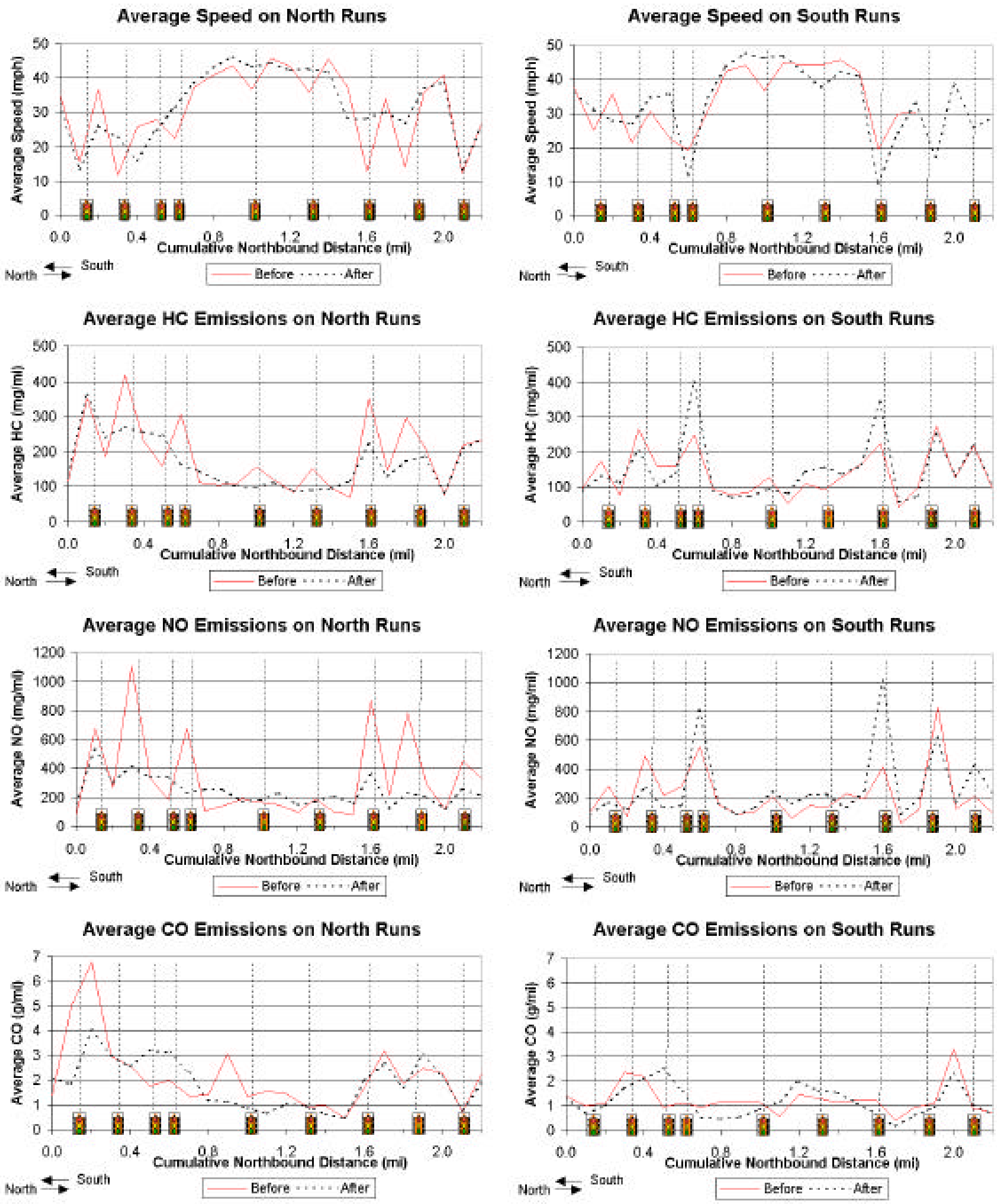


Figure 11-4. Spatial Analysis of Oldsmobile Cutlass PM Peak Runs on Walnut Street

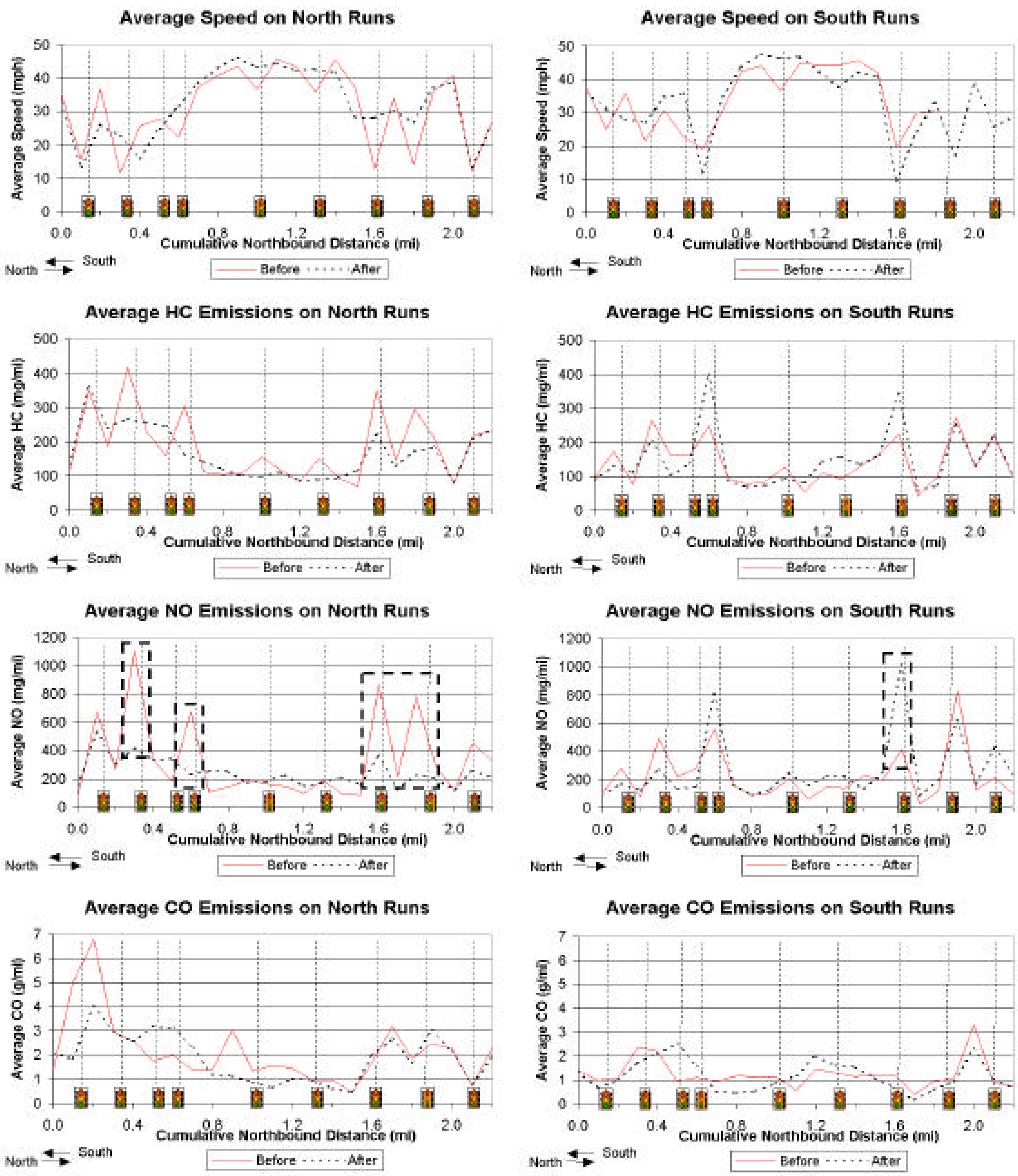


Figure 11-5. Spatial Analysis of Oldsmobile Cutlass PM Peak Runs on Chapel Hill Road with Statistically Different Sections Highlighted

As shown in Figure 11-5, a number of small sections show local statistically significant differences in the before and after runs even when corridor-level average is not statistically different. An analysis of the differences in before and after emissions on a micro-level was completed by determining the magnitude of change in emission spikes and whether the changes were statistically significant.

As shown in Table 11-15, a number of small areas on the Walnut Street corridor experienced statistically significant differences in before and after emission rates, even though the corridor-level average did not change at a statistically significant level. Specifically, two small areas changed significantly for HC emissions, six small areas changed for NO emissions, and four for CO emissions.

A number of the emissions differences were not statistically significant despite a large percentage change. For example, the 77.5 percent decrease for the emissions spike with the Oldsmobile Cutlass AM south runs was not statistically significant. Figure 11-6 shows a CDF graph of the before and after emissions for this spike, with each point representing one run. Similar CDF graphs are shown in Appendix V for all emission spikes investigated in Table 11-15.

As shown in Figure 11-6, the reason for the before average value is higher is primarily due to three outlying runs that produced CO emissions higher than 20 grams/mile. Without these three runs, the before and after CO emissions would have been very similar for this section of the Walnut Street corridor.

Outlying runs, where the average emissions for a small area were exceptionally higher than the other runs, were identified for all of the cases which are given in Table 11-15. A total of 16 runs with exceptionally high emissions spikes were identified. It is important to understand why these runs produced such a high emissions spike because often these spikes compose a high proportion of the total corridor-average emissions.

For these 16 runs, a number of potential explanatory factors were investigated, including the roadway grade, proximity to a traffic signal, and likelihood of whether the vehicle producing the emissions spike was at the front of the queue waiting at a traffic signal. Research for the in-development MEASURE model has found that vehicles at the front of a queue produce higher emissions than vehicles further back in a queue because

Table 11-15. Summary of Changes in Emissions Before and After Signal Coordination on Walnut Street

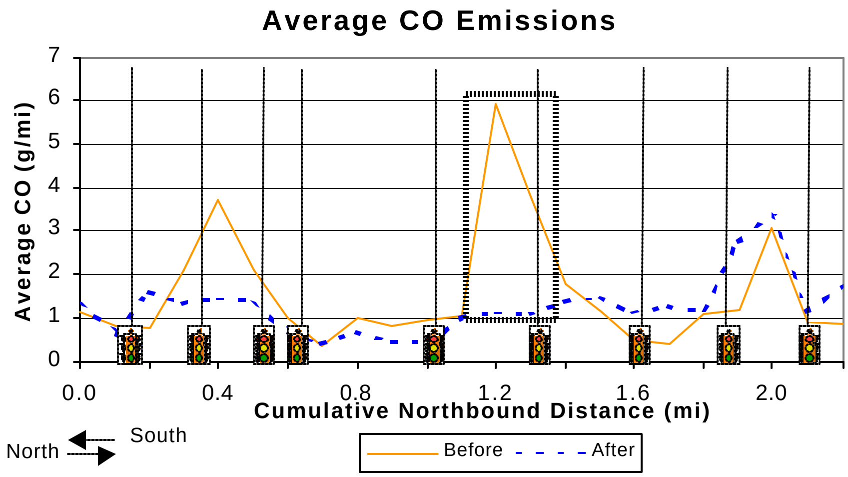
Vehicle: Peak & Direction	Corridor-Level % Change (Stat. Signif.?)[1]	Micro-Level Location[2]	Micro-Level % Change[3]	Micro-Level Stat. Signif.?[4] (P-Value)
HC Emissions				
Taurus: AM North	+10.3% (No)	None	-	-
Taurus: AM South	+12.7% (No)	None	-	-
Taurus: PM North	+3.4% (No)	0.3	-56.2%	Yes (0.004)
Taurus: PM South	+24.4% (No)	1.6	+108.2%	Yes (0.008)
Cutlass: AM North	+5.6% (No)	None	-	-
Cutlass: AM South	+9.6% (No)	None	-	-
Cutlass: PM North	-12.0% (No)	None	-	-
Cutlass: PM South	+5.7% (No)	None	-	-
NO Emissions				
Taurus: AM North	-35.6% (Yes)	N/A	N/A	N/A
Taurus: AM South	-24.9% (No)	1.0-1.1	-59.9%	Yes (0.0003)
Taurus: PM North	-25.0% (No)	None	-	-
Taurus: PM South	-30.2% (Yes)	N/A	N/A	N/A
Cutlass: AM North	-17.3% (No)	0.3-0.6	-47.1%	Yes (0.000)
Cutlass: AM South	+5.7% (No)	None	-	-
Cutlass: PM North	-27.4% (Yes)	0.3 0.6 1.6-1.8	-62.3% -66.1% -61.3%	Yes (0.005) Yes (0.048) Yes (0.000)
Cutlass: PM South	+16.0% (No)	1.6	+16.2%	Yes (0.001)
CO Emissions				
Taurus: AM North	-52.6% (Yes)	N/A	N/A	N/A
Taurus: AM South	-38.7% (No)	0.7-1.1	-81.7%	Yes (0.0005)
Taurus: PM North	-23.0% (No)	0.3-0.6 1.1 1.8-2.1	-61.1% +376% -59%	Yes (0.003) No (0.27) No (0.06)
Taurus: PM South	-13.8% (No)	None	-	-
Cutlass: AM North	-4.4% (No)	0.2-0.3	+96.6%	Yes (0.003)
Cutlass: AM South	-20.6% (No)	0.4-0.5 1.2-1.3	-47.7% -77.5%	Yes (0.02) No (0.10)
Cutlass: PM North	-14.9% (No)	0.1-0.2	-50.3%	No (0.18)
Cutlass: PM South	-3.8% (No)	None	-	-

Notes: N/A = No analysis was performed because the corridor-level average change was statistically significant.

1. More detailed corridor-level results shown in Tables XX through XX.
2. In miles from beginning of south end of corridor.
3. Calculated as (After value – Before value)/Before value.
4. Statistically significant at 95% confidence level ($\alpha = 0.05$).

they are not following a vehicle and can thus accelerate more quickly and travel at a higher speed (Bachman, 1999).

There was no clear correlation between roadway grade and these emission spikes. Of the 16 outlying emissions spikes, 14 occurred adjacent to a traffic signal. The queue



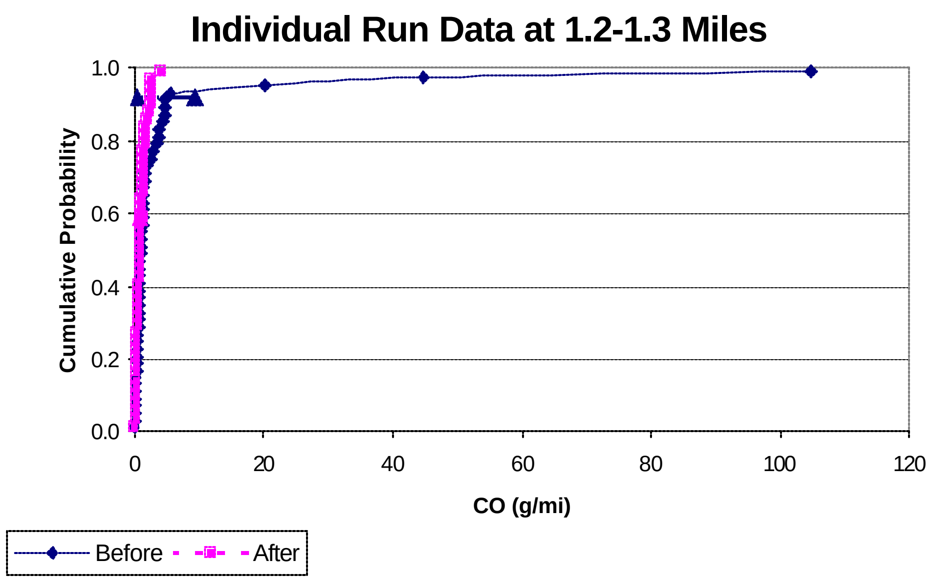
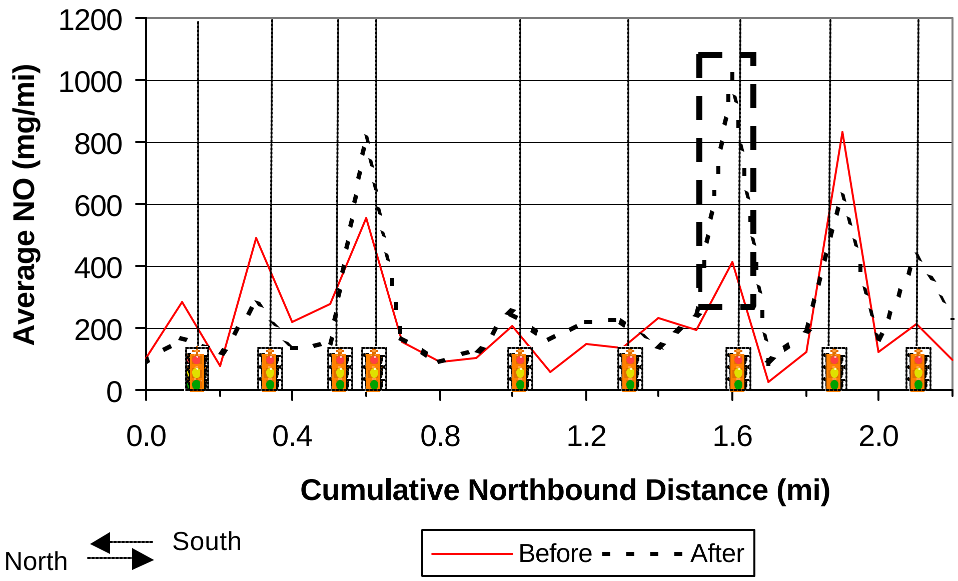


Figure 11-6. Spatial and CDF Graphs of Oldsmobile Cutlass AM South Runs on Walnut Street

position during a run was estimated by comparing the times when the vehicle passed the center of the intersection and the time when the green phase began. Not all corridor runs recorded timestamps for the beginning of the green phase. Of the 14 emission spikes occurring adjacent to a traffic signal, seven of them had timestamps where green phase was recorded during the run. Of these seven runs, the test vehicle was within the first three vehicles in the queue at the signal where the outlying emissions spike occurred. Thus, this limited data set indicates that there may be some correlation



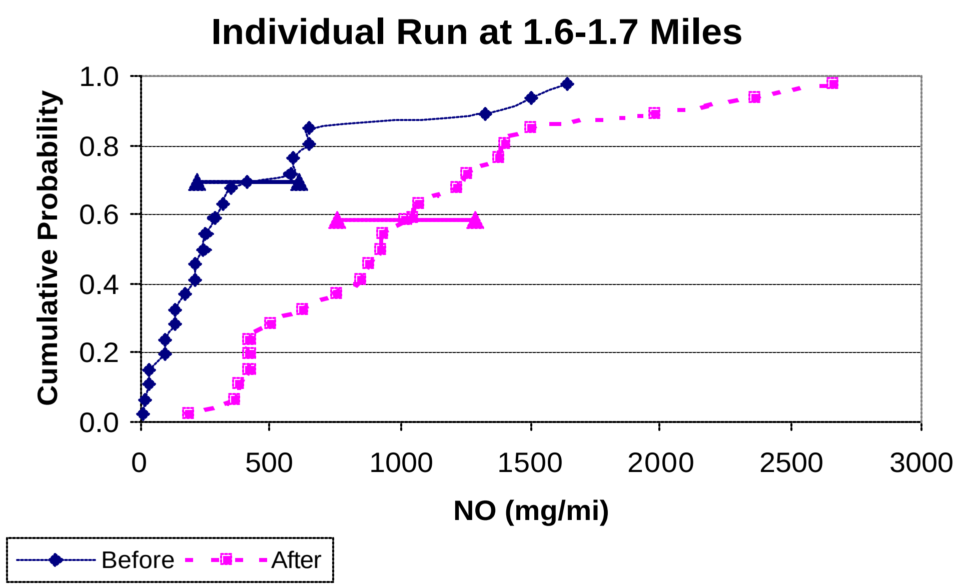


Figure 11-7. Spatial and CDF Graphs of Oldsmobile Cutlass PM South Runs on Walnut Street

between an emissions spike occurring when a vehicle is at the beginning of the queue at a traffic signal. Figure 11-7 shows another CDF graph of the before and after emissions for a spike shown in the spatial distribution graph for CO emissions. As shown in Figure 11-7, the CDFs for the before and after cases are substantially different from each other. The CDF for the after case generally has larger values of emissions for a given percentile than for the after case.

11.6 Non-Priority Movement Results

The non-priority movements (side street and turning movements) were analyzed to understand the effect of signal coordination on emissions. Figure 11-8 shows the non-priority routes driven on Walnut Street. Table 11-16 displays the number of non-priority runs driven on Walnut Street.

Fewer runs were completed with the non-priority runs compared to the priority runs. Table 11-16 shows the number of non-priority runs completed on Walnut Street. A non-priority run is defined where a vehicle enters corridor from a side street and exits corridor to another side street at the next intersection (i.e. S1 in Figure 11-8).

Number of non-priority runs given in Table 11-16 is a combination of different side street runs. For example, 7 runs were completed with 1999 Ford Taurus on Chapel Hill for AM North. This number is sum of N1, N2, and N3 runs collected in AM peak time with this particular vehicle.

Table 11-17 through Table 11-20 show the run-level changes in traffic parameters and vehicle emissions before and after signal coordination was implemented. The tables are arranged as follows:

Table 11-17 – AM Peak Ford Taurus runs

Table 11-18 – AM Peak Oldsmobile Cutlass runs

Table 11-19 – PM Peak Ford Taurus runs,

Table 11-20 – PM Peak Oldsmobile Cutlass runs.

As shown in Table 11-17, the AM north and AM south speeds decreased approximately 17 percent. This is not unexpected because the signal coordination plan allocated more green time to the priority movements, which thus caused less green time for the non-priority movements. There was not a statistically significant change in NO or CO emissions. However, there is a statistically significant increase in HC emissions for both the AM north and AM south HC emissions. To examine the reason for this significance CDFs are plotted for before and after cases for HC emissions in Figure 11-9 for the AM North case.

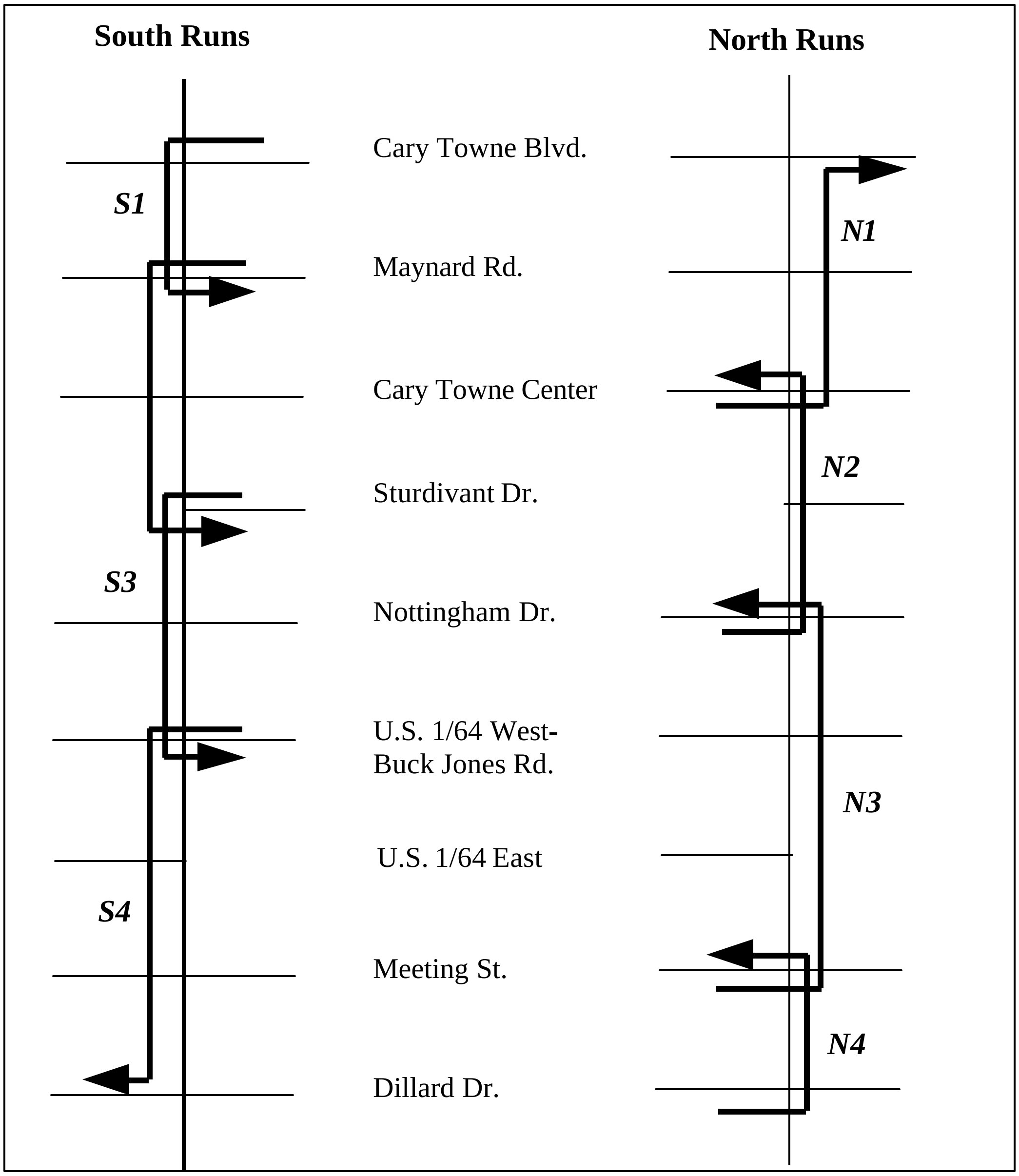


Figure 11-8. Non-Priority Runs on Walnut Street

Table 11-16. Number of Non-Priority Runs on Walnut Street

Peak – Direction	Ford Taurus		Oldsmobile Cutlass	
	Before	**After**	**Before**	**After**
AM North	7	8	12	11
AM South	10	6	12	12
PM North	11	8	7	9
PM South	10	10	8	7

Table 11-17. Walnut Street Ford Taurus AM Peak Non-Priority Runs

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat, Signif.? (P-Value)
AM NORTH				
Speed, mph	17.1 (3.51)	14.2 (2.15)	-17.0%	No (0.496)
HC, mg/mi	116. (27.4)	216. (34.8)	+86.6%	Yes (0.042)
NO, mg/mi	112. (37.6)	143. (19.1)	+28.0%	No (0.477)
CO, mg/mi	3453. (1034.)	2262. (645.8)	-34.5%	No (0.351)
AM SOUTH				
Speed, mph	15.8 (2.04)	13.1 (1.56)	-17.6%	No (0.294)
HC, mg/mi	87.3 (10.8)	197. (32.5)	+125.6%	Yes (0.018)
NO, mg/mi	70.2 (13.8)	136. (33.7)	+93.9%	No (0.115)
CO, mg/mi	1328. (328.)	2182. (528.)	+64.3%	No (0.203)

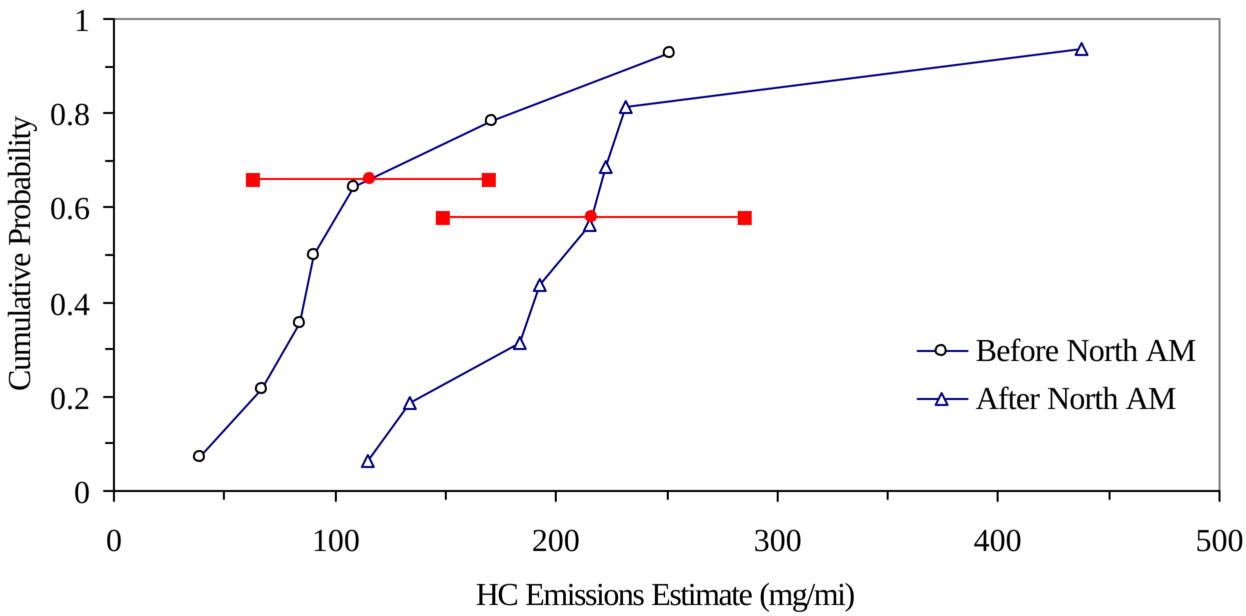


Figure 11-9. Comparison of Cumulative Distribution Functions for Before and After HC Emissions for 1999 Ford Taurus Driven on Walnut Street for AM North Non-Priority Runs

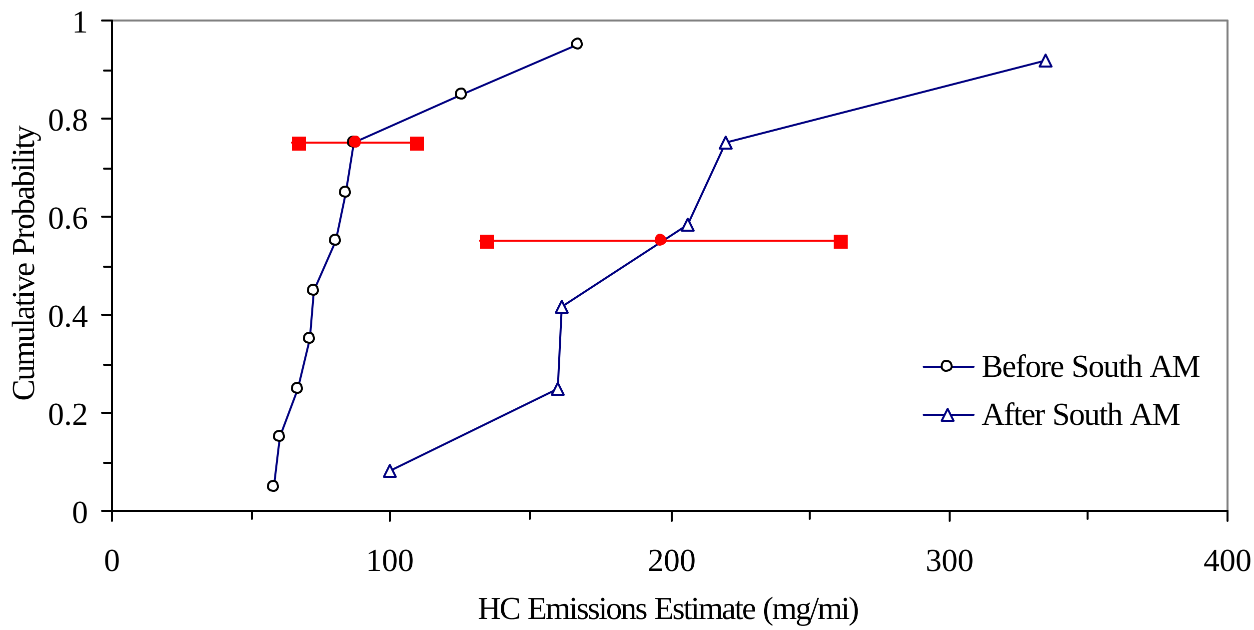


Figure 11-10. Comparison of Cumulative Distribution Functions for Before and After HC Emissions for 1999 Ford Taurus Driven on Walnut Street for AM South Non-Priority Runs

The CDFs for the before and the after cases, in Figure 11-9, are different from each other. The CDF for the after case generally has larger values of emissions for a given percentile than for the before case. However, excluding the highest HC emission data for before case could yield a statistically insignificant comparison. When the highest HC emission data is excluded, the t-test gave a statistically insignificant comparison, with a p-value of 0.06.

Figure 11-10, shows a comparison of the distribution of before emissions versus that of after emissions for the AM South case. The CDF for the after case generally has larger values of emissions for a given percentile than for the before case. However, there is one value of HC emissions in the after case which is higher than the rest of the data. However, even exclusion of this data point gave a statistically significant difference between the before and after runs for AM South case, with a p-value of 0.02. This result indicates that there is a statistically significant increase in HC emissions for AM South case.

Table 11-18. Walnut Street Oldsmobile Cutlass AM Peak Non-Priority Runs

Measure	**Before: Average (Std. Error)**	**After: Average (Std. Error)**	**% Difference (A-B/B)**	**Stat, Signif.? (P-Value)**
AM NORTH				
Speed, mph	19.3 (2.44)	13.8 (1.60)	-28.6%	No (0.073)
HC, mg/mi	230. (21.9)	316. (26.7)	+37.3%	No (0.051)
NO, mg/mi	526. (70.7)	647. (57.1)	+23.1%	No (0.055)
CO, mg/mi	2059. (413.)	2295. (270.)	+11.5%	No (0.088)
AM SOUTH				
Speed, mph	21.2 (2.25)	13.7 (1.21)	-35.3%	Yes (0.009)
HC, mg/mi	147. (12)	261. (23)	+44.0%	Yes (0.0005)
NO, mg/mi	353. (66)	685. (132)	+48.5%	Yes (0.038)
CO, mg/mi	964. (180.)	1594. (193.)	+39.5%	Yes (0.0257)

Table 11-18 shows that the Oldsmobile Cutlass, like the Ford Taurus, experienced slower vehicle speeds in the after cases during the AM runs. There are no statistically significant differences in average speed and emissions for the northbound case. All of the before and after results for south runs are statistically significantly different from each other. CDFs for before and after cases for HC, NO, and CO emissions are given in Figure 11-11.

As seen in Figure 11-11, the CDFs for before and after cases are different from each other for all of the pollutants. The CDF for after case generally has larger values of emissions for a given percentile than for the before case for three of the pollutants. However, except for HC emissions, differences between the average emissions between the before and after cases are not substantial. The reason for this might be due to the fact that there is a statistically significant decrease in average speed.

As shown in Table 11-19, changes in vehicle speed, NO and CO emissions are statistically insignificant for both northbound and southbound runs. There is a statistically significantly difference between the before and after runs for the PM north and south HC emission rates. To examine the reason for this significance CDFs are plotted for before and after cases for HC emissions for northbound and southbound in Figure 11-12 and Figure 11-13 respectively.

The CDFs for before and after cases are different from each other for HC emissions. The CDFs for after case generally have larger values of emissions for a given

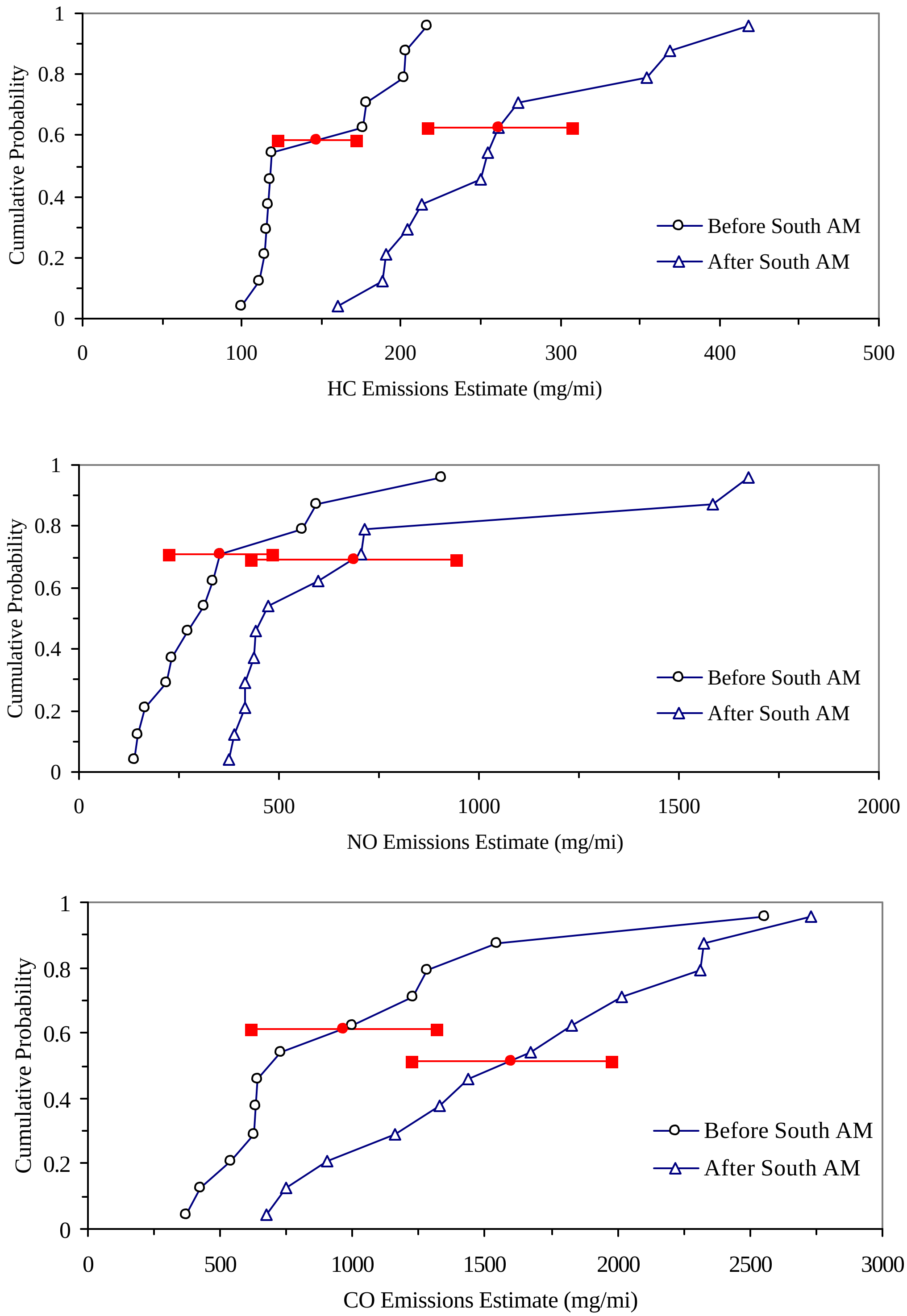


Figure 11-11. Comparison of Cumulative Distribution Functions for Before and After HC, NO, and CO Emissions for 1996 Oldsmobile Cutlass on Walnut Street for AM South Non-Priority Runs

Table 11-19. Walnut Street Ford Taurus PM Peak Non-Priority Runs

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat, Signif.? (P-Value)
PM NORTH				
Speed, mph	15.1 (1.79)	13.3 (0.88)	-12.3%	No (0.367)
HC, mg/mi	76.1 (8.33)	143. (11.8)	+88.6%	Yes (0.0004)
NO, mg/mi	86.7 (9.44)	169. (54.7)	+94.7%	No (0.179)
CO, mg/mi	1012. (192.)	2439. (1253.)	+141.%	No (0.296)
PM SOUTH				
Speed, mph	14.9 (0.90)	12.0 (1.17)	-19.5%	No (0.0662)
HC, mg/mi	71.7 (6.86)	134. (11.8)	+86.2%	Yes (0.006)
NO, mg/mi	84.6 (16.4)	104. (13.5)	+22.9%	No (0.375)
CO, mg/mi	993.5 (332.7)	1142. (196.)	+15.0%	No (0.705)

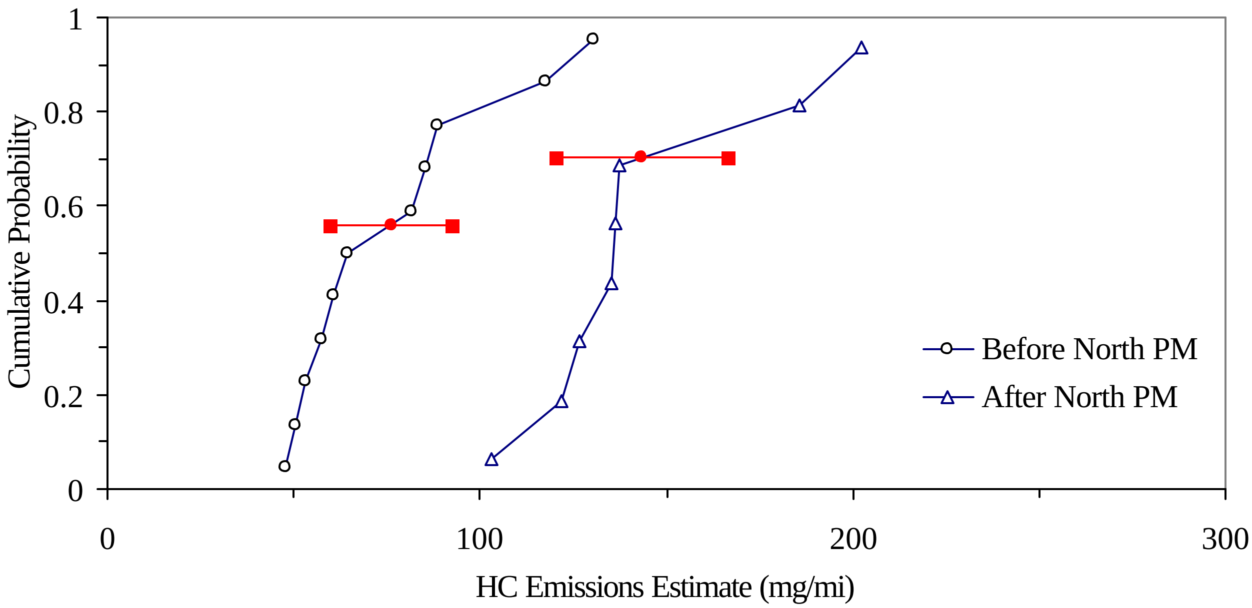


Figure 11-12. Comparison of Cumulative Distribution Functions for Before and After HC Emissions for 1999 Ford Taurus Driven on Walnut Street for PM North Non-Priority Runs

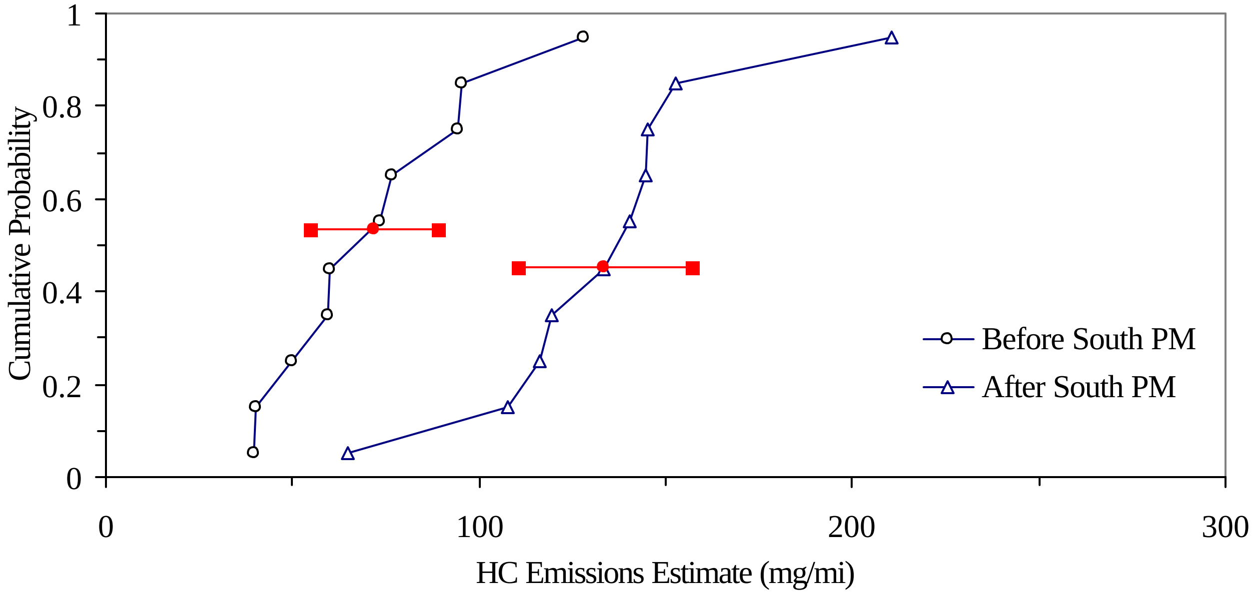


Figure 11-13. Comparison of Cumulative Distribution Functions for Before and After HC Emissions for 1999 Ford Taurus Driven on Walnut Street for PM South Non-Priority Runs

percentile than for the before case. Differences in the average values for both northbound and southbound for HC emissions are substantial.

Table 11-20 indicates that there are no statistically significant differences between the vehicle speed and emissions for northbound runs between the before and after cases. In the southbound runs difference for vehicle speed and NO, and CO emissions are not significant. However, there is statistically significant difference between the before and after runs for HC emissions. The CDFs are plotted in Figure 11-14 for the before and after cases for HC emissions for southbound runs.

The CDFs for before and after cases are different from each other for HC emissions. The CDFs for after case generally have larger values of emissions for a given percentile than for the before case. However, confidence intervals for the mean values are very close, hence, difference is not substantial.

Table 11-20. Walnut Street Oldsmobile Cutlass PM Peak Non-Priority Runs

Measure	Before: Average (Std. Error)	After: Average (Std. Error)	% Difference (A-B/B)	Stat, Signif.? (P-Value)
PM NORTH				
Speed, mph	13.8 (1.97)	11.5 (1.31)	-16.9%	No (0.344)
HC, mg/mi	392. (49.5)	412. (29.4)	+4.9%	No (0.282)
NO, mg/mi	985. (251.)	1008. (118.)	+2.3%	No (0.215)
CO, mg/mi	11400. (4651.)	2487. (523.)	-78.2%	No (0.406)
PM SOUTH				
Speed, mph	14.9 (2.28)	12.3 (1.27)	-17.8%	No (0.33)
HC, mg/mi	360. (37.5)	442. (31.3)	+22.6%	Yes (0.032)
NO, mg/mi	819. (110.)	1199. (240.)	+46.5%	No (0.127)
CO, mg/mi	9880. (2296.)	3329. (639.)	-66.3%	No (0.435)

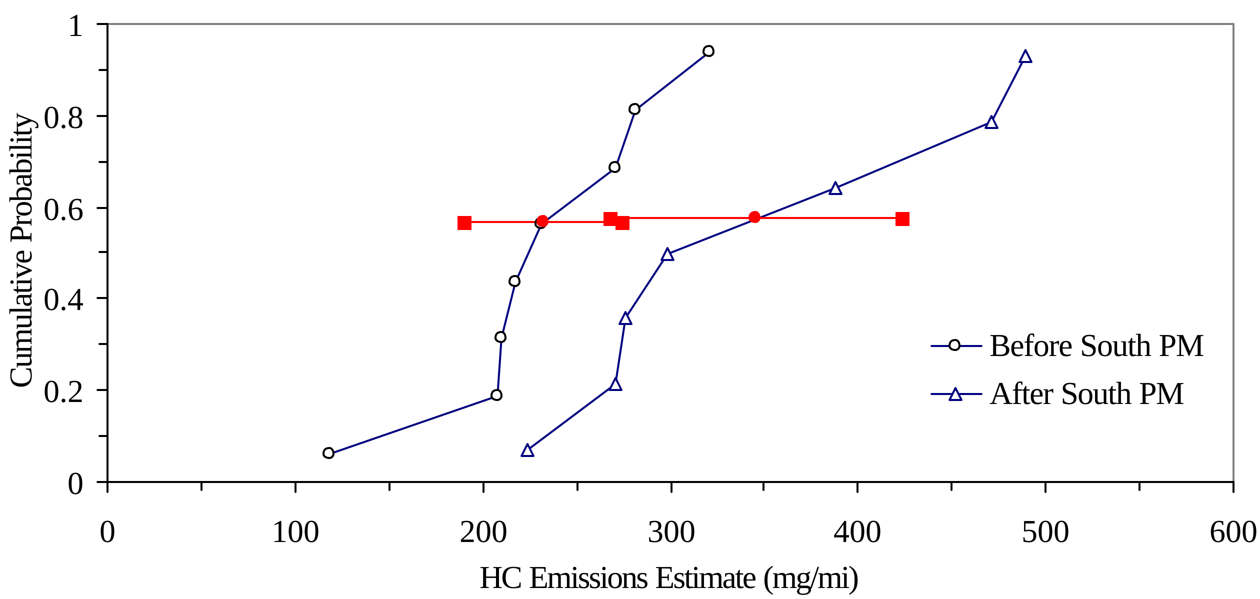


Figure 11-14. Comparison of Cumulative Distribution Functions for Before and After HC Emissions for 1996 Oldsmobile Cutlass Driven on Walnut Street for PM South Non-Priority Runs

11.7 Summary

This chapter presented detailed and summary data regarding predicted and observed changes in emissions on the Walnut Street corridor based upon measurements made with primary vehicles both before and after a signal timing and coordination change was implemented. Detailed data were presented regarding observed modal emission rates, the fraction of time spent in each driving mode, and the trip duration in the before and after cases. Sensitivity analyses were conducted to evaluate the relative importance of variation in emission factors and trip duration with respect to estimates of total trip emissions and of changes in emissions when comparing the before and after cases. Key measures of observed traffic flow, including average speed, control delay, and total stops, were presented for the two primary vehicles, two peak time periods (morning and afternoon), and two travel directions. Simultaneously, key measures of trip average emissions were presented for HC, NO, and CO. The spatial distribution of emissions along the corridors was evaluated both graphically and statistically. Analyses were also conducted for non-priority movements.

Based upon the data and the analyses, the following key findings are supported regarding methods for making comparisons:

- Average modal emission rates calculated based upon combining data for all peak periods and travel directions are comparable in the before and after cases for most vehicle/pollutant combinations
- Average modal emission rates for specific vehicles, time periods, travel directions, and pollutants in each of the before and after cases were reviewed and in some cases noticeable differences were observed which helped explain observed differences in total trip emissions
- Trip emissions estimated from time-based modal emission rates are sensitive to the trip duration.
- Predictions of differences in emissions when comparing before and after cases appear to be robust to the choice of modal emission factors to use. For example, similar insights are obtained if only the "before" modal emission rates are used or if only the "after" modal emission rates are used to predict both before and after total emissions.

Thus, relative comparisons are deemed to be robust even though the absolute value of emissions may differ depending upon which emission factor data set is used.

- When evaluating observed changes in emissions based upon direct comparison of measured data, it is important to take into account any differences that exist regarding the modal emission rates. If changes in modal emissions in the after case compared to the before case are not accounted for, one can make misleading inferences regarding apparent changes in emissions.
- There is substantial variability in both the traffic and emissions data. This variability must be accounted for when doing comparisons so that only statistically significant results are used as the basis for policy recommendations.
- Spatial analysis of the traffic flow and emissions data can reveal emissions hotspots, which are specific locations where emissions tend to be much higher than average because of some characteristic roadway or traffic flow feature at that location.
- Even though changes in emissions may not be statistically significant on average for a corridor, there can be statistically significant changes in emissions at specific locations as revealed by spatial analysis of emissions hotspots.
- This project demonstrates that a study can be designed and successfully executed to collect, analyze, and interpret data regarding before and after comparisons associated with a change in traffic control.

The following key findings are supported regarding the specific results for Walnut Street:

- For Walnut Street, there was an improvement in traffic flow during the morning peak period in both directions and during the afternoon peak period in only the northbound direction. The same finding was obtained based upon measurements collected with two different primary vehicles.
- For Walnut Street, modest improvements in emissions were typically either directly observed and/or predicted associated with statistically significant improvements in traffic flow.
- For Walnut Street, if there was not a statistically significant change in traffic flow, there was also not a significant change in emissions.

- There are specific locations along the Walnut Street corridor where emissions tend to be higher than at other locations.
- Although it was difficult to observe significant changes in nonpriority movements, the available data typically suggest a decrease in the average speed of selected nonpriority movements on Walnut Street and a potential increase in emissions for such movements. However, the results are not conclusive because of the large variability in the data and the relatively small sample sizes.

Overall, the Walnut Street case study illustrates the successful application of a transportation control measure leading to a reduction in vehicle emissions. Specifically, the changes in signal time and coordination generally had a beneficial effect in reducing average vehicle emissions on the corridor. The improvement in average emissions was associated with measureable improvements in traffic flow, as quantified based upon increases in average speed and reductions in average control delay and the average number of stops per mile.

12.0 GENERALIZED POLLUTION PREVENTION STRATEGIES

In this section, pollution prevention strategies that are based upon the results of this study will be discussed. First, strategies regarding vehicle characteristics are presented. Then strategies based upon traffic flow and corridor characteristics are discussed. Finally, strategies regarding driver characteristics are presented.

12.1 Vehicle Characteristics

In this study it was found that vehicle characteristics such as vehicle make and model have significant effects on vehicle emissions. However, the relation between vehicle characteristics and emissions are not clear. As discussed in Section 7.3 different vehicles have different behavior for different pollutants. For example, for HC emissions the Chevrolet minivan tested has the highest emissions among the group of vehicles tested. However, for NO the 15-passenger Ford van has the highest emissions. The Chevrolet Breeze has the highest CO emissions. It should be noted that this study's main purpose was not to find the effect of different vehicle make and models. Therefore, the effects of vehicle characteristics were not controlled in this study. With new data for a variety of vehicles, one could compare their on-road emissions rate and select vehicles for that meet a user defined environmental objective. In addition to considering vehicle emissions, emissions could also be normalized with respect to passenger or cargo load.

12.2 Traffic Flow and Corridor Characteristics

The results obtained from this study indicated that traffic flow characteristics have significant effects on vehicle emissions. As discussed in detail in Section 7.4 and Section 7.5, traffic flow characteristics such as average speed, time in delay, number of stops, and driving mode, can explain some of the variability in vehicle emissions.

The driving mode analysis in Section 7.4 indicated that acceleration events have significantly higher emission rates for all pollutants and for all vehicles. Depending on the vehicle, the mean emission rate during acceleration varies from five to 200 times the idle emissions rate. A qualitative observation from these modal rates is that traffic control devices and geometric designs that lead to an increase in the number of accelerations can lead to a degradation in air quality. Ramp meters, speed humps and other traffic calming devices, and sharp horizontal and vertical curves are examples of designs that can potentially cause high emissions hotspots.

The analyses of traffic parameters revealed that generally an increase in traffic congestion (higher delay and stops, lower average speed) results in *lower* emission rates *per unit tim*e. This is because a higher proportion of time is spent in idle mode rather than cruise mode. Conversely, an increase in traffic congestion in some cases results in *higher* emission rates *per unit distanc*e. This is because of additional time spent on the corridor, which offsets the lower emissions rate *per unit tim*e. HC emissions most consistently show this inverse relationship. NO and CO emissions show a less clear trend with traffic congestion for the vehicles studied in this research. These measures have different effects on the distribution of time spent in different driving modes. Occasionally, a signal timing improvement may increase delay and decrease stops, or vice versa.

Arranging the data into groups of congested and uncongested conditions allowed a direct assessment of traffic congestion on emissions. The analysis showed that HC emissions generally increased with traffic congestion. NO and CO emissions did not vary significantly, even under significant changes in traffic congestion. This concurs with the findings in Section 7.5 that HC emissions are more correlated with traffic measures than are NO and CO emissions.

12.3 Driver Characteristics

The results obtained in this study are not enough to determine the pollution prevention strategies based upon driver characteristics since these parameters were not found to be significant. However, they can be indirectly related to emissions since they might affect the percent distribution of driving modes. Some of the measurements done during the pilot study indicated that emissions can be significantly different for different drivers, with more aggressive drivers tending to produce higher emissions associated with larger acceleration rates.

12.4 Summary

Pollution prevention strategies can be significantly influenced by traffic flow characterististics, as well as by vehicle type and driver behavior. For example, measures that improve traffic flow have the potential to substantially reduce real-world emissions.

13.0 CONCLUSIONS

In this study, novel methods have been used for evaluating the impacts of the strategies aimed at preventing motor vehicle air pollutant emissions through better traffic management. Actual on-road emissions measurements were utilized in contrast to the laboratory-based dynamometer tests employed in many current projects. A summary of the major findings of this study is presented briefly in Table 13-1. A detailed discussion of the findings of this study are presented in the following text.

13.1 On-Road Emissions Measurements

This study is among the first ones that has utilized real-world on-board vehicle emissions measurement device (OEM-2100^{TM}) developed by Clean Air Technologies. In this research, a method for on-board measurement of on-road tailpipe emissions for gasoline-fueled light duty vehicles has been successfully demonstrated.

A substantial amount of time was spent on developing and improving methodologies for on-board data collection. This step was extremely important in developing an accurate database. The first step in this process is to make sure that the instrument used has good precision and accuracy. In other studies, at the New York Department of Environmental Conservation (DEC) and at the U.S. EPA's National Fuels and Vehicle Emissions Laboratory in Ann Arbor, Michigan (Clean Air Technologies, 2000), comparison of OEM-2100^{TM} to dynamometer tests revealed that OEM-2100 ^{TM} has good precision and accuracy.

The OEM-2100^{TM} instruments were calibrated against a calibration gas of known concentrations frequently, approximately every three months. This was essential to check whether instruments drifted from real values or not. The results of the calibration tests revealed that instruments were stable and hold calibration reasonably well. Instruments were zeroed using ambient air periodically, approximately every thirty minutes after warm-up. This is a means of preventing drift in the measurements. Overall, using these methodologies reliable data were obtained from OEM-2100^{TM} instruments.

Another aspect of on-board emissions data collection was feasibility. Researchers were able to setup the OEM-2100^{TM} equipment in approximately 15 minutes. After warm-up of the instrument, a period of approximately 50 minutes, researchers were able

Table 13-1. Summary of the Key Findings of this Project.

The key findings of this work are: • This study has established the feasibility of using on-board emissions measurements to collect real-world on-road tailpipe emissions data for CO, NO, and HC. • Modal (acceleration, deceleration, idle, cruise) emission rates are for the most part stable for the same vehicle/driver combination. • Measured emission rates (on a gram per second basis) are highest during the acceleration driving mode. • Measured emissions tend to increase with traffic congestion since there are more acceleration events, as observed on Chapel Hill Road. • Signal improvements such as coordination and retiming have resulted in lower emissions on Walnut Street.

to collect data. This allowed the researchers to collect data on any corridor selected and at any time of the day. The OEM-2100™ instrument had only one significant constraint in terms of data collection. OEM-2100™ units that were available in this study could only be used with vehicles that have on-board diagnostic connections, which typically are vehicles that have a model year of later than 1990. However, this was not a problem in terms of the objectives of this study.

13.2 Other Data Collection

As part of this project's objectives data regarding explanatory variables were collected throughout this study. These explanatory variables include: traffic, roadway, vehicle, engine and driver behavior characteristics.

Some traffic parameters, such as second-by-second vehicle speed, were collected by OEM-2100™ instruments. Other traffic parameters were determined from time stamps which were recorded using laptop computer in the field using a Visual Basic program specifically written for this purpose.

One of the findings of this study is that control delay is difficult to directly measure in the field because of the difficulty in identifying the points when a vehicle enters and exits the period of control delay. A methodology was developed to estimate control delay as a function of total delay and stopped delay. Total delay and stopped delay were calculated using a second-by-second decision tree.

Among other exploratory analysis roadway grade was measured in this study. A digital level has been utilized for this purpose. Collected grade data have been incorporated to the emissions database by using the Visual Basic program developed for this purpose. This allowed evaluating the effect of roadway grade on vehicle emissions.

Another parameter estimated in this study is the length of the study corridors. Two methods were used for this purpose. The first method is based upon the OEM-2100^{TM} speed trace and the second method is based upon odometer data collected using different vehicles. Based upon the analysis it was found that second method gives more accurate results, but the first method can be used to estimate vehicle location between two fixed reference points. The distance estimates calculate from the speed data were normalized based upon odometer data using a Visual Basic program.

13.3 Experimental Design

The main lesson learned from pilot study was the high variability in emissions data for vehicles of the same make and model. It was found that two different vehicles of the same make and model can produce significantly different emission rates. Because it is important to control all emissions variability so that the only difference in the before and after runs is the presence of signal coordination, the pilot study highlighted the importance to drive the exact same vehicles in the before and after runs. However, a study with different objective may not need to be as concerned as concerned with this particular point.

The pilot study also highlighted the importance of using the same fuel type in the before and after runs. For the evaluation study regular unleaded gasoline fuel was used.

Because both vehicle make and model and driver style can have an impact on vehicle emissions, it became clear from the pilot study that the evaluation study should be based on similar driver-vehicle combinations in the before and after runs. An equal number of runs with the same driver and vehicle in both the before and after cases would reduce the likelihood of undesired emissions variability due to driver style and/or vehicle make and model.

Overall, the design of the evaluation study was much improved over the pilot study design by reducing the amount of emissions variability due to vehicle make and model, driver style, and fuel type that was present in the pilot study.

An objective of the evaluation study was that the before and after runs should be performed within a short enough time period to preclude major changes in traffic volumes or weather conditions. Even though the before and after runs for the Chapel Hill Road corridor were completed within a two month period, temperatures were approximately 10 degrees Fahrenheit colder in the after runs. Data collection on Walnut Street was completed less than two months and temperatures were approximately 20 degrees Fahrenheit colder in the after runs. Past research has indicated that ambient temperature does have an effect on vehicle emissions and as such, future experiments of this kind should attempt to minimize the temperature effect by performing the before and after runs in a short time period. However, based upon a comparison of modal emissions for both the before and after cases, no significant impact of temperature or other uncontrolled factors were identified. Therefore, it is not likely that the uncontrollable change in temperature observed over the time frame of the study adversely affected emissions comparisons.

13.4 Data Reduction and Screening

A substantial amount of effort was spent in developing methods and protocols for data reduction and screening. Methods developed in this study were aimed at producing an accurate emissions and traffic parameters database. New programs were developed in Visual Basic environment that would allow combination of emissions data collected from OEM-2100™ and traffic data collected from laptop computer.

Experience gained during fieldwork and data processing has lead to the development of a rigorous quality assurance procedure involving several levels of screening. These include identification of known sources of possible errors in field data arising from potential problems with clock synchronization, battery depletion, lack of field data entry, engine analyzer errors, gas analyzer errors, instrument zeroing, and instrument drift, among others. Knowledge of these possible sources of errors has lead to improved data collection protocols which attempt to reduce the frequency of errors. A high proportion (more than 80 percent) of measurement attempts resulted in valid vehicle activity and emissions files.

Another type of problem regarding the emissions data were identified after a study where two OEM-2100^{TM} units were compared. It was observed that filter clogging can cause a time synchronization problem in OEM-2100^{TM}. Methods were determined to detect the amount of time lag in OEM-2100^{TM} data and files were corrected using a program written in Visual Basic. It was determined that macro level analysis (i.e., run-based averages) are not sensitive to this error. For example, there was less than five percent change in the data for corridor level average values. However, micro-level analysis, such as modal analysis and spatial analysis, are sensitive to the time lag problem. It was found that the error in the modal analysis can be as high as 150 percent. For this reason micro-level analysis results were redone using the corrected data whereas results for macro-level analysis were kept the same.

13.5 Exploratory Analysis

In order to determine the effect of explanatory variables different statistical methods were utilized. The ANOVA method revealed that vehicle and traffic coordination were among the parameters that have significant effects on vehicle emissions. Other significant parameters include: ambient temperature; ambient humidity; time-direction of the trip; and average speed of the vehicle.

Another important finding of the exploratory analysis was that two vehicles of the same make and model can produce different emissions rates.

From the analysis of the speed and emissions time traces it was determined that some events might be causing higher emissions than the corridor average. This led to modal analyses where driving modes were developed empirically from the data. It was found that emissions in different driving modes are statistically different from each other which is an indication of the fact that driving modes can explain some of the variability in vehicle emissions.

Vehicle emissions are generally highest while vehicles are accelerating and lowest while idling. Cruising and decelerating produce mean emission rates between acceleration and idling, on average. Depending on the vehicle, the mean emission rate during acceleration varies from five to 200 times the idle emissions rate. A qualitative observation from these modal rates is that traffic control devices and geometric designs that lead to an increase in the number of accelerations can lead to a degradation in air quality. Ramp meters, speed humps and other traffic calming devices, and sharp horizontal and vertical curves are examples of designs that can potentially cause high emissions hotspots.

Because of the variability in emissions by vehicle make and model, it was critical to group vehicles exhibiting similar modal emission rates before exploring trends between traffic parameters and vehicle emissions. A total of nine "emissions groups" were developed, three each for HC, NO, and CO pollutants. This grouping process helped isolate the variability associated with the vehicle properties to enable the determination of the true effects of traffic parameters on vehicle emissions.

13.6 Emissions Analysis Approach

As part of this study, relations between macro and micro level parameters and vehicle emissions were determined. Based upon these relations an approach for emissions analysis is proposed.

From these analyses it was found generally that an increase in traffic congestion (higher delay and stops, lower average speed) results in *lower* emission rates *per unit time*. This is because a higher proportion of time is spent in idle mode rather than cruise mode. Conversely, an increase in traffic congestion in some cases results in *higher* emission rates *per unit distance*. This is because of additional time spent on the corridor, which offsets the lower emissions rate *per unit time*. HC emissions most consistently show this inverse relationship. NO and CO emissions show a less clear trend with traffic congestion for the vehicles studied in this research. A macroscopic traffic model that predicts emissions should include both control delay and total stops as inputs. These measures have different effects on the distribution of time spent in different driving modes. Occasionally, a signal timing improvement may increase delay and decrease stops, or vice versa. A model based solely on average speed will not truly capture the change in traffic and emission conditions. Generalized effects of delay and stops on vehicle emissions can be gained by studying the relationship between control delay per stop-mile and emissions per stop-mile. This transformation makes delay and stops essentially independent. The majority of emissions groups showed that control delay and total stops had a statistically significant impact on vehicle emissions. HC emissions showed the most significant dependence on delay and stops. NO and CO showed a less significant relationship with delay and stops.

13.7 Empirical Study Results

A sensitivity analysis was conducted to investigate the effects of change in trip duration, time spent in each driving mode, and modal emission factors. It was revealed from the sensitivity analysis of the emissions data for the before and after cases that average modal emission rates calculated based upon combining data for all peak periods and travel directions are comparable in the before and after cases for most vehicle/pollutant combinations. There are however specific vehicles, time periods, travel directions, and pollutants in each of the before and after cases where noticeable differences were observed which helped explain observed differences in total trip emissions.

Another key finding of the sensitivity analysis is that trip emissions are sensitive to the trip duration. Change in time spent in each driving mode was found to have a modest effect on emissions. Change in the modal emission rates, on the other hand, significantly affects emissions.

It was observed that for Chapel Hill Road that, the signal coordination plan did not statistically significantly change the traffic measures with the exception of degradation in traffic flow for the AM north runs, which was observed with measurements collected with Chevrolet Venture only. There were significant changes in emissions in Chapel Hill Road between the before and after cases where there was not a statistically significant change in traffic flow. This is due mainly to changes in modal emission rates between the before and after cases.

Traffic congestion analysis conducted on Chapel Hill Road data revealed that emissions of pollutants, especially HC emissions, tend to increase with traffic congestion. Other pollutants would have increased if there were no changes in modal emission rates.

For Walnut Street, there was an improvement in traffic flow during the morning peak period in both directions and during the afternoon peak period in only the northbound direction. Improvement in traffic flow generally caused reductions in emissions.

Spatial analysis of the traffic flow and emissions data both for Chapel Hill Road and Walnut Street data revealed emissions hotspots, specific locations where emissions tend to be much higher than average because of some characteristic roadway or traffic flow feature at that location. In some cases even though changes in emissions were not statistically significant on average for a corridor, there were statistically significant changes in emissions at specific locations as revealed by spatial analysis of emissions hotspots.

Overall, it is clear from the results of the comparison of uncongested and congested traffic flow for the same travel directions on Chapel Hill Road, and from the before and after comparisons on Walnut Street, that improvements in real world traffic flow can lead to real world reductions in tailpipe air pollutant emissions from highway vehicles. In the case of the Walnut Street corridor, the increases in average speed, and reductions in control delay and average stops per mile are quantitative measures of the effectiveness of the signal timing and coordination change with respect to improved traffic flow. Improvements in traffic flow, and especially those improvements that reduce or eliminate accelerations, can effectively reduce average vehicle emissions over the length of the corridor as well as at specific locations.

It would not be possible to predict microscale emissions impacts of the change in signal timing and coordination with existing modeling tools such as the Mobile models. The real-world microscale emissions results obtained in this work were made possible by on-road measurement of tailpipe emissions at a high spatial and temporal resolution.

14.0 RECOMMENDATIONS

A number of recommendations were developed based upon the experience gained and lessons learned in the course of this research. The recommendations are summarized in this section. A summary of the key recommendations is given in Table 14-1.

14.1 Experimental Design

In any research, the experimental design should address what vehicles are to be tested, which drivers are to be used, what routes are to be tested, which instruments are to be used, when testing will be done, and the scheduling and logistics of deployment of vehicles, drivers, and instruments. The specifics of the study design depend upon the objective. For example, in a before and after study, the objective is to intensively collect data with a limited number of vehicle/driver combinations so that variability associated with the change of interest can be observed. In a study of driver behavior, one would want to collect data with a sufficient number of drivers but could use a relatively small fleet of vehicles. A study aimed at developing fleet average emission factors would involve deployment of a sufficient number of vehicle and driver combinations on whatever roadway facility types are the focus of the study, but would not require a large number of replications for any one vehicle/driver pair. Other study designs would similarly motivate other specific study designs. Thus, the study objective should be clearly defined, and the study should be designed to appropriate isolate any key factors of interest, to control for as many other factors as possible, and to make observations if possible for any factors that are uncontrollable. The latter is necessary to attempt to account for variation in uncontrollable factors (e.g., ambient temperature) that might play in a role in comparison studies.

14.2 Calibration and Maintenance of Equipment

It is critically important to properly calibrate and maintain the emissions measurement equipment. Thus, a regular schedule of calibration and maintenance is recommended. Future improvements in the design of the OEM-2100 or similar devices should include, if possible, methods for detecting plugging in the gas sampling line and other diagnostics to assist the user in determining when maintenance or repair is required.

Table 14-1. Summary of the Key Recommendations of this Project.

The key recommendations of this work are:

- On-board emissions measurement methods should be used in future studies to improve knowledge of real-world on-road emissions.
- On-road measurement studies should be carefully designed taking into account well-defined study objectives.
- Objectives for future studies should include but not be limited to empirical evaluation of Transportation Control Measures (TCMs) and Transportation Improvement Projects (TIPs) and plans; assessment of emissions hotspots; evaluation of driver behavior; validation of emission factor models; development of public education tools to educate drivers about their role in pollution prevention.
- Appropriate and thorough data screening, reduction, and analysis protocols should be used.
- Variability and uncertainty should be accounted for in the study design and when making inferences based upon measured data.
- NCDOT and others should use on-road data to aid in the design and evaluation of TCMs and TIPs.

14.3 Protocols for Data Screening, Reduction, and Analysis

On-board emissions measurement produces a substantial data stream. Regardless of the study objective, methods are needed for data screening, reduction, and analysis. The methods produced in this study are generally applicable to these three important tasks. The protocols developed in this study have been designed to seek and, if possible, correct typical problems encountered during the course of the study. These protocols should be used and improved in future studies.

14.4 Need for Application of Multiple Analysis Techniques

It is rarely the case that any one method of analysis can fully reveal patterns in the data. In this study, a variety of approaches have been used, including various graphical, statistical, and engineering-based methods for exploring relationships in the data. Future studies should also attempt to employ more than one technique to determine the robustness of results. Moreover, it is important to account for variability in the data when making comparisons, such as has been done here in comparing modal emission rates or in making before and after comparisons of the effect of traffic signal timing and coordination. Because vehicle emissions exhibit substantial variability, mistakenly overconfident inferences can be made if variability is not properly accounted for.

14.5 Variability and Uncertainty in Traffic and Emissions Data

This study used relatively large sample sizes of repeated runs in the before and after studies as a basis for developing average emission rates and confidence intervals for the averages. The change in traffic flow and emissions was evaluated using statistical significance tests. A substantial amount of inter-run variability in emissions for a given vehicle and driver pair was observed, which in turn influences the width of the confidence intervals for the mean. In order to obtain statistically stable results for a particular study objective, such as in a before and after comparison, careful attention should be paid to determining how many repeated vehicle runs are needed in order to obtain sufficiently narrow confidence intervals for the mean to allow for meaningful comparisons.

14.6 Objectives for Future Studies

Some specific recommendations arise from this study regarding future study objectives. For example, the spatial analyses presented in Chapters 10 and 11 suggest that studies can be designed to look for and/or characterize emissions hotspots. Because of the high variability in emissions among driving modes, it is clear that it is possible for there to be specific locations on a roadway, corridor, or route that are conducive to producing high emissions. Thus, on-board emissions measurement should be used to identify emissions hotspots that are hypothesized to be of importance.

On-board emissions measurement makes possible the real-world verification or validation of projects or plans aimed at reducing emissions. This approach should be used with appropriate study design to evaluate the real world impacts of a variety of traffic control measures and other efforts that claim to reduce vehicle emissions. On-board emissions measurements can also be used to validate existing emission factor models.

On-board emissions measurement should also be used to help develop emissions databases and models. For example, measurements should be made on a larger set of vehicles, for a representative set of roadway functional classes, and with respect to other variations in design, time of year, and characteristics (e.g., road grade) to enable development of a representative database. Such a database would be extremely valuable in serving as a basis for predicting real-world emissions at various scales, including the micro-scale. While such data can be used to explore and develop refined models (e.g., based upon traffic and/or vehicle parameters), the main benefit of such work will be an accurate source of information. Because traffic and air quality management decisions are associated with allocation of substantial resources, there is a considerable pay-off to be gained from developing better-informed air quality management strategies that lead to real world benefits.

The information obtained from on-road studies should be used to develop public education messages aimed at the driving public, so as to inform them about how their driving behavior relates to air pollutant emissions from their vehicles.

14.7 Strategies to Reduce On-Road Emissions

The results of this project suggest at least some strategies that can effectively reduce real-world on-road tailpipe emissions. Specifically, examples on two different corridors illustrate that an improvement in traffic flow can lead to substantial reductions in on-road vehicle emissions. The first example, based upon a comparison of congested and uncongested flow in the same travel direction on Chapel Hill Road, illustrates the potential emissions rate reduction that could accrue if measures could be implemented on that corridor to increase capacity, or reduce demand, so as to improve traffic flow. The second example, on Walnut Street, illustrates the positive impact of a change in signal timing and coordination with respect to both traffic flow and emissions. Reductions in emissions appear to be strongly related to reductions in the portion of time spent in acceleration. NCDOT and other agencies should implement strategies such as improved signal timing and coordination, on corridors that are not bottlenecked by capacity problems, as a means to reduce emission rates on those corridors. Other strategies that improve traffic flow should also be considered. However, as noted in the next section, it can be potentially misleading to make a priori assumptions about the effect of a particular TCM or TIP without first having empirical evidence of its efficacy.

The use of empirical real-world method for evaluating the air quality benefits of transportation projects should be considered in place of, or complementary to, methods based upon models, especially when commonly available models are not capable of analyzing microscale impacts of changes in traffic flow.

NCDOT should be encouraged to carry out projects that reduce congestion on signalized arterials and/or improve coordination and signal timing as those strategies have been shown in this work to have a demonstrable effect on emission rate reduction.

14.8 Validate or Falsify "Conventional Wisdom"

The methodology demonstrated here should be applied to empirical evaluation of a wide variety of transportation control measures and transportation improvement projects, so that actual benefits can be measured under real-world conditions. Specific measures of performance related to each TCM or TIP can be empirically evaluated in the context of specific projects. For example, the relationship between green time, traffic flow, and emissions can be explored in future work regarding the relationship between traffic signal timing and coordination and emissions.

The results of this study also suggest caution regarding the conventional wisdom about some traffic control measures, such as those aimed at "traffic calming". Measures such as frequent stop signs or speed bumps have the potential to increase real-world emissions because each occurrence of a stop sign or speed bump is also a likely location of accelerations. Another key example of conventional wisdom is the notion that idling contributes strongly to total emissions during a trip. The measurements in this study suggest that the time-based emission rate during acceleration can be an order of magnitude higher than during idle. Therefore, total trip emissions can be more sensitive to changes in the portion of the trip spent in acceleration than to changes in the portion of the trip spent in idle. Real world measurements are an important and effective means for confirming or falsifying conventional wisdom. As more data are obtained from well-designed studies regarding the real world effect of various TCM and TIP approaches, traffic engineers will be able to understand the air quality benefits of such approaches at the microscale with increasing confidence and thereby develop a new “conventional wisdom” that is informed by real data.

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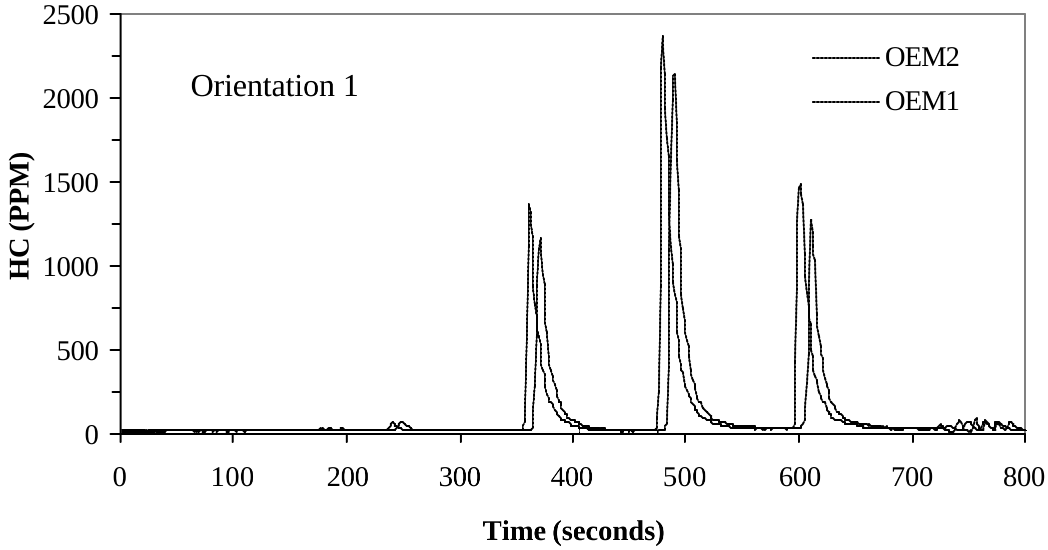
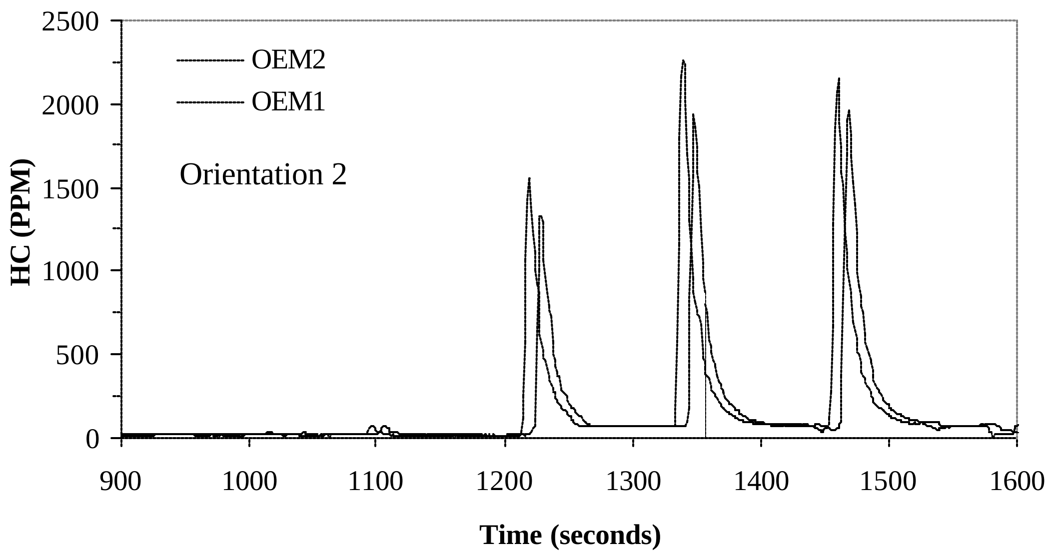
APPENDIX I

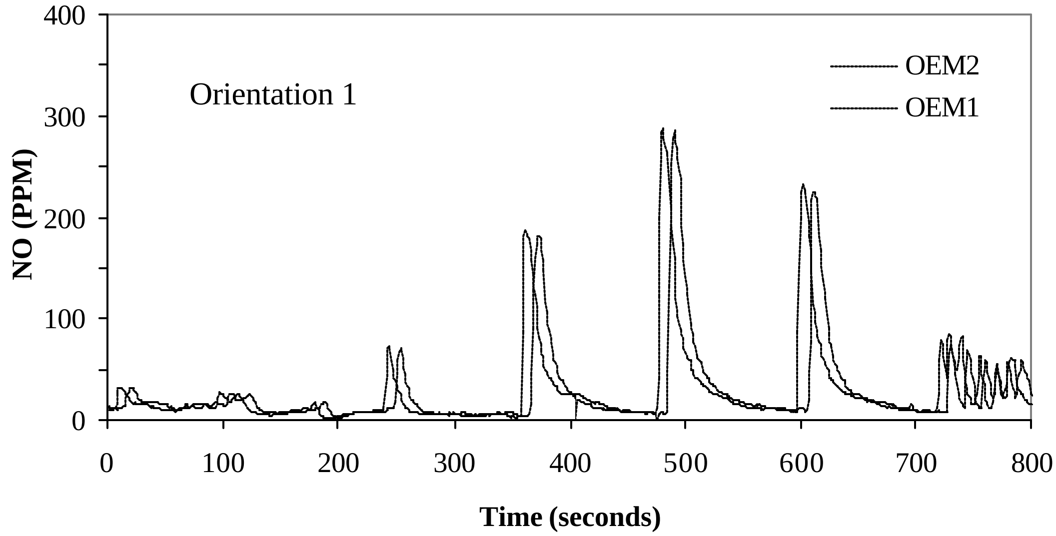
- OEM-2100^{TM} Comparison Graphs for 1996 Honda Civic
- OEM-2100^{TM} Comparison Graphs for 1999 Toyota Corolla

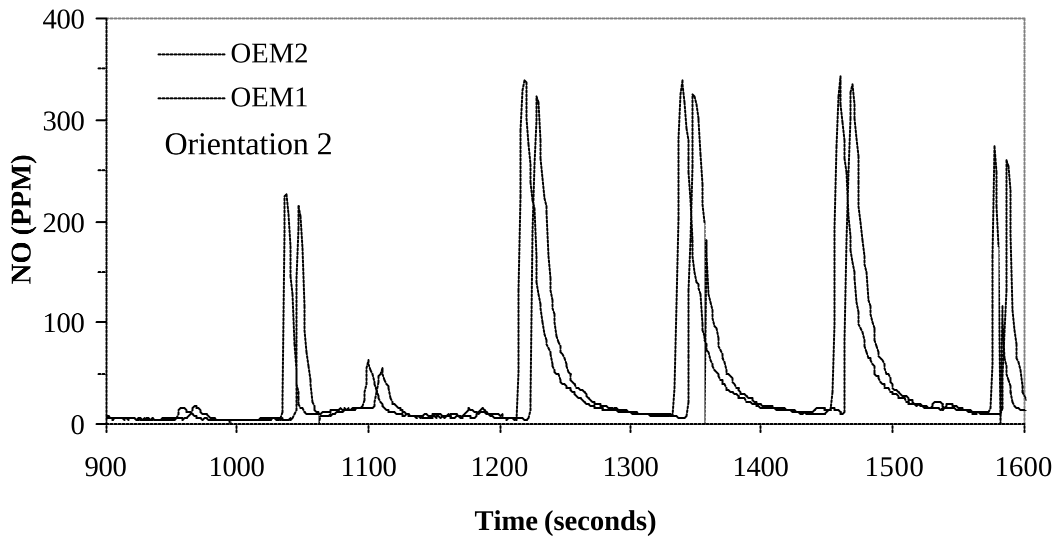
Appendix I. OEM-2100™ Comparison Test Results for 1996 Honda Civic



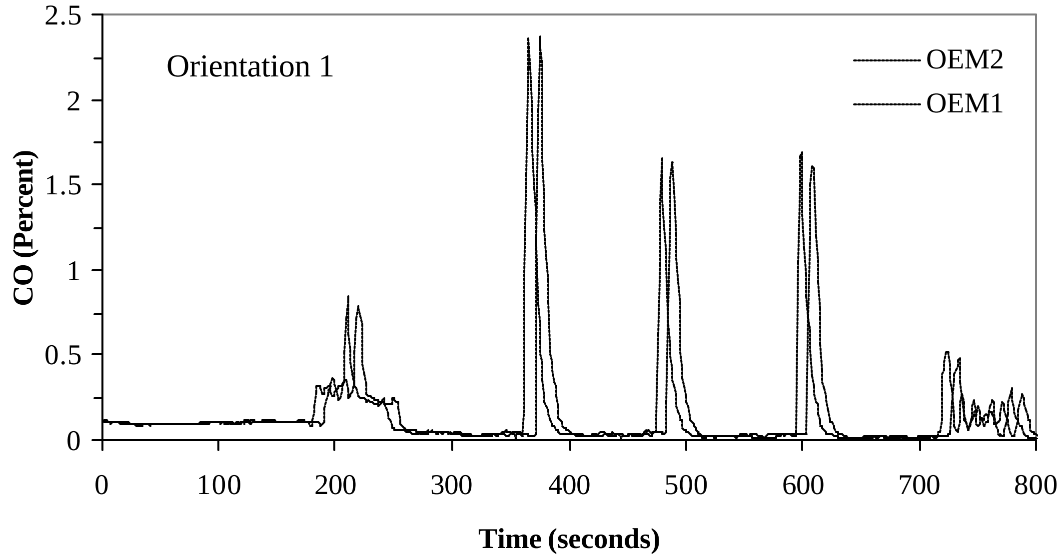


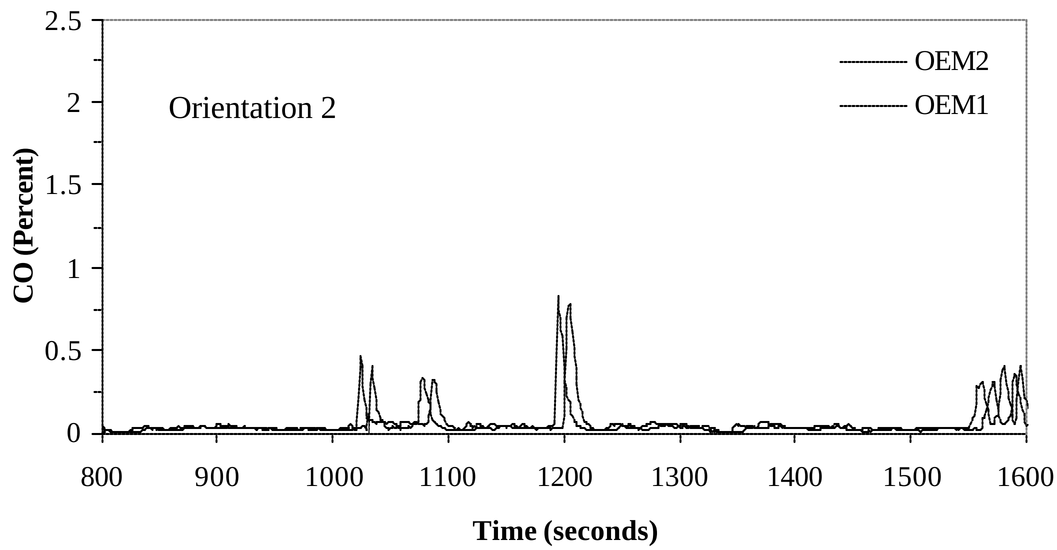
Appendix I. OEM-2100™ Comparison Test Results for 1996 Honda Civic



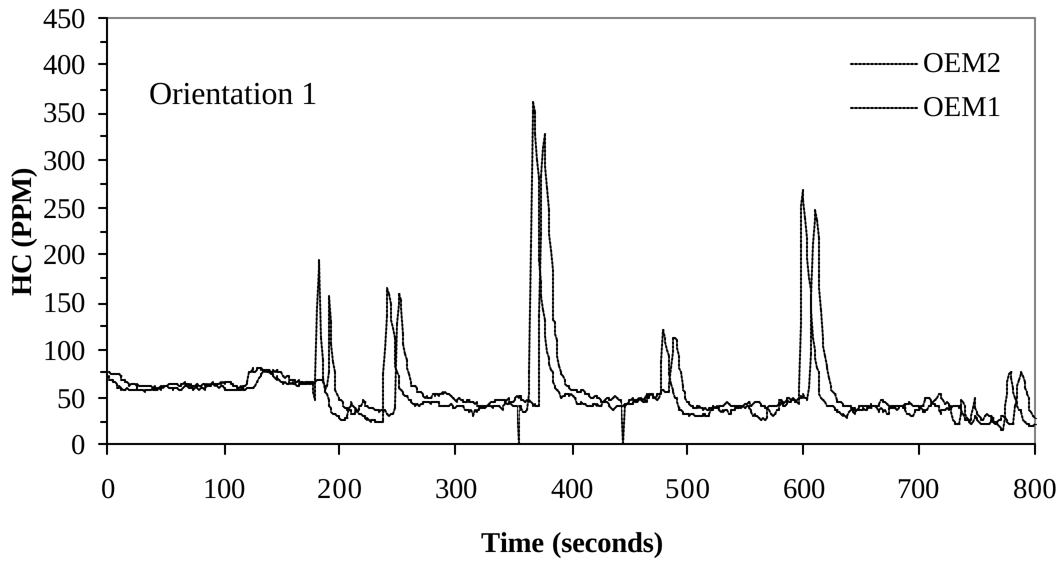


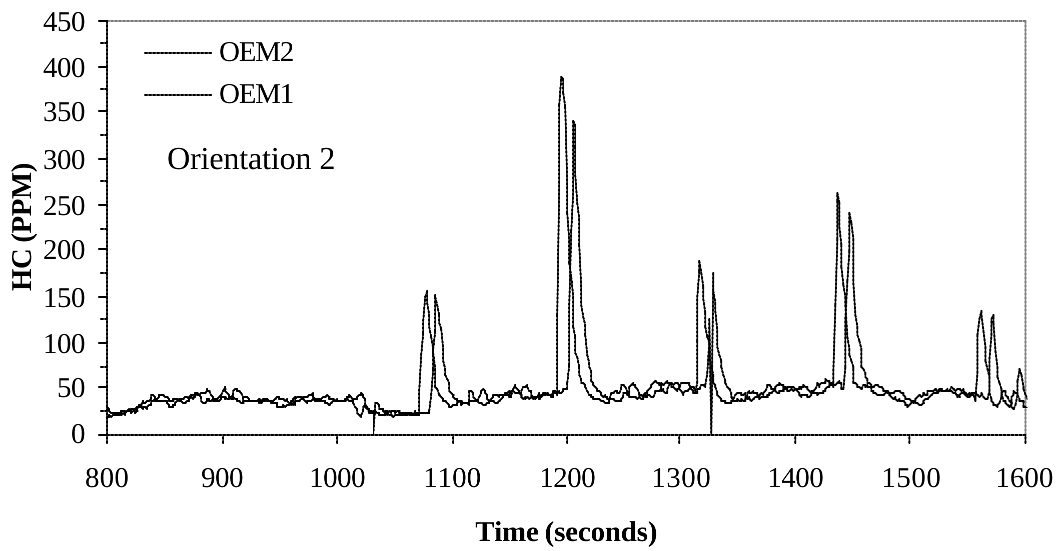
Appendix I. OEM-2100™ Comparison Test Results for 1999 Toyota Corolla



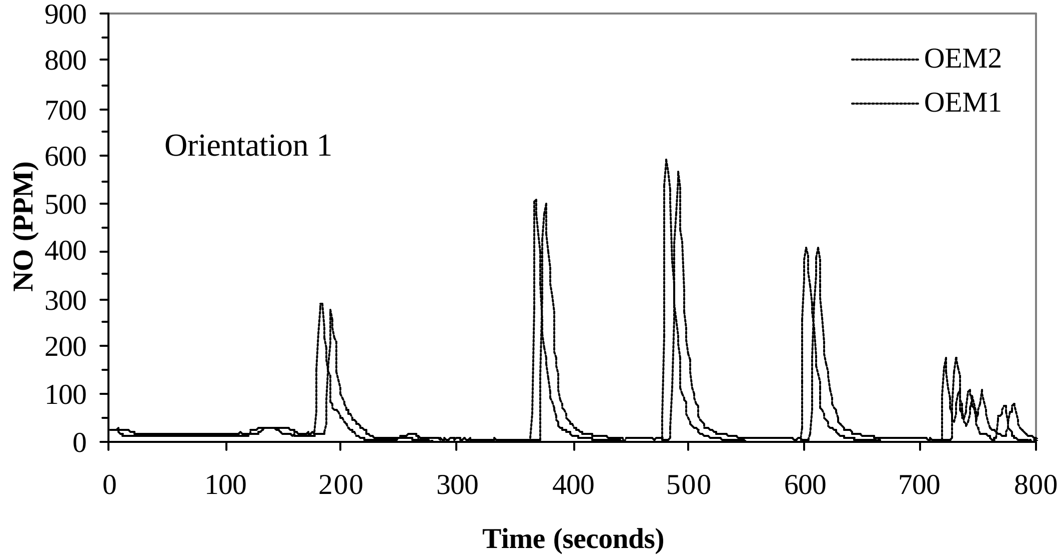


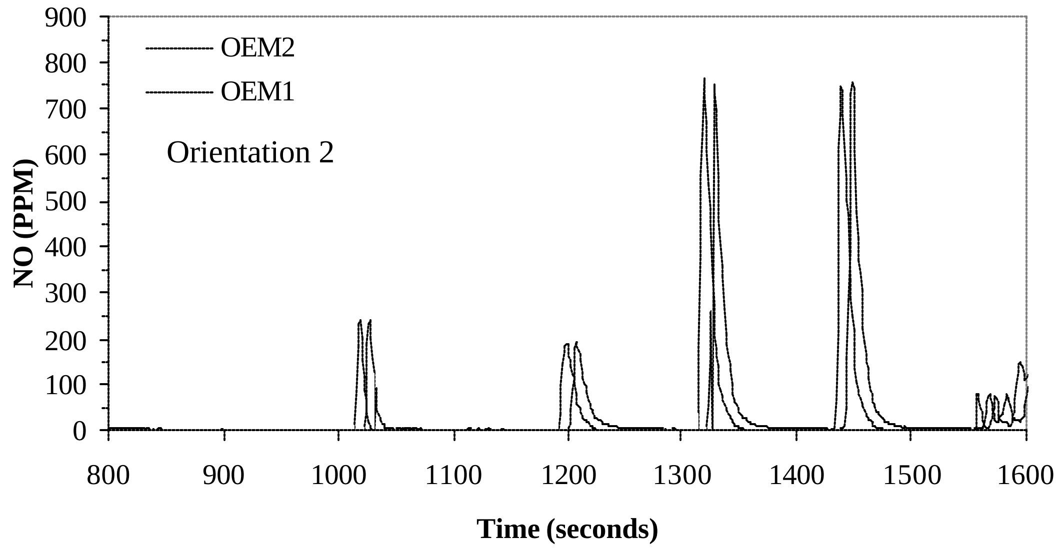
Appendix I. OEM-2100™ Comparison Test Results for 1999 Toyota Corolla





Appendix I.OEM-2100™ Comparison Test Results for 1999 Toyota Corolla





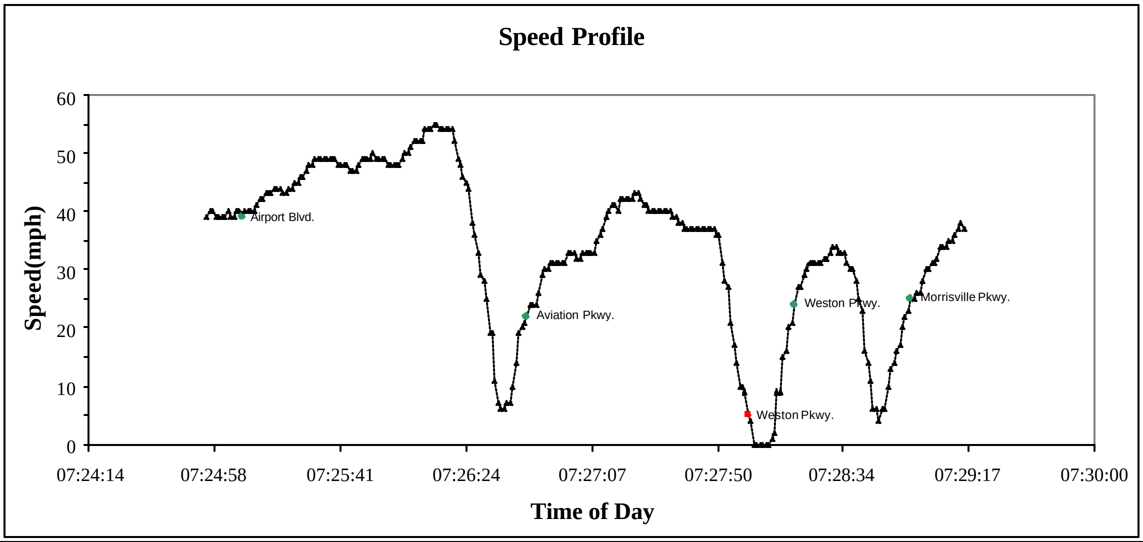
APPENDIX II

Sample File of Second-by-Second Engine and Emissions Data for One Corridor Run

Appendix II. Sample File of Second-by-Second Data for One Run

On-Board Emissions File Summary
File 422 - Chapel Hill Rd. South

Run Information					
Date:	10/10/00	**Assistant:**	na	**Outside Weather:**	open sky
Corridor:	Chapel Hill Rd.	**A/C (on/off):**	off	**Start Time:**	7:24:56
Direction:	South	**Peak Period:**	am	**End Time:**	7:29:16
Driver:	alper	**Outside Temp. (f):**	36f/66%	**Warning Flag:**	No
Vehicle Information					
Veh. Year:	1999	**Curb Weight:**	4722lb	**Fuel Delivery:**	FI
Veh. Model:	Ford	**Veh. Vin#:**	1FAFP522XXG149718	**Odometer:**	39548
Veh. Class.:	Taurus	**Engine Size:**	3.0L	**Cruise Control (yes/no):**	Yes
Body Type:	4S	**Transmission:**	Automatic	**Trailer (yes/no):**	No
Trim Line:	Sedan	**Fuel Type:**	Gasoline		
OEM Information					
OEM File:	422	**ES Adaptor:**	OBD2-K2A	**OEM Equipment #:**	1
OEM Bag:	1	**ES Interface:**	Specific		



Fuel Data Summary					
Fuel Composition	C (%)	H (%)	O (%)	**Fuel Density (g/gallon)**	2800
	85.0	15.0	0.00		

Speed Data Summary					
Hour		*# of Cells Accel. >10*	*# of Cells Accel. >15*	*# of Cells Speed 0, RPM>1000*	
Average Total Speed (mph)	33.74	0	0	0	
Average Running Speed (mph)	34.53				

Appendix II. Sample File of Second-by-Second Data for One Run (Cont.)

Real Time	recording	mph	Distance (mi)	accel[mph/s]	eng_rpm	coolant[C]	throttle[%]	intake_air[g/s]	dry_exh[g/s]	fuel[g/s]	fuel[mpg]	NOx[ppm]	HC[ppm]	CO[%]	CO2[%]	O2[%]
7:24:55	Bag 1	39	0.0108	0	1442	11	0	20.23	19.32	1.37	22.10	118	9	0.02	15.4	0
7:24:56	Bag 1	40	0.0111	1	1536	11	0	10.07	9.62	0.68	45.50	90	8	0.02	15.4	0
7:24:57	Bag 1	40	0.0111	0	1536	11	0	9.35	8.93	0.63	49.10	66	9	0.02	15.4	0
7:24:58	Bag 1	39	0.0108	-1	1556	11	0	7.90	7.56	0.54	56.60	51	10	0.02	15.4	0
7:24:59	Bag 1	39	0.0108	0	1552	11	0	7.76	7.44	0.53	57.60	39	9	0.02	15.3	0
7:25:00	Bag 1	39	0.0108	0	1538	11	0	7.76	7.41	0.53	57.60	33	9	0.02	15.4	0
7:25:01	Bag 1	39	0.0108	0	1543	11	0	7.62	7.29	0.52	58.60	17	10	0.02	15.4	0
7:25:02	Bag 1	40	0.0111	1	1541	11	0	9.39	9.05	0.64	48.70	14	9	0.02	15.3	-0.1
7:25:03	Bag 1	39	0.0108	-1	1541	11	0	9.74	9.36	0.66	45.90	12	8	0.02	15.3	0
7:25:04	Bag 1	39	0.0108	0	1590	11	0	10.25	9.85	0.70	43.60	11	8	0.02	15.3	0
7:25:05	Bag 1	40	0.0111	1	1590	11	0	8.96	8.66	0.61	51.20	9	9	0.02	15.2	0
7:25:06	Bag 1	40	0.0111	0	1588	11	0	8.64	8.32	0.58	53.30	8	7	0.02	15.2	0.1
7:25:07	Bag 1	39	0.0108	-1	1574	11	0	8.22	7.95	0.56	54.60	8	7	0.01	15.1	0.1
7:25:08	Bag 1	40	0.0111	1	1564	11	0	7.99	7.71	0.54	57.90	5	8	0.01	15.1	0.2
7:25:09	Bag 1	40	0.0111	0	1556	11	0	7.76	7.50	0.52	59.90	4	7	0.01	15	0.3
7:25:10	Bag 1	40	0.0111	0	1610	11	0	18.94	18.22	1.26	24.60	4	6	0.01	15	0.4
7:25:11	Bag 1	40	0.0111	0	1691	11	0	20.94	20.11	1.40	22.20	3	6	0	15.1	0.3
7:25:12	Bag 1	41	0.0114	1	1781	11	0	23.93	22.91	1.60	20.00	3	7	0.01	15.1	0.4
7:25:13	Bag 1	42	0.0117	1	1737	11	0	24.16	23.21	1.62	20.20	3	6	0.01	15.1	0.3
7:25:14	Bag 1	42	0.0117	0	1561	10	0	24.16	23.21	1.62	20.20	3	7	0.01	15.1	0.3
7:25:15	Bag 1	43	0.0119	1	1603	10	0	24.76	23.78	1.66	20.20	3	7	0.01	15.1	0.3
7:25:16	Bag 1	43	0.0119	0	1603	10	0	24.76	23.78	1.66	20.20	3	6	0.01	15.1	0.3
7:25:17	Bag 1	43	0.0119	0	1633	10	0	19.68	18.79	1.32	25.40	3	8	0.01	15.2	0.3
7:25:18	Bag 1	44	0.0122	1	1633	10	0	15.24	14.53	1.02	33.50	3	9	0.01	15.2	0.3
7:25:19	Bag 1	44	0.0122	0	1673	10	0	15.24	14.49	1.02	33.50	2	10	0.01	15.3	0.3
7:25:20	Bag 1	44	0.0122	0	1663	10	0	12.56	11.97	0.84	40.50	3	10	0.01	15.3	0.2
7:25:21	Bag 1	43	0.0119	-1	1660	10	0	12.81	12.21	0.86	38.80	3	9	0.01	15.3	0.2
7:25:22	Bag 1	43	0.0119	0	1683	10	0	12.98	12.38	0.88	38.10	10	9	0.01	15.4	0.1
7:25:23	Bag 1	44	0.0122	1	1683	10	0	16.65	15.96	1.13	30.30	12	7	0.01	15.3	0
7:25:24	Bag 1	44	0.0122	0	1677	10	0	20.33	19.42	1.38	24.80	13	9	0.02	15.4	0
7:25:25	Bag 1	45	0.0125	1	1675	10	0	21.71	20.73	1.47	23.80	13	8	0.03	15.4	0
7:25:26	Bag 1	45	0.0125	0	1672	10	0	21.71	20.82	1.48	23.70	13	9	0.03	15.4	-0.1
7:25:27	Bag 1	46	0.0128	1	1729	9	0	21.71	20.84	1.48	24.20	13	9	0.03	15.4	-0.1
7:25:28	Bag 1	46	0.0128	0	1729	9	0	20.91	20.08	1.42	25.20	12	8	0.02	15.3	0
7:25:29	Bag 1	47	0.0131	1	1765	9	0	17.69	17.00	1.20	30.50	8	7	0.02	15.3	0
7:25:30	Bag 1	48	0.0133	1	1817	9	0	16.35	15.70	1.11	33.70	7	8	0.01	15.3	0
7:25:31	Bag 1	48	0.0133	0	1817	9	0	16.35	15.65	1.10	33.80	5	7	0.01	15.3	0.1
7:25:32	Bag 1	49	0.0136	1	1843	9	0	13.39	12.85	0.91	42.00	4	7	0.01	15.3	0
7:25:33	Bag 1	49	0.0136	0	1843	9	0	13.39	12.82	0.91	42.10	3	8	0.01	15.3	0.1
7:25:34	Bag 1	49	0.0136	0	1862	9	0	9.28	8.92	0.63	60.50	2	7	0.01	15.3	0
7:25:35	Bag 1	49	0.0136	0	1880	9	0	11.08	10.65	0.75	50.70	2	8	0.02	15.3	0
7:25:36	Bag 1	49	0.0136	0	1884	9	0	11.08	10.65	0.75	50.70	3	8	0.02	15.3	0
7:25:37	Bag 1	49	0.0136	0	2069	9	0	23.70	22.78	1.61	23.70	3	8	0.01	15.3	0
7:25:38	Bag 1	49	0.0136	0	1999	9	0	22.40	21.53	1.52	25.10	2	9	0.01	15.3	0
7:25:39	Bag 1	49	0.0136	0	1952	9	0	21.53	20.74	1.46	26.10	3	7	0.01	15.3	0
7:25:40	Bag 1	48	0.0133	-1	1916	9	0	18.06	17.46	1.23	30.50	2	8	0.02	15.2	0
7:25:41	Bag 1	48	0.0133	0	1863	8	0	18.06	17.48	1.22	30.60	2	6	0.03	15.1	0.1
7:25:42	Bag 1	48	0.0133	0	1840	8	0	18.06	17.48	1.22	30.60	1	7	0.04	15.1	0.1
7:25:43	Bag 1	48	0.0133	0	1840	8	0	18.00	17.36	1.21	30.80	1	8	0.04	15.1	0.2
7:25:44	Bag 1	47	0.0131	-1	1817	8	0	17.78	16.99	1.19	30.70	1	9	0.04	15.2	0.3
7:25:45	Bag 1	47	0.0131	0	1816	8	0	18.20	17.34	1.22	30.00	1	8	0.06	15.2	0.3
7:25:46	Bag 1	47	0.0131	0	1816	8	0	18.20	17.40	1.23	29.80	3	9	0.09	15.2	0.2
7:25:47	Bag 1	48	0.0133	1	1803	8	0	18.06	17.32	1.22	30.50	3	9	0.11	15.2	0.1
7:25:48	Bag 1	49	0.0136	1	1803	8	0	21.90	20.97	1.48	25.70	4	9	0.1	15.2	0.1
7:25:49	Bag 1	49	0.0136	0	1852	8	0	21.90	20.90	1.48	25.70	4	10	0.09	15.3	0.1
7:25:50	Bag 1	49	0.0136	0	1852	8	0	21.31	20.37	1.44	26.40	4	10	0.05	15.3	0.1
7:25:51	Bag 1	49	0.0136	0	1862	8	0	21.16	20.31	1.44	26.50	2	9	0.05	15.3	0
7:25:52	Bag 1	50	0.0139	1	1873	8	0	9.98	9.55	0.68	57.40	2	9	0.04	15.4	0
7:25:53	Bag 1	49	0.0136	-1	1881	8	0	9.76	9.31	0.66	57.50	2	11	0.04	15.4	0
7:25:54	Bag 1	49	0.0136	0	1920	8	0	9.61	9.17	0.65	58.40	2	11	0.04	15.4	0

Appendix II. Sample File of Second-by-Second Data for One Run (Cont.)

Real Time	recording	mph	Distance (mi)	accel[mph/s]	eng_rpm	coolant[C]	throttle[%]	intake_air[g/s]	dry_exh[g/s]	fuel[g/s]	fuel[mpg]	NOx[ppm]	HC[ppm]	CO[%]	CO2[%]	O2[%]
7:25:55	Bag 1	49	0.0136	0	1906	8	0	9.24	8.82	0.63	60.80	3	10	0.03	15.4	0
7:25:56	Bag 1	49	0.0136	0	1892	8	0	9.29	8.82	0.63	60.40	5	10	0.03	15.5	0
7:25:57	Bag 1	48	0.0133	-1	1870	8	0	9.37	8.87	0.64	58.50	10	11	0.03	15.6	-0.1
7:25:58	Bag 1	48	0.0133	0	1868	8	0	9.47	8.94	0.64	58.00	15	12	0.04	15.6	0
7:25:59	Bag 1	48	0.0133	0	1859	8	0	11.83	11.15	0.80	46.50	21	12	0.05	15.6	0
7:26:00	Bag 1	48	0.0133	0	1899	8	0	21.25	20.21	1.45	25.80	23	12	0.06	15.5	-0.1
7:26:01	Bag 1	48	0.0133	0	1923	8	0	21.54	20.67	1.46	25.60	23	11	0.06	15.3	0
7:26:02	Bag 1	49	0.0136	1	2043	8	0	22.96	22.07	1.55	24.50	22	10	0.05	15.2	0.1
7:26:03	Bag 1	50	0.0139	1	1878	7	0	28.00	27.30	1.88	20.70	16	9	0.03	14.9	0.2
7:26:04	Bag 1	50	0.0139	0	1878	7	0	28.00	27.17	1.87	20.80	12	8	0.02	14.9	0.3
7:26:05	Bag 1	51	0.0142	1	1906	7	0	24.39	23.53	1.63	24.40	9	9	0.02	14.9	0.4
7:26:06	Bag 1	52	0.0144	1	1913	7	0	19.44	18.70	1.30	31.20	7	8	0.01	15	0.4
7:26:07	Bag 1	52	0.0144	0	1945	6	0	18.20	17.44	1.21	33.50	5	7	0.01	15	0.5
7:26:08	Bag 1	52	0.0144	0	1955	6	0	18.31	17.52	1.22	33.20	4	8	0.01	15.1	0.4
7:26:09	Bag 1	52	0.0144	0	1962	6	0	18.38	17.51	1.23	32.90	15	7	0.01	15.2	0.4
7:26:10	Bag 1	54	0.0150	2	1982	6	0	18.48	17.59	1.24	33.80	38	8	0.01	15.3	0.2
7:26:11	Bag 1	54	0.0150	0	2001	6	0	15.13	14.42	1.02	41.30	59	9	0.02	15.3	0.2
7:26:12	Bag 1	54	0.0150	0	2038	6	0	10.11	9.66	0.68	61.50	73	8	0.04	15.3	0.1
7:26:13	Bag 1	55	0.0153	1	2048	6	0	10.30	9.83	0.70	61.40	77	10	0.07	15.3	0.1
7:26:14	Bag 1	55	0.0153	0	2087	6	0	10.28	9.82	0.70	61.40	74	10	0.08	15.3	0.1
7:26:15	Bag 1	54	0.0150	-1	2081	6	0	10.21	9.79	0.69	60.60	70	9	0.07	15.3	0
7:26:16	Bag 1	54	0.0150	0	2083	6	0	10.17	9.76	0.69	60.80	46	7	0.04	15.3	0
7:26:17	Bag 1	54	0.0150	0	2094	7	0	9.98	9.57	0.68	62.10	41	6	0.03	15.3	0
7:26:18	Bag 1	54	0.0150	0	2082	7	0	9.79	9.39	0.66	63.40	38	7	0.02	15.3	0.1
7:26:19	Bag 1	54	0.0150	0	2082	7	0	9.79	9.45	0.66	63.20	35	8	0.02	15.2	0
7:26:20	Bag 1	52	0.0144	-2	2080	7	0	10.02	9.64	0.68	59.70	30	7	0.02	15.2	0.1
7:26:21	Bag 1	49	0.0136	-3	2079	7	0	9.40	9.10	0.64	59.90	28	8	0.02	15.1	0
7:26:22	Bag 1	48	0.0133	-1	1962	7	0	9.24	8.98	0.62	59.90	21	7	0.02	15	0.2
7:26:23	Bag 1	46	0.0128	-2	1895	7	0	9.18	8.90	0.61	58.40	14	6	0.01	14.9	0.4
7:26:24	Bag 1	45	0.0125	-1	1851	7	0	9.14	8.86	0.61	57.70	10	6	0.01	14.8	0.5
7:26:25	Bag 1	44	0.0122	-1	1789	7	0	8.77	8.50	0.58	58.80	8	7	0.01	14.8	0.5
7:26:26	Bag 1	38	0.0106	-6	1745	7	0	8.03	7.76	0.53	55.70	6	7	0	14.8	0.6
7:26:27	Bag 1	36	0.0100	-2	1678	7	0	7.74	7.44	0.51	54.70	5	7	0	14.9	0.6
7:26:28	Bag 1	33	0.0092	-3	1491	7	0	7.16	6.87	0.47	54.20	4	6	0	14.9	0.6
7:26:29	Bag 1	29	0.0081	-4	1451	7	0	6.14	5.88	0.40	55.80	4	5	0	14.9	0.7
7:26:30	Bag 1	28	0.0078	-1	1292	7	0	6.07	5.82	0.40	54.40	5	7	0	14.9	0.6
7:26:31	Bag 1	25	0.0069	-3	1155	7	0	5.77	5.53	0.38	50.80	5	7	0	15	0.5
7:26:32	Bag 1	19	0.0053	-6	1155	7	0	5.72	5.47	0.38	39.00	4	6	0	15	0.6
7:26:33	Bag 1	19	0.0053	0	1233	7	0	5.72	5.45	0.38	38.90	4	8	0	15.1	0.5
7:26:34	Bag 1	11	0.0031	-8	1081	7	0	5.22	4.92	0.35	24.70	3	8	0	15.3	0.5
7:26:35	Bag 1	7	0.0019	-4	1043	7	0	5.11	4.81	0.34	16.00	4	8	0	15.3	0.5
7:26:36	Bag 1	6	0.0017	-1	917	7	0	5.08	4.78	0.34	13.80	5	9	0	15.4	0.4
7:26:37	Bag 1	6	0.0017	0	852	7	0	5.02	4.72	0.33	13.90	5	9	0	15.4	0.4
7:26:38	Bag 1	7	0.0019	1	820	7	0	4.99	4.71	0.33	16.30	5	8	0	15.4	0.3
7:26:39	Bag 1	7	0.0019	0	824	7	0	15.75	14.87	1.05	5.20	4	10	0	15.4	0.3
7:26:40	Bag 1	10	0.0028	3	824	7	0	21.11	19.93	1.41	5.50	3	10	0	15.4	0.3
7:26:41	Bag 1	14	0.0039	4	1733	6	0	29.15	27.91	1.96	5.60	2	10	0	15.2	0.2
7:26:42	Bag 1	19	0.0053	5	1876	6	0	26.33	25.26	1.77	8.30	2	9	0	15.2	0.2
7:26:43	Bag 1	20	0.0056	1	2447	6	0	25.61	24.56	1.72	9.00	2	10	0	15.2	0.2
7:26:44	Bag 1	21	0.0058	1	2002	5	0	24.16	23.18	1.62	10.10	1	10	0	15.2	0.2
7:26:45	Bag 1	22	0.0061	1	1982	5	0	23.90	22.79	1.61	10.60	1	9	0	15.3	0.2
7:26:46	Bag 1	24	0.0067	2	1900	5	0	22.87	21.81	1.54	12.10	1	8	0	15.3	0.2
7:26:47	Bag 1	24	0.0067	0	1900	5	0	5.72	5.45	0.38	48.50	2	8	0.02	15.3	0.2
7:26:48	Bag 1	24	0.0067	0	1517	5	0	5.72	5.45	0.38	48.50	3	8	0.03	15.3	0.2
7:26:49	Bag 1	26	0.0072	2	1495	5	0	24.30	23.19	1.64	12.30	6	9	0.04	15.3	0.1
7:26:50	Bag 1	29	0.0081	3	1490	5	0	24.30	23.27	1.65	13.70	19	9	0.04	15.3	0.1
7:26:51	Bag 1	30	0.0083	1	1658	5	0	23.24	22.25	1.57	14.80	36	10	0.04	15.3	0.1
7:26:52	Bag 1	30	0.0083	0	1653	5	0	12.98	12.45	0.88	26.50	40	8	0.03	15.3	0
7:26:53	Bag 1	31	0.0086	1	1651	5	0	7.85	7.54	0.53	45.30	42	9	0.03	15.3	0
7:26:54	Bag 1	31	0.0086	0	1657	5	0	8.82	8.41	0.60	40.30	43	10	0.05	15.4	0

Appendix II. Sample File of Second-by-Second Data for One Run (Cont.)

Real Time	recording	mph	Distance (mi)	accel[mph/s]	eng_rpm	coolant[C]	throttle[%]	intake_air[g/s]	dry_exh[g/s]	fuel[g/s]	fuel[mpg]	NOx[ppm]	HC[ppm]	CO[%]	CO2[%]	O2[%]
7:26:55	Bag 1	31	0.0086	0	1657	5	0	9.12	8.70	0.62	38.90	45	10	0.08	15.4	0
7:26:56	Bag 1	31	0.0086	0	1734	5	0	9.42	9.02	0.64	37.70	49	9	0.09	15.3	0
7:26:57	Bag 1	31	0.0086	0	1743	5	0	13.39	12.71	0.91	26.60	49	9	0.06	15.4	0.1
7:26:58	Bag 1	31	0.0086	0	1757	5	0	13.39	12.78	0.91	26.60	45	9	0.07	15.3	0.1
7:26:59	Bag 1	33	0.0092	2	1762	5	0	10.25	9.78	0.69	37.00	43	9	0.09	15.3	0.1
7:27:00	Bag 1	33	0.0092	0	1782	5	0	9.94	9.50	0.67	38.10	43	11	0.12	15.2	0.1
7:27:01	Bag 1	33	0.0092	0	1245	5	0	8.68	8.33	0.59	43.60	43	11	0.13	15.2	0.1
7:27:02	Bag 1	32	0.0089	-1	1245	5	0	8.96	8.60	0.61	40.90	41	12	0.14	15.2	0
7:27:03	Bag 1	32	0.0089	0	1283	5	0	8.96	8.50	0.60	41.30	29	12	0.1	15.3	0.2
7:27:04	Bag 1	33	0.0092	1	1254	5	0	13.12	12.42	0.88	29.20	22	12	0.07	15.3	0.3
7:27:05	Bag 1	33	0.0092	0	1248	5	0	12.70	12.08	0.85	30.20	17	12	0.05	15.2	0.3
7:27:06	Bag 1	33	0.0092	0	1249	5	0	12.61	12.02	0.85	30.40	12	12	0.04	15.2	0.3
7:27:07	Bag 1	33	0.0092	0	1269	5	0	15.34	14.63	1.03	25.00	9	10	0.04	15.2	0.3
7:27:08	Bag 1	33	0.0092	0	1274	5	0	15.34	14.68	1.03	24.90	8	11	0.03	15.2	0.2
7:27:09	Bag 1	35	0.0097	2	1288	5	0	19.31	18.50	1.30	20.90	5	10	0.02	15.2	0.2
7:27:10	Bag 1	36	0.0100	1	1288	5	0	20.14	19.10	1.36	20.70	4	11	0.02	15.4	0.2
7:27:11	Bag 1	37	0.0103	1	1357	5	0	20.97	19.76	1.41	20.40	3	11	0.01	15.5	0.2
7:27:12	Bag 1	39	0.0108	2	1420	5	0	19.77	18.70	1.34	22.70	3	10	0.01	15.5	0.1
7:27:13	Bag 1	40	0.0111	1	1515	5	0	19.33	18.23	1.31	23.80	2	11	0.01	15.5	0.1
7:27:14	Bag 1	41	0.0114	1	1514	5	0	18.66	17.55	1.26	25.30	3	11	0.01	15.6	0.1
7:27:15	Bag 1	41	0.0114	0	1518	5	0	17.02	16.00	1.15	27.70	3	10	0.01	15.6	0.1
7:27:16	Bag 1	40	0.0111	-1	1535	4	0	10.44	9.81	0.71	44.10	6	13	0.03	15.6	0.1
7:27:17	Bag 1	42	0.0117	2	1535	4	0	17.14	16.09	1.16	28.20	6	12	0.04	15.6	0.1
7:27:18	Bag 1	42	0.0117	0	1649	5	0	17.14	16.19	1.16	28.10	8	12	0.06	15.5	0
7:27:19	Bag 1	42	0.0117	0	1580	4	0	16.95	16.09	1.15	28.50	10	13	0.06	15.4	0.1
7:27:20	Bag 1	42	0.0117	0	1580	4	0	20.79	19.77	1.41	23.20	10	13	0.06	15.4	0.1
7:27:21	Bag 1	42	0.0117	0	1613	4	0	20.79	19.81	1.41	23.10	11	12	0.06	15.4	0
7:27:22	Bag 1	43	0.0119	1	1619	4	0	21.23	20.31	1.45	23.10	18	14	0.05	15.4	-0.1
7:27:23	Bag 1	43	0.0119	0	1621	4	0	21.34	20.36	1.45	23.10	22	12	0.04	15.4	0
7:27:24	Bag 1	42	0.0117	-1	1625	4	0	20.23	19.32	1.37	23.80	23	11	0.03	15.4	0
7:27:25	Bag 1	41	0.0114	-1	1628	4	0	16.27	15.61	1.11	28.80	24	10	0.03	15.4	-0.1
7:27:26	Bag 1	41	0.0114	0	1590	4	0	13.63	13.09	0.93	34.50	23	9	0.03	15.3	0
7:27:27	Bag 1	40	0.0111	-1	1582	4	0	14.36	13.82	0.98	31.90	23	9	0.03	15.3	0
7:27:28	Bag 1	40	0.0111	0	1570	4	0	14.36	13.85	0.98	31.80	22	9	0.03	15.3	-0.1
7:27:29	Bag 1	40	0.0111	0	1575	4	0	15.75	15.17	1.07	29.00	18	9	0.03	15.3	-0.1
7:27:30	Bag 1	40	0.0111	0	1585	4	0	14.61	14.03	0.99	31.40	18	10	0.05	15.3	0
7:27:31	Bag 1	40	0.0111	0	1513	4	0	10.07	9.66	0.68	45.50	19	11	0.06	15.3	0
7:27:32	Bag 1	40	0.0111	0	1513	4	0	14.41	13.81	0.98	31.80	20	10	0.08	15.3	0
7:27:33	Bag 1	40	0.0111	0	1522	4	0	14.41	13.80	0.98	31.80	20	10	0.1	15.3	0
7:27:34	Bag 1	40	0.0111	0	1539	4	0	8.96	8.58	0.61	51.10	21	10	0.1	15.3	0
7:27:35	Bag 1	39	0.0108	-1	1539	4	0	7.11	6.83	0.48	62.60	19	10	0.09	15.3	-0.1
7:27:36	Bag 1	39	0.0108	0	1532	4	0	7.11	6.81	0.48	62.80	18	10	0.09	15.3	0
7:27:37	Bag 1	38	0.0106	-1	1532	4	0	13.72	13.14	0.93	31.70	17	9	0.1	15.3	0
7:27:38	Bag 1	38	0.0106	0	1532	4	0	13.72	13.14	0.93	31.70	18	10	0.09	15.3	0
7:27:39	Bag 1	37	0.0103	-1	1679	4	0	20.70	19.84	1.41	20.50	20	11	0.07	15.3	0
7:27:40	Bag 1	37	0.0103	0	1728	4	0	18.89	18.12	1.28	22.40	21	11	0.07	15.3	0
7:27:41	Bag 1	37	0.0103	0	1402	4	0	17.69	16.99	1.20	23.90	22	10	0.06	15.3	0
7:27:42	Bag 1	37	0.0103	0	1419	4	0	23.56	22.70	1.60	18.00	20	11	0.06	15.2	0
7:27:43	Bag 1	37	0.0103	0	1436	4	0	22.67	21.79	1.53	18.80	21	11	0.05	15.2	0.1
7:27:44	Bag 1	37	0.0103	0	1399	4	0	21.34	20.51	1.44	19.90	21	10	0.05	15.2	0.1
7:27:45	Bag 1	37	0.0103	0	1414	4	0	20.50	19.71	1.39	20.80	21	9	0.04	15.2	0.1
7:27:46	Bag 1	37	0.0103	0	1475	4	0	17.14	16.48	1.16	24.90	20	10	0.03	15.2	0.1
7:27:47	Bag 1	37	0.0103	0	1467	4	0	20.14	19.32	1.36	21.20	19	11	0.02	15.2	0.2
7:27:48	Bag 1	37	0.0103	0	1467	4	0	19.65	18.82	1.33	21.70	34	9	0.01	15.3	0.1
7:27:49	Bag 1	37	0.0103	0	1420	4	0	17.23	16.49	1.16	24.70	47	9	0.01	15.3	0.1
7:27:50	Bag 1	36	0.0100	-1	1420	4	0	6.42	6.13	0.44	64.30	58	8	0.01	15.4	0
7:27:51	Bag 1	36	0.0100	0	1442	4	0	6.42	6.13	0.44	64.30	66	10	0.02	15.4	0
7:27:52	Bag 1	31	0.0086	-5	1403	4	0	6.28	6.00	0.43	56.60	76	9	0.02	15.4	0
7:27:53	Bag 1	28	0.0078	-3	1282	4	0	5.97	5.70	0.41	53.70	83	9	0.02	15.4	0
7:27:54	Bag 1	27	0.0075	-1	1222	4	0	5.82	5.56	0.39	53.20	86	9	0.03	15.4	0

Appendix II. Sample File of Second-by-Second Data for One Run (Cont.)

Real Time	recording	mph	Distance (mi)	accel[mph/s]	eng_rpm	coolant[C]	throttle[%]	intake_air[g/s]	dry_exh[g/s]	fuel[g/s]	fuel[mpg]	NOx[ppm]	HC[ppm]	CO[%]	CO2[%]	O2[%]
7:27:55	Bag 1	21	0.0058	-6	1163	4	0	5.31	5.06	0.36	45.30	80	9	0.05	15.4	0
7:27:56	Bag 1	17	0.0047	-4	1124	4	0	4.92	4.72	0.34	39.50	71	10	0.06	15.3	-0.1
7:27:57	Bag 1	14	0.0039	-3	1131	4	0	4.66	4.47	0.32	34.40	63	10	0.06	15.3	0
7:27:58	Bag 1	10	0.0028	-4	1039	4	0	4.57	4.43	0.31	24.90	53	11	0.06	15.2	-0.1
7:27:59	Bag 1	10	0.0028	0	902	4	0	4.56	4.42	0.31	25.00	45	10	0.05	15.2	-0.1
7:28:00	Bag 1	9	0.0025	-1	959	4	0	4.52	4.35	0.31	22.90	41	9	0.05	15.2	0.1
7:28:01	Bag 1	5	0.0014	-4	947	4	0	4.52	4.35	0.31	12.70	26	8	0.02	15.2	0.1
7:28:02	Bag 1	4	0.0011	-1	897	4	0	4.50	4.34	0.30	10.20	21	9	0.02	15.2	0.1
7:28:03	Bag 1	0	0.0000	-4	813	5	0	4.43	4.26	0.30	NA	17	9	0.02	15.2	0.1
7:28:04	Bag 1	0	0.0000	0	789	5	0	4.34	4.15	0.29	NA	13	9	0.01	15.3	0.2
7:28:05	Bag 1	0	0.0000	0	789	5	0	4.30	4.08	0.29	NA	10	9	0.01	15.5	0.1
7:28:06	Bag 1	0	0.0000	0	753	5	0	4.29	4.06	0.29	NA	10	8	0.01	15.5	0.1
7:28:07	Bag 1	0	0.0000	0	755	5	0	4.20	3.97	0.28	NA	8	8	0.01	15.5	0.1
7:28:08	Bag 1	0	0.0000	0	740	5	0	4.20	3.97	0.28	NA	4	9	0.01	15.5	0.1
7:28:09	Bag 1	1	0.0003	1	729	5	0	7.19	6.80	0.49	1.60	4	10	0.01	15.5	0.1
7:28:10	Bag 1	2	0.0006	1	750	5	0	9.19	8.66	0.62	2.50	4	10	0.01	15.5	0.2
7:28:11	Bag 1	9	0.0025	7	986	5	0	21.43	20.26	1.45	4.80	3	10	0.01	15.5	0.1
7:28:12	Bag 1	9	0.0025	0	1341	5	0	21.43	20.18	1.44	4.90	3	10	0.01	15.5	0.2
7:28:13	Bag 1	15	0.0042	6	1947	5	0	26.70	25.14	1.80	6.50	2	9	0.02	15.5	0.2
7:28:14	Bag 1	16	0.0044	1	1947	5	0	28.10	26.44	1.89	6.60	3	11	0.03	15.5	0.2
7:28:15	Bag 1	20	0.0056	4	2581	4	0	33.68	31.82	2.28	6.80	1	11	0.03	15.5	0.1
7:28:16	Bag 1	21	0.0058	1	2581	4	0	33.77	31.84	2.27	7.20	2	12	0.02	15.5	0.2
7:28:17	Bag 1	24	0.0067	3	2192	4	0	34.14	32.31	2.30	8.10	2	11	0.02	15.4	0.2
7:28:18	Bag 1	27	0.0075	3	2192	4	0	32.62	30.85	2.20	9.50	1	12	0.01	15.5	0.1
7:28:19	Bag 1	27	0.0075	0	2370	4	0	32.62	30.79	2.20	9.50	2	12	0.01	15.5	0.2
7:28:20	Bag 1	29	0.0081	2	2370	4	0	30.66	28.87	2.07	10.90	16	11	0.01	15.5	0.2
7:28:21	Bag 1	30	0.0083	1	2117	3	0	30.17	28.43	2.04	11.40	75	11	0.01	15.6	0.1
7:28:22	Bag 1	31	0.0086	1	2010	3	0	21.34	20.15	1.45	16.70	111	10	0.01	15.6	0
7:28:23	Bag 1	31	0.0086	0	1956	3	0	14.36	13.50	0.97	24.80	131	12	0.01	15.6	0.1
7:28:24	Bag 1	31	0.0086	0	1695	3	0	12.61	11.90	0.86	28.20	131	10	0.01	15.6	0
7:28:25	Bag 1	31	0.0086	0	1695	3	0	19.85	18.70	1.35	17.90	117	12	0.01	15.6	0
7:28:26	Bag 1	31	0.0086	0	1687	4	0	24.67	23.10	1.67	14.50	107	10	0.01	15.7	0.1
7:28:27	Bag 1	32	0.0089	1	1708	4	0	22.96	21.52	1.56	16.00	59	11	0.03	15.7	0
7:28:28	Bag 1	32	0.0089	0	1708	4	0	22.96	21.89	1.56	15.90	40	10	0.03	15.5	-0.1
7:28:29	Bag 1	33	0.0092	1	1850	3	0	20.88	19.93	1.42	18.10	32	11	0.03	15.4	0
7:28:30	Bag 1	34	0.0094	1	1744	3	0	17.88	17.11	1.22	21.70	29	12	0.03	15.4	-0.1
7:28:31	Bag 1	34	0.0094	0	1322	3	0	16.55	15.82	1.12	23.50	29	11	0.02	15.4	0
7:28:32	Bag 1	33	0.0092	-1	1264	3	0	11.22	10.72	0.76	33.70	31	10	0.02	15.4	0
7:28:33	Bag 1	33	0.0092	0	1264	3	0	11.22	10.72	0.76	33.70	36	10	0.02	15.4	0
7:28:34	Bag 1	33	0.0092	0	1274	3	0	7.80	7.47	0.53	48.40	52	9	0.02	15.4	-0.1
7:28:35	Bag 1	31	0.0086	-2	1281	4	0	6.51	6.23	0.44	54.50	70	9	0.02	15.4	0
7:28:36	Bag 1	30	0.0083	-1	1283	4	0	6.19	5.91	0.42	55.60	86	8	0.02	15.4	0
7:28:37	Bag 1	30	0.0083	0	1244	4	0	6.19	5.96	0.42	55.30	93	9	0.03	15.3	-0.1
7:28:38	Bag 1	28	0.0078	-2	1219	4	0	6.19	5.91	0.42	51.80	89	10	0.03	15.4	0
7:28:39	Bag 1	25	0.0069	-3	1206	4	0	6.02	5.77	0.41	47.60	85	9	0.03	15.3	0
7:28:40	Bag 1	23	0.0064	-2	1155	4	0	5.91	5.67	0.40	44.60	76	9	0.03	15.3	0
7:28:41	Bag 1	16	0.0044	-7	1177	4	0	5.49	5.23	0.37	33.40	33	9	0.02	15.4	0
7:28:42	Bag 1	14	0.0039	-2	1211	4	0	5.34	5.05	0.36	30.20	24	9	0.01	15.5	0.1
7:28:43	Bag 1	11	0.0031	-3	955	4	0	5.12	4.84	0.35	24.70	19	9	0.01	15.5	0.1
7:28:44	Bag 1	6	0.0017	-5	920	4	0	5.17	4.89	0.35	13.40	14	10	0.01	15.5	0.1
7:28:45	Bag 1	6	0.0017	0	849	4	0	5.15	4.87	0.35	13.40	11	10	0.01	15.5	0.1
7:28:46	Bag 1	4	0.0011	-2	771	4	0	5.08	4.81	0.34	9.10	10	10	0.01	15.5	0.1
7:28:47	Bag 1	6	0.0017	2	771	4	0	16.44	15.55	1.11	4.20	7	9	0.01	15.5	0.1
7:28:48	Bag 1	6	0.0017	0	777	4	0	16.44	15.49	1.11	4.20	5	10	0.01	15.5	0.2
7:28:49	Bag 1	10	0.0028	4	1447	4	0	18.66	17.57	1.26	6.20	3	10	0	15.6	0.1
7:28:50	Bag 1	13	0.0036	3	1581	4	0	24.13	22.84	1.63	6.20	3	11	0	15.5	0.1
7:28:51	Bag 1	14	0.0039	1	1871	4	0	25.50	24.12	1.72	6.30	3	10	0.01	15.5	0.1
7:28:52	Bag 1	16	0.0044	2	1871	4	0	26.46	25.04	1.79	7.00	3	10	0	15.5	0.1
7:28:53	Bag 1	17	0.0047	1	2369	4	0	26.70	25.27	1.80	7.30	3	10	0	15.5	0.1
7:28:54	Bag 1	20	0.0056	3	2120	4	0	28.46	26.93	1.92	8.10	3	10	0	15.5	0.1

Appendix II. Sample File of Second-by-Second Data for One Run (Cont.)

Real Time	recording	mph	Distance (mi)	accel[mph/s]	eng_rpm	coolant[C]	throttle[%]	intake_air[g/s]	dry_exh[g/s]	fuel[g/s]	fuel[mpg]	NOx[ppm]	HC[ppm]	CO[%]	CO2[%]	O2[%]
7:28:55	Bag 1	22	0.0061	2	1954	4	0	29.93	28.31	2.02	8.50	2	11	0.01	15.5	0.1
7:28:56	Bag 1	23	0.0064	1	2128	3	0	30.91	29.07	2.09	8.60	4	9	0.01	15.6	0.1
7:28:57	Bag 1	25	0.0069	2	1973	3	0	19.49	18.33	1.32	14.80	10	11	0	15.6	0.1
7:28:58	Bag 1	25	0.0069	0	1741	3	0	19.49	18.33	1.32	14.80	18	12	0.01	15.6	0.1
7:28:59	Bag 1	26	0.0072	1	1751	3	0	20.42	19.20	1.38	14.70	25	10	0.01	15.6	0.1
7:29:00	Bag 1	26	0.0072	0	1751	3	0	19.44	18.25	1.32	15.30	28	12	0.01	15.7	0
7:29:01	Bag 1	28	0.0078	2	1466	3	0	15.52	14.56	1.05	20.70	28	12	0.01	15.7	0
7:29:02	Bag 1	30	0.0083	2	1466	3	0	19.49	18.23	1.32	17.70	26	11	0.02	15.7	0.1
7:29:03	Bag 1	30	0.0083	0	1604	3	0	19.49	18.25	1.32	17.60	19	13	0.05	15.7	0
7:29:04	Bag 1	31	0.0086	1	1641	3	0	15.24	14.41	1.04	23.20	16	13	0.07	15.6	-0.1
7:29:05	Bag 1	31	0.0086	0	1641	3	0	15.24	14.34	1.04	23.30	15	12	0.06	15.6	0
7:29:06	Bag 1	32	0.0089	1	1699	3	0	20.51	19.31	1.40	17.80	15	11	0.05	15.7	0
7:29:07	Bag 1	34	0.0094	2	1714	3	0	19.85	18.75	1.35	19.60	14	10	0.03	15.6	0
7:29:08	Bag 1	34	0.0094	0	1757	3	0	19.68	18.52	1.34	19.80	15	10	0.03	15.6	0
7:29:09	Bag 1	34	0.0094	0	1484	3	0	21.43	20.16	1.46	18.20	17	11	0.02	15.7	0
7:29:10	Bag 1	35	0.0097	1	1302	3	0	21.65	20.47	1.48	18.50	20	10	0.01	15.6	-0.1
7:29:11	Bag 1	35	0.0097	0	1323	3	0	21.80	20.49	1.48	18.40	22	10	0.01	15.7	0
7:29:12	Bag 1	36	0.0100	1	1335	3	0	22.26	21.20	1.52	18.50	22	9	0.01	15.5	-0.1
7:29:13	Bag 1	37	0.0103	1	1352	3	0	22.96	22.02	1.56	18.40	24	9	0.01	15.4	-0.1
7:29:14	Bag 1	38	0.0106	1	1392	3	0	19.22	18.43	1.31	22.60	24	11	0.01	15.4	0
7:29:15	Bag 1	37	0.0103	-1	1396	3	0	17.47	16.86	1.19	24.20	22	10	0.02	15.3	-0.1

APPENDIX III

- Results of Kolmogorov-Smirnov Test for Cumulative Distribution Function Comparison
- Driver Aggressiveness Analysis for Drivers AU and JC
- Modal Emission Rates for Each Vehicle ID
- Correlation between Speed, Control Delay, and Corridor Stops for NC 54 and Miami Boulevard Runs
- Trends between Control Delay and Emissions, and Corridor Stops and Emissions, for Each Vehicle Emissions Group

Appendix III. Results of Kolmogorov-Smirnov Tests

AC Effect for HC Emissions:
data: x: logHCgmi with AC = 0 , and y: logHCgmi with AC = 1
ks = 0.2308, p-value = 0.3606
alternative hypothesis:
cdf of x: logHCgmi with AC = 0 does not equal the
cdf of y: logHCgmi with AC = 1 for at least one sample point.

Driver Effect for HC Emissions:
data: x: logHCgmi with Driver = 1 , and y: logHCgmi with Driver = 2
ks = 0.1686, p-value = 0.4571
alternative hypothesis:
cdf of x: logHCgmi with Driver = 1 does not equal the
cdf of y: logHCgmi with Driver = 2 for at least one sample point.

Driver Effect for HC Emissions:
data: x: logHCgmi with Driver = 1 , and y: logHCgmi with Driver = 2
ks = 0.3318, p-value = 0.0151
alternative hypothesis:
cdf of x: logHCgmi with Driver = 1 does not equal the
cdf of y: logHCgmi with Driver = 2 for at least one sample point.

AC Effect for HC Emissions:
data: x: logHCgmi with AC = 0 , and y: logHCgmi with AC = 1
ks = 0.4671, p-value = 0.001
alternative hypothesis:
cdf of x: logHCgmi with AC = 0 does not equal the
cdf of y: logHCgmi with AC = 1 for at least one sample point.

Date Effect for HC Emissions

	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Date	6	1.45475	0.2424584	9.997131	6.781594e-008
Residuals	68	1.64919	0.0242528		

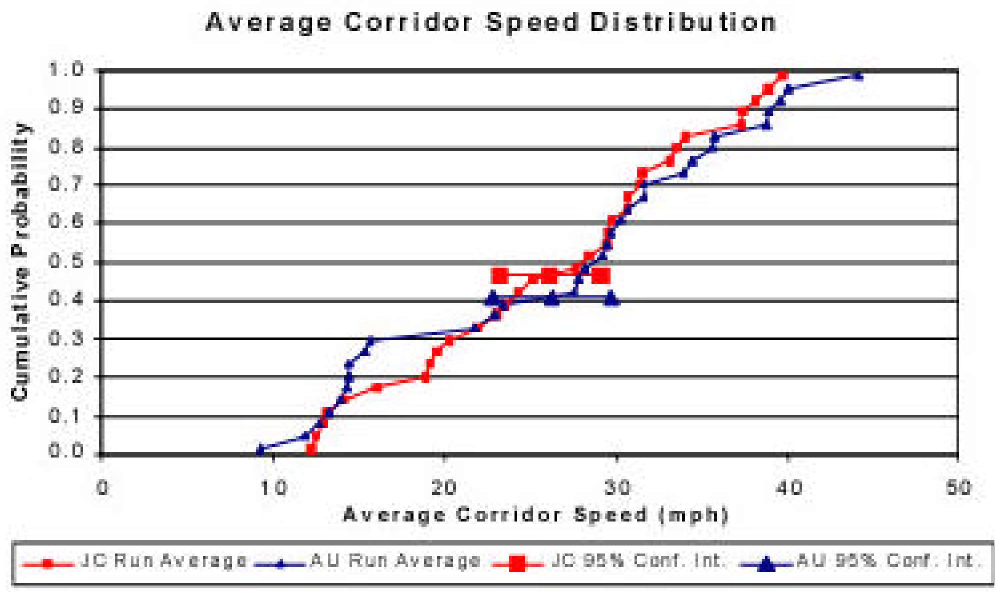
AC Effect for NO Emissions:
data: x: logNOgmi with AC = 0 , and y: logNOgmi with AC = 1
ks = 0.8353, p-value = 0
alternative hypothesis:
cdf of x: logNOgmi with AC = 0 does not equal the
cdf of y: logNOgmi with AC = 1 for at least one sample point.

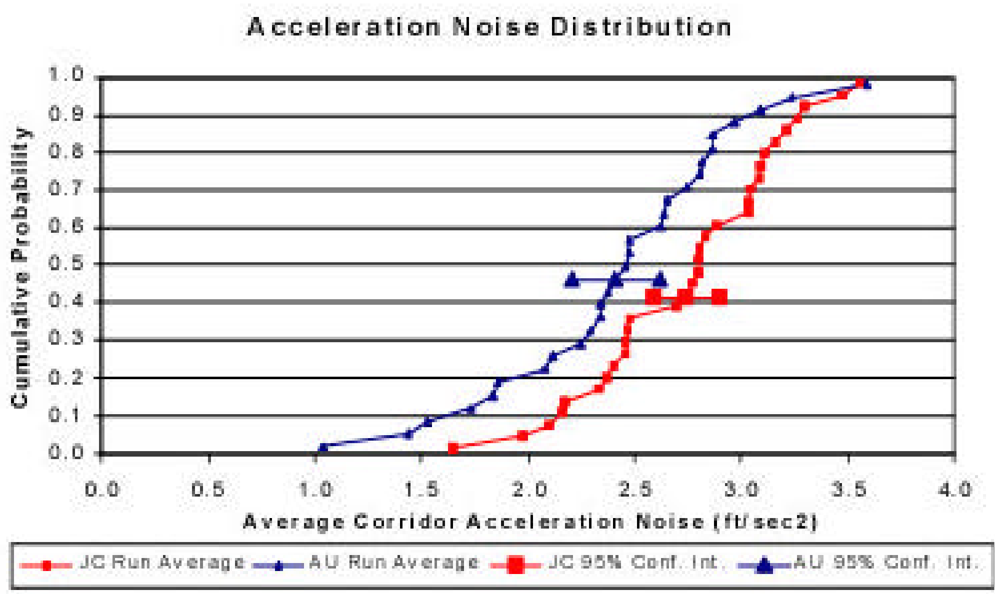
Date Effect for NO Emissions:

	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Date	7	0.260261	0.03718008	2.056283	0.05747766
Residuals	83	1.500740	0.01808121		

Driver Effect for CO Emissions:
data: x: logCOgmi with Driver = 1 , and y: logCOgmi with Driver = 2
ks = 0.5296, p-value = 0
alternative hypothesis:
cdf of x: logCOgmi with Driver = 1 does not equal the
cdf of y: logCOgmi with Driver = 2 for at least one sample point.

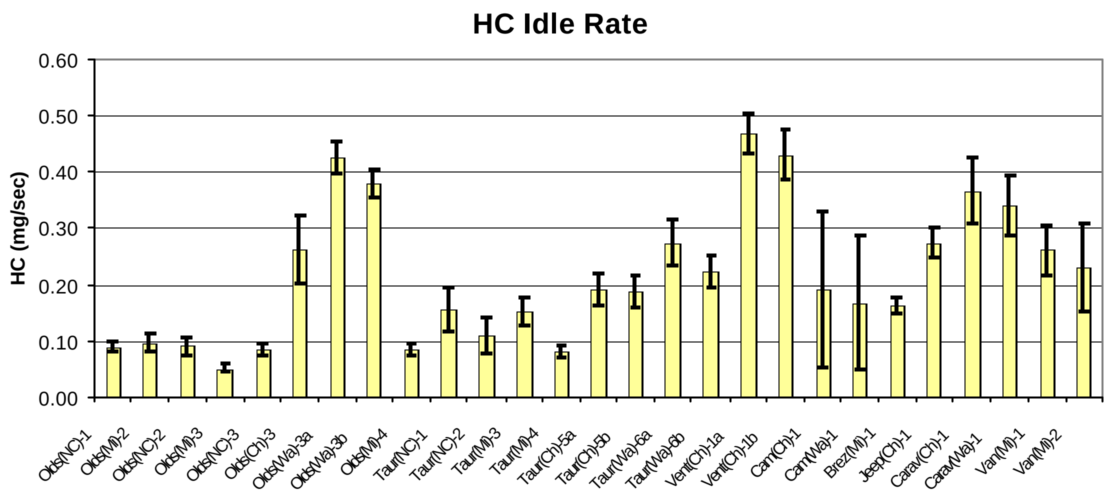
<u>**Appendix III. Driver Aggressiveness Analysis for Drivers AU and JC**</u>

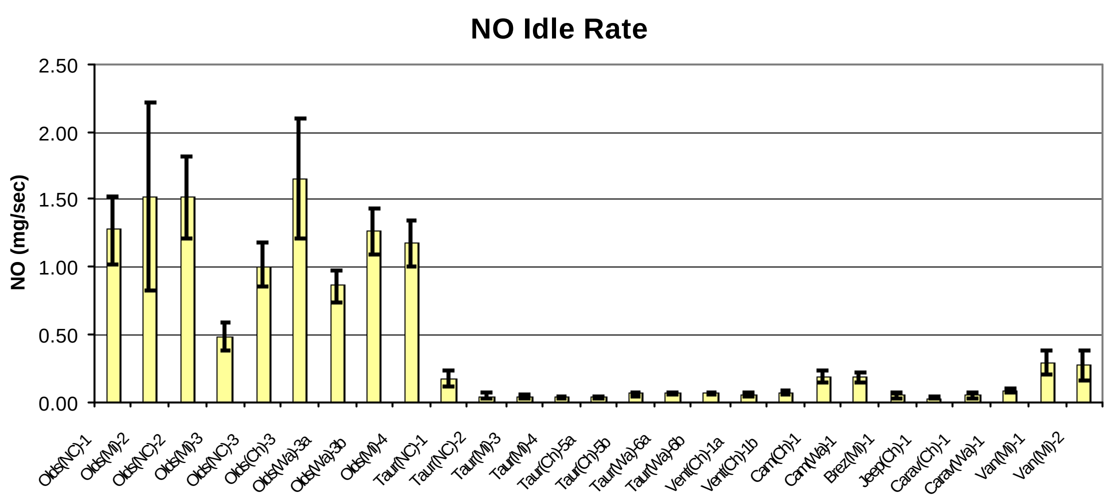


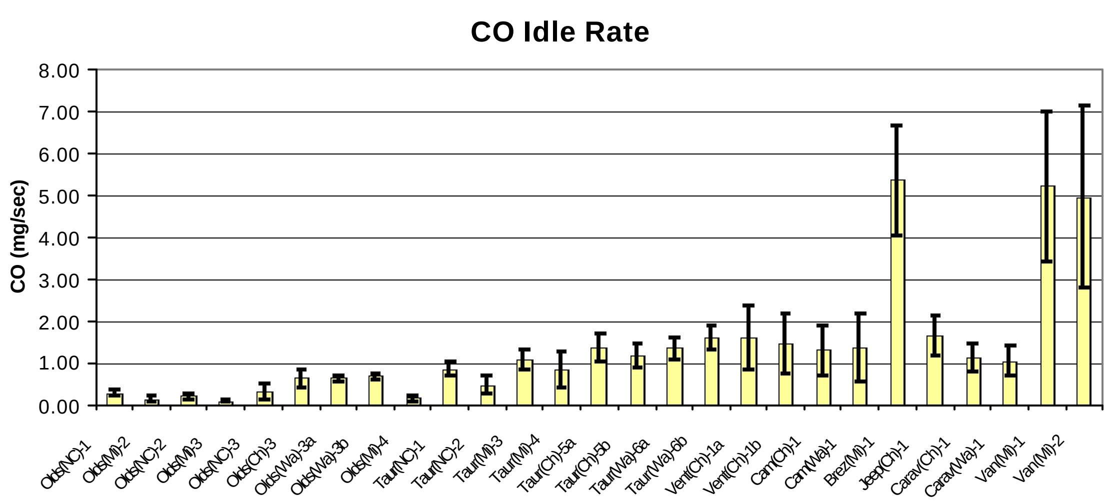


Notes: Data represent 32 runs driven on Chapel Hill Road with Ford Taurus during the p.m. peak. Both average speed and acceleration noise are not statistically different between drivers JC and AU.

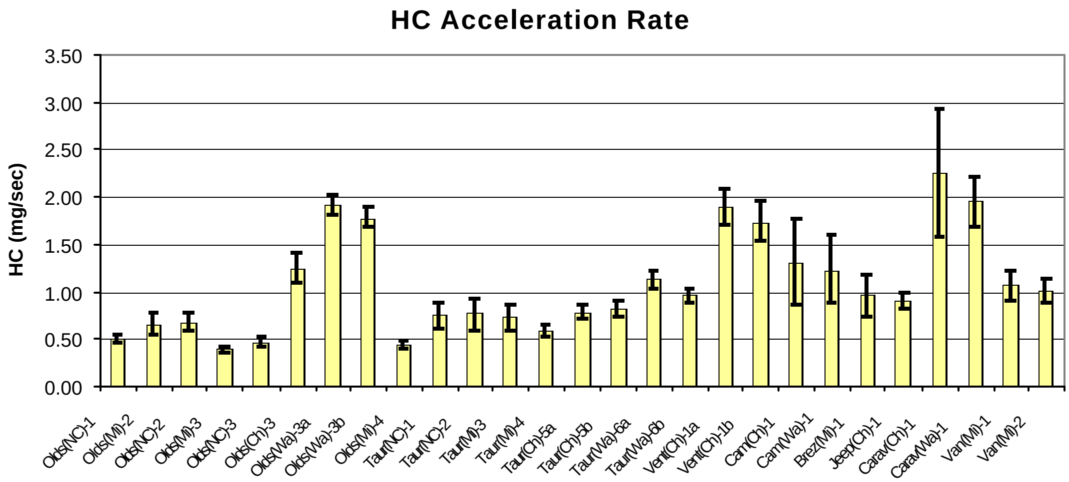
Appendix III. Modal Emission Rates for Each Vehicle ID

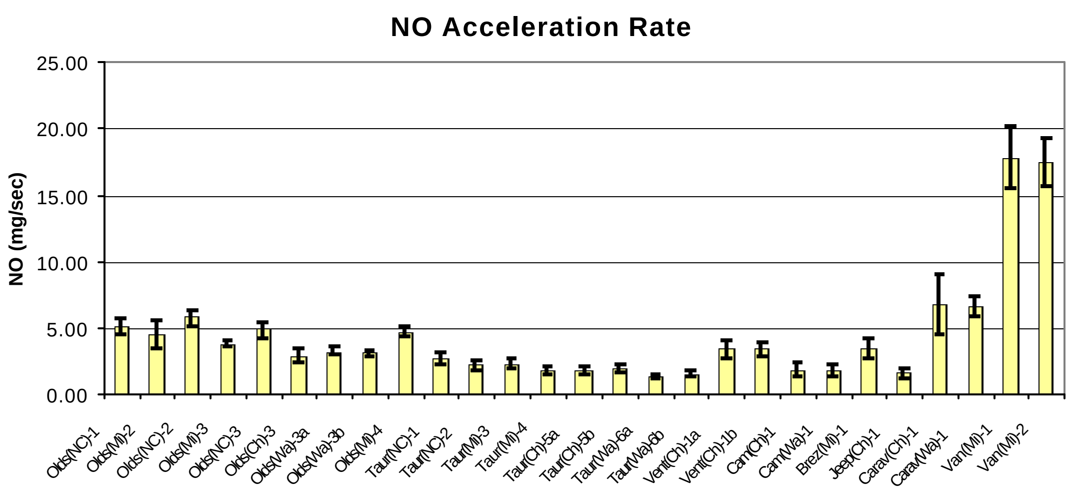


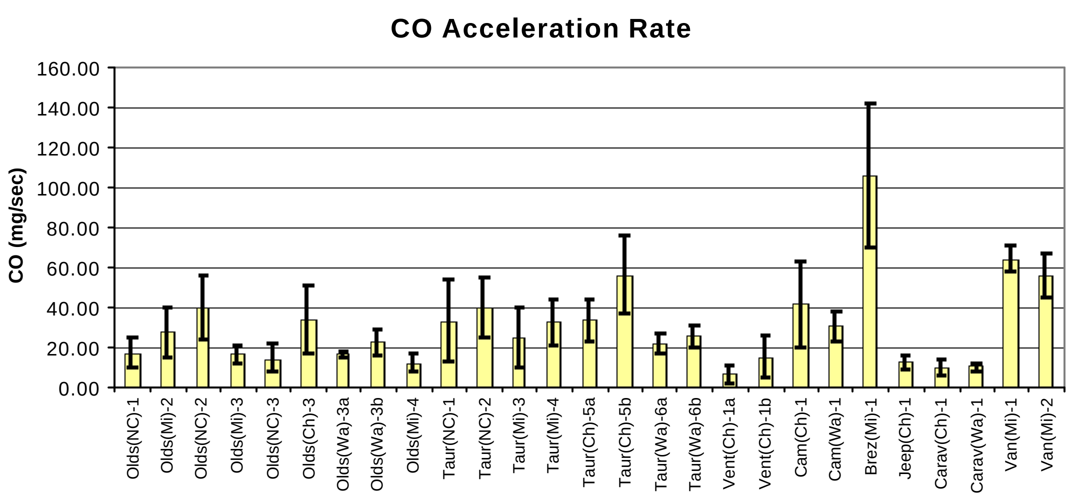




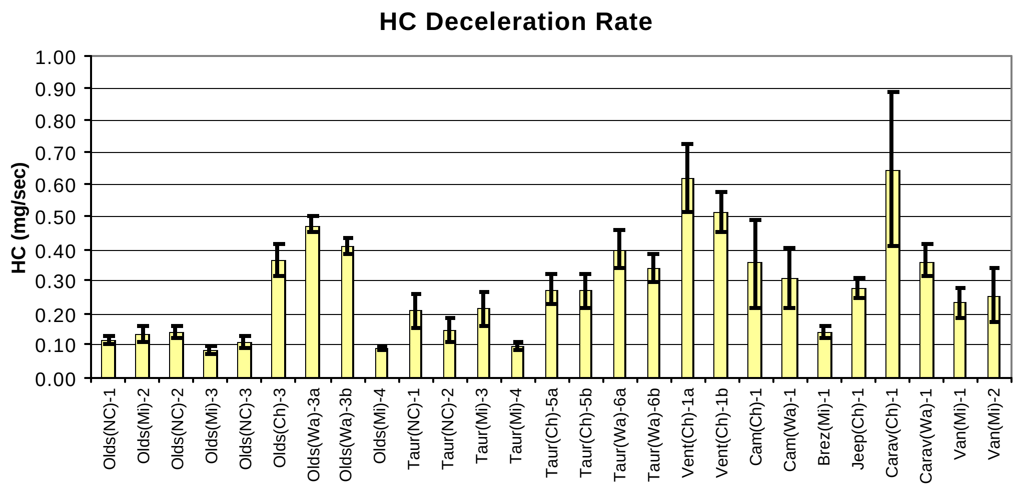
Appendix III. Modal Emission Rates for Each Vehicle ID

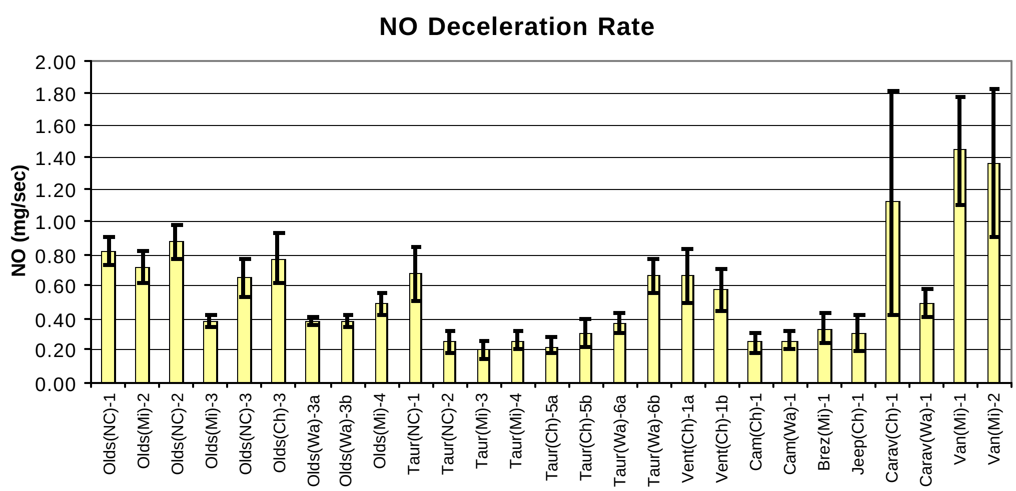


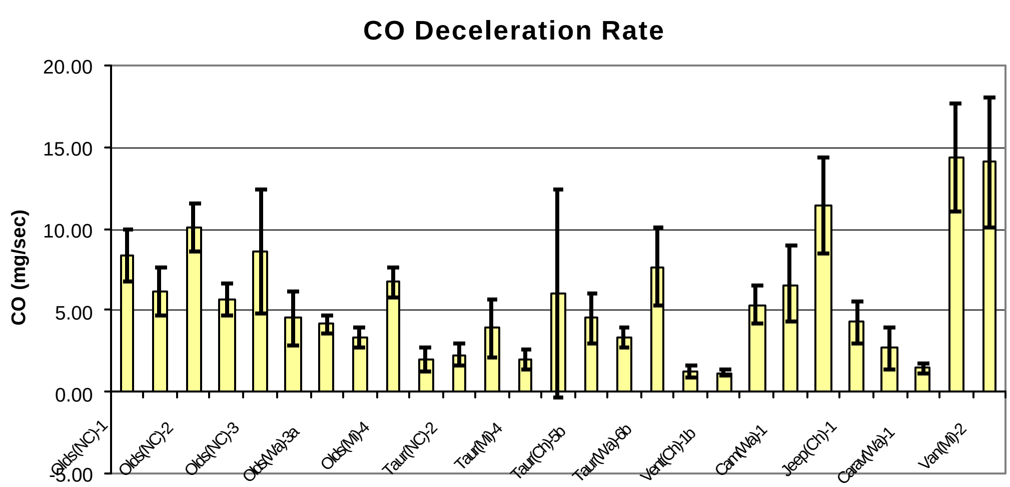




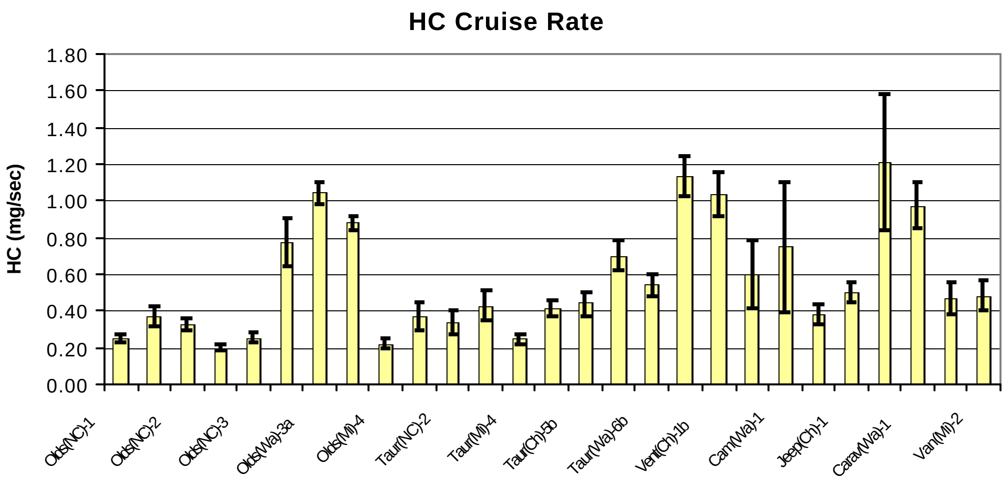
Appendix III. Modal Emission Rates for Each Vehicle ID

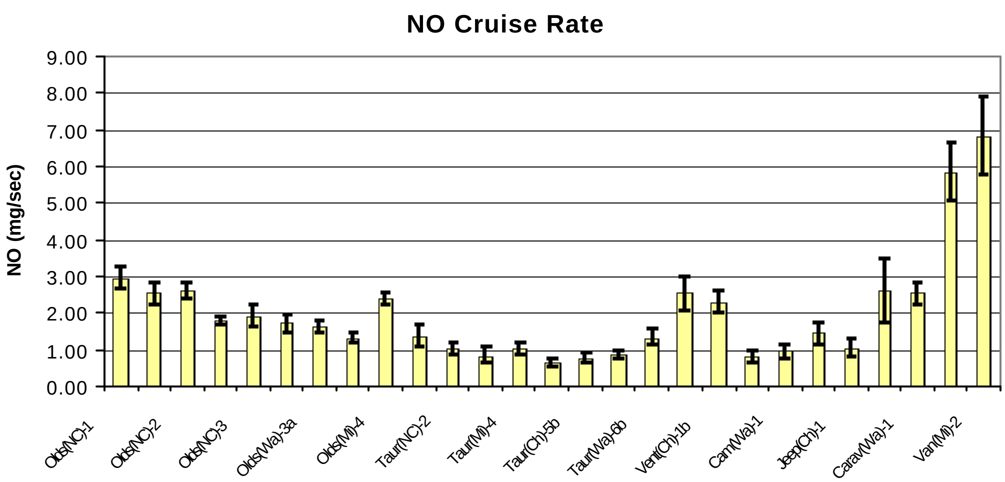


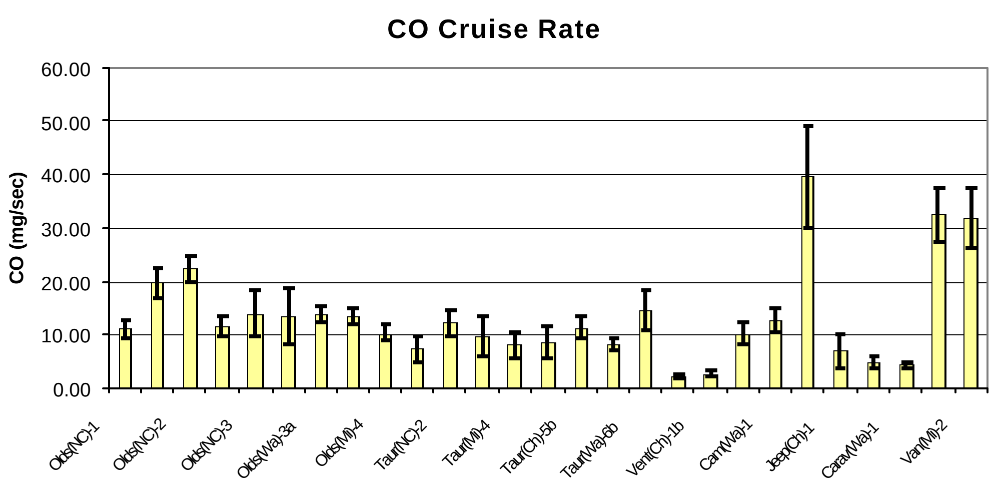




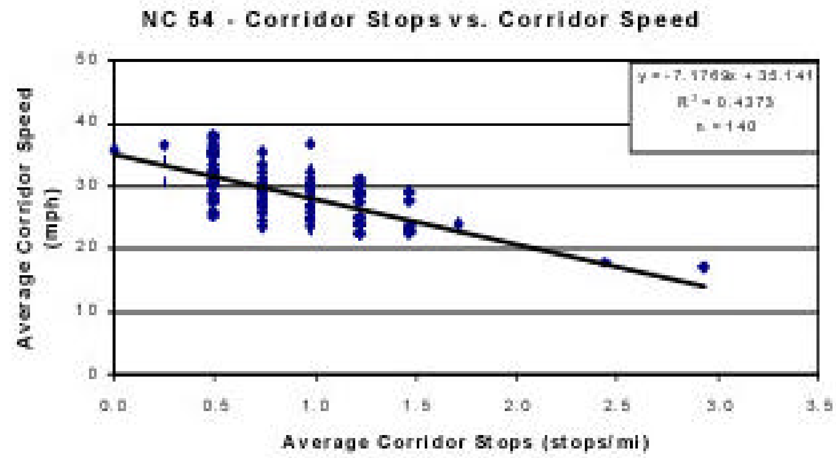
Appendix III. Modal Emission Rates for Each Vehicle ID

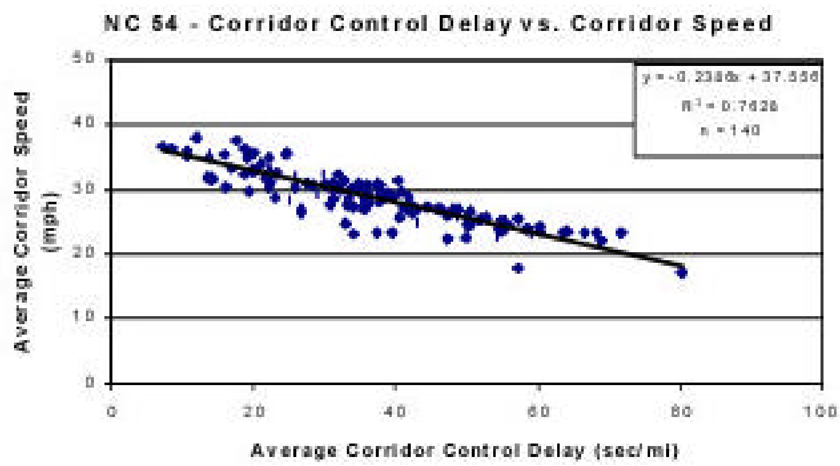


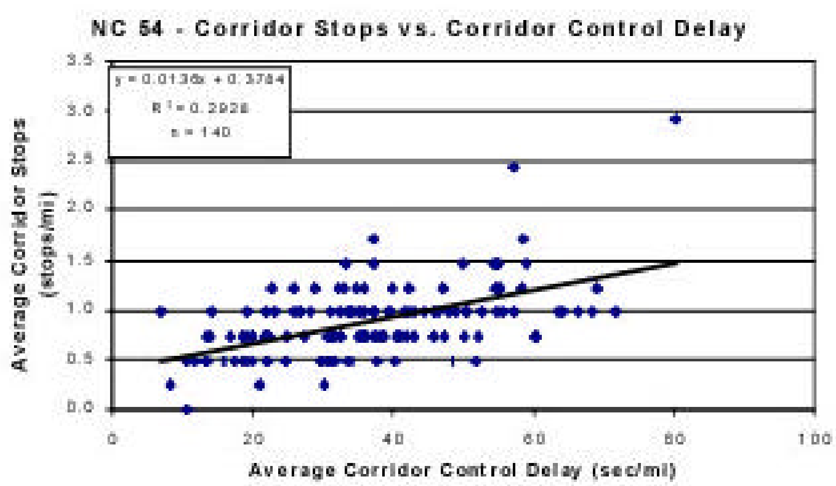




Appendix III. Correlation between Speed, Control Delay, and Corridor Stops for NC 54 and Miami Boulevard Runs







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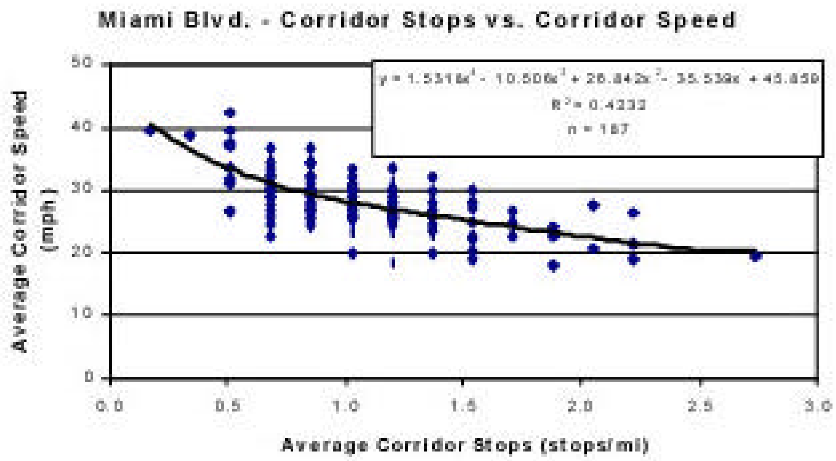
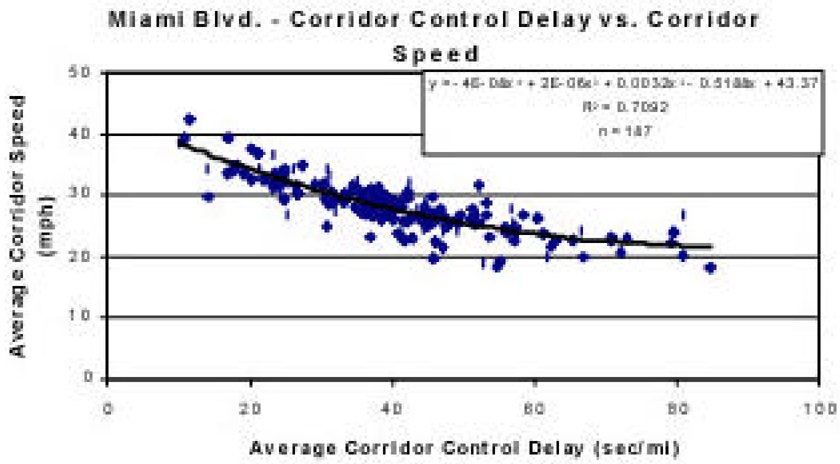
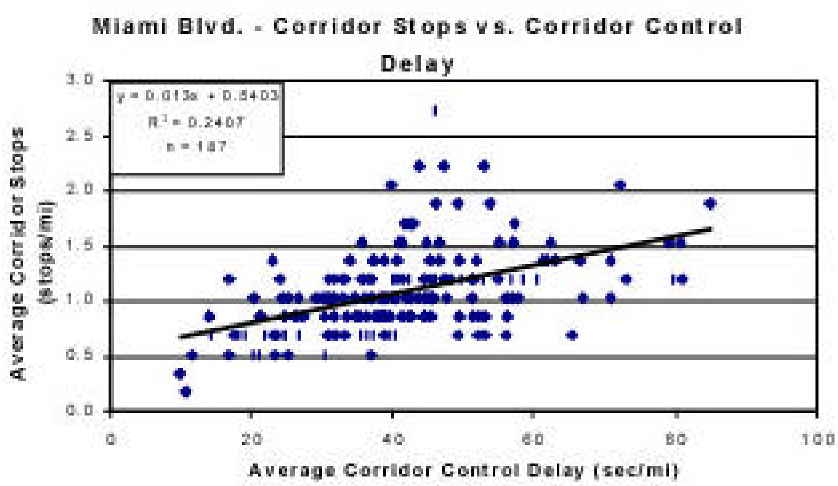
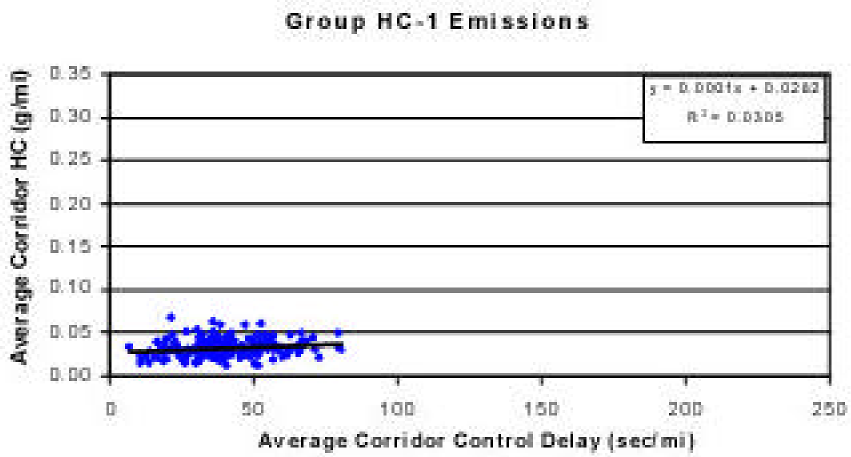
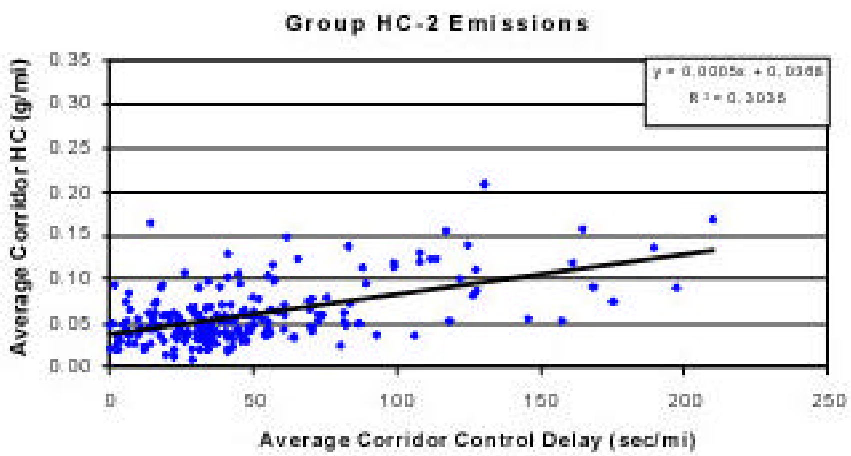


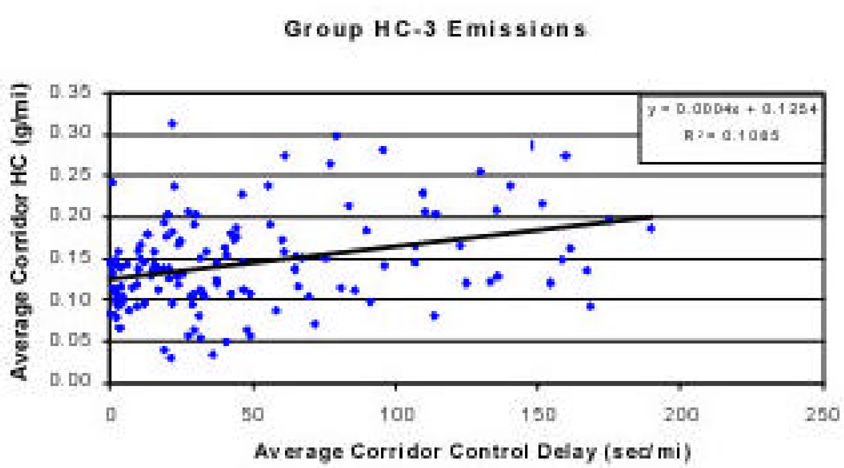




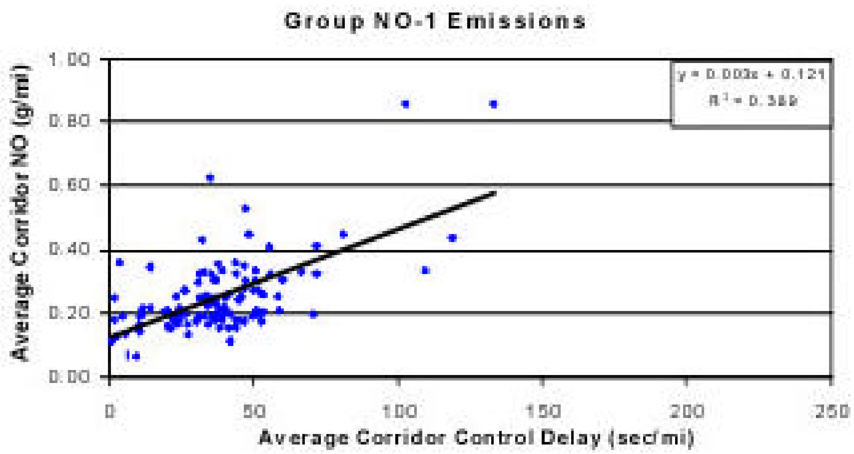
Appendix III. Trends between Control Delay and Emissions, and Corridor Stops and Emissions, for Each Vehicle Emissions Group

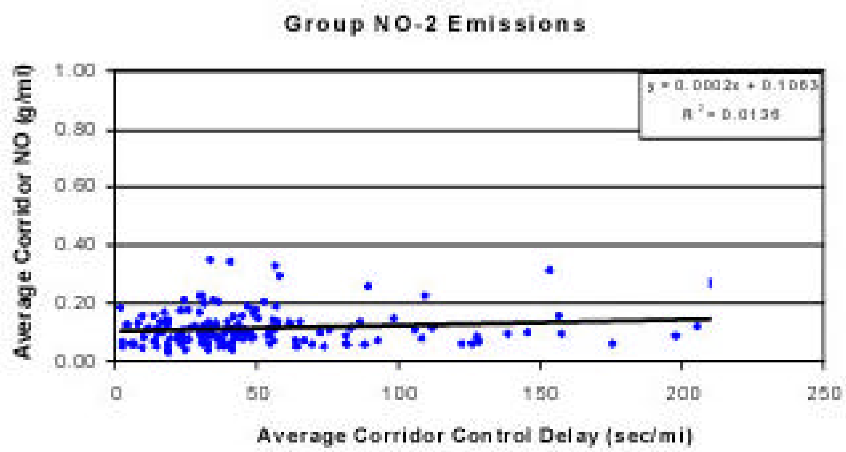


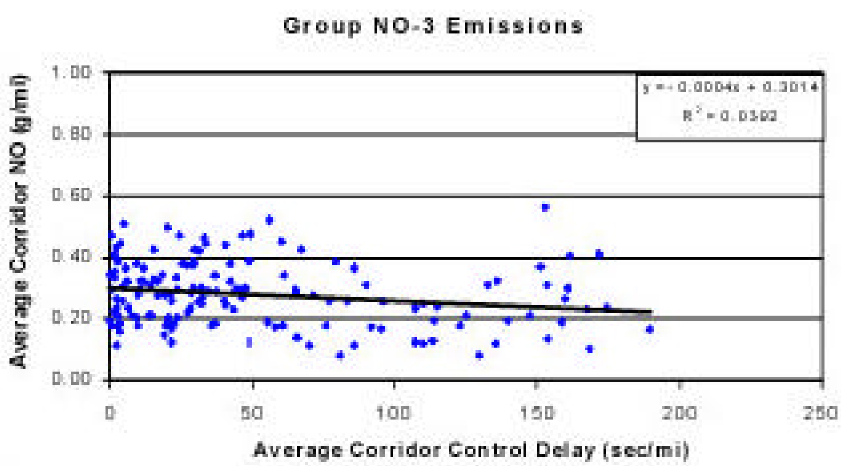




Appendix III. Trends between Control Delay and Emissions, and Corridor Stops and Emissions, for Each Vehicle Emissions Group







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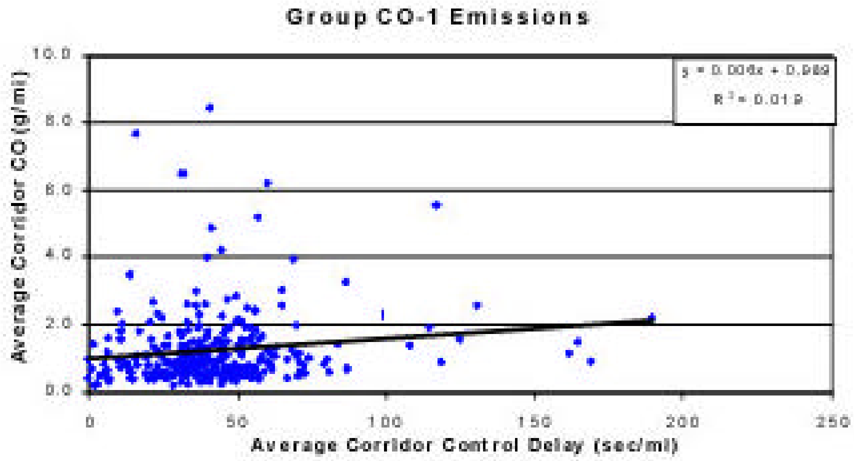
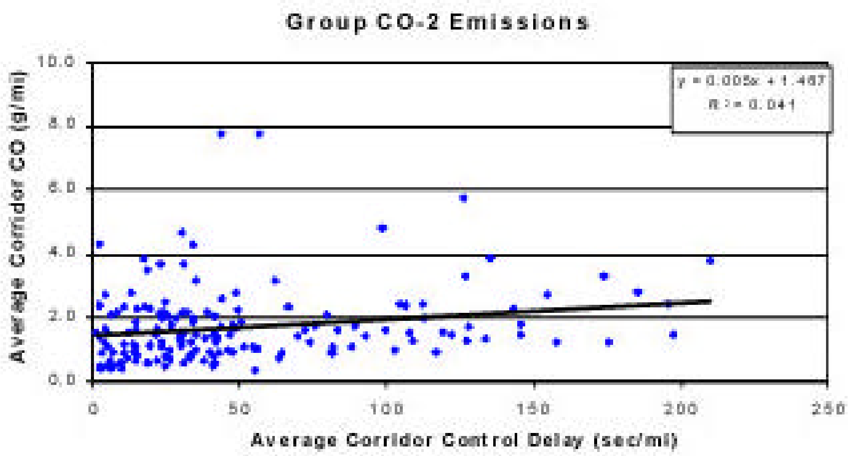
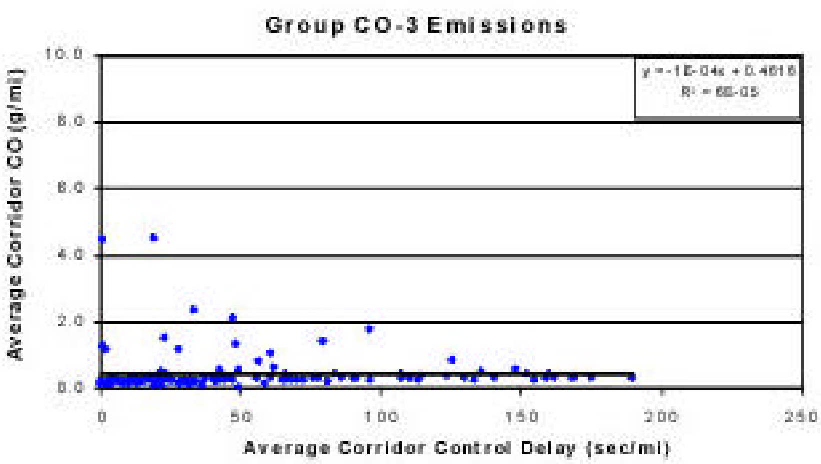
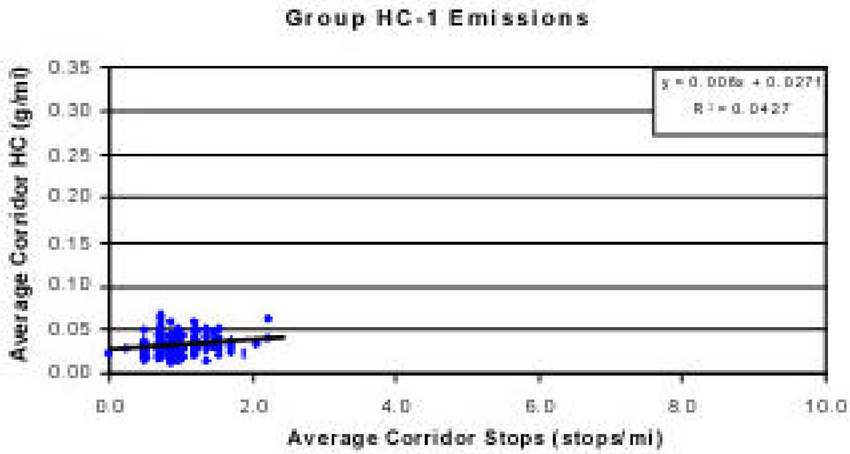
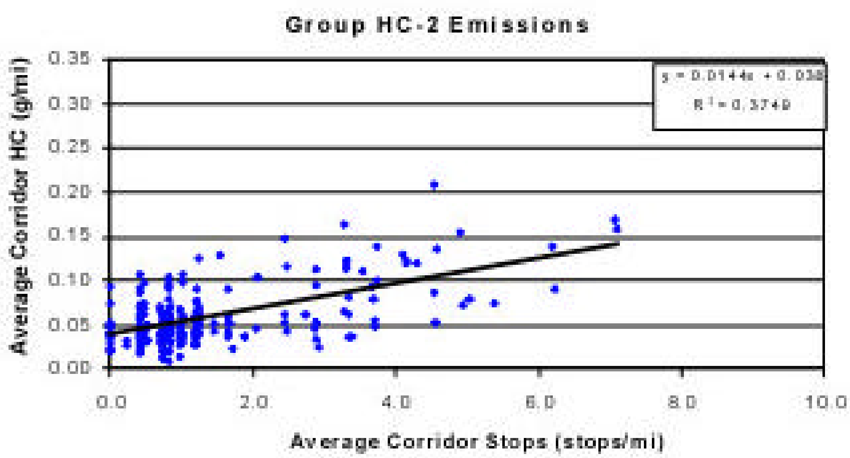


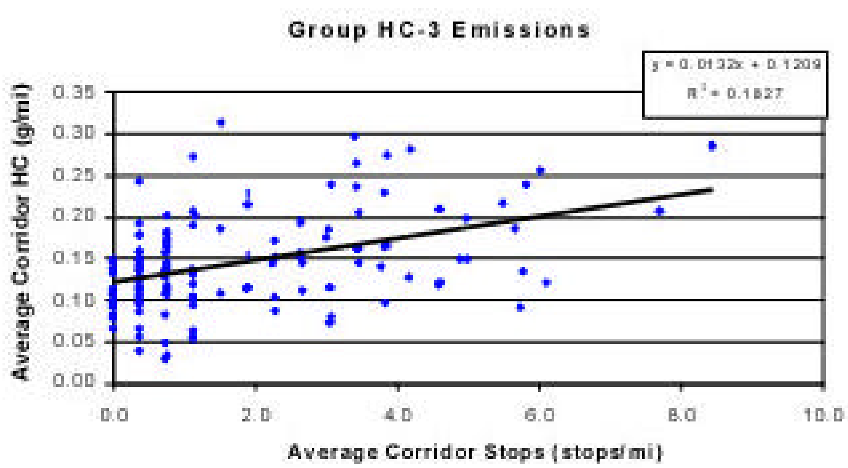




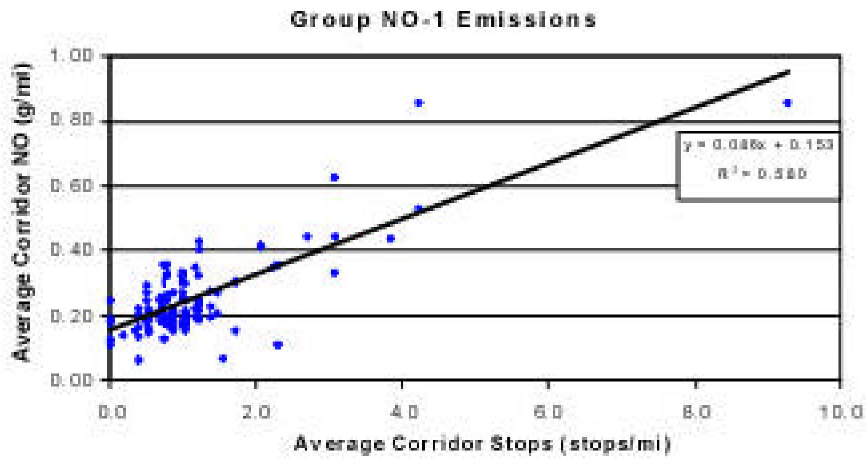
Appendix III. Trends between Control Delay and Emissions, and Corridor Stops and Emissions, for Each Vehicle Emissions Group

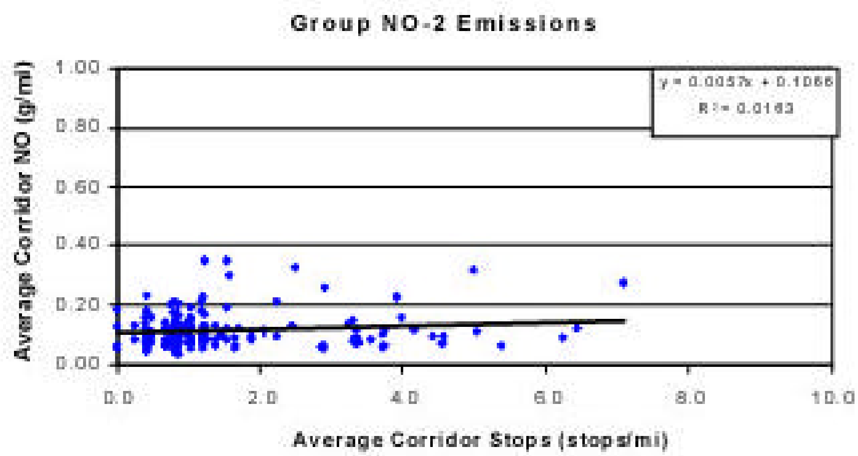


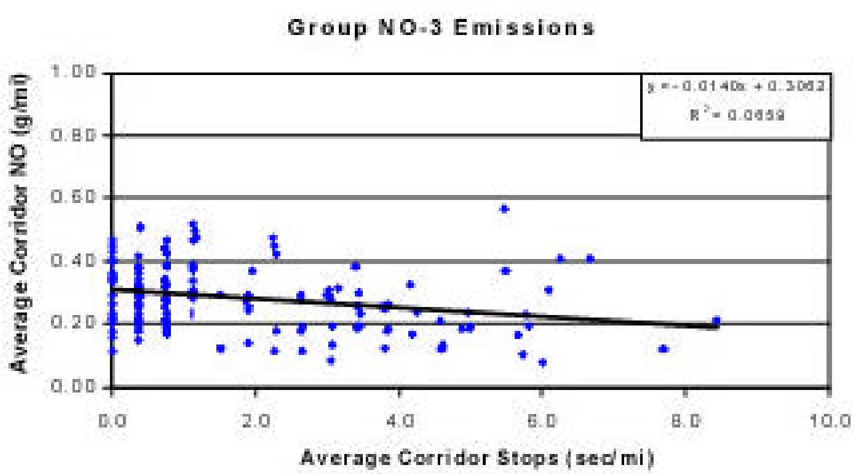




Appendix III. Trends between Control Delay and Emissions, and Corridor Stops and Emissions, for Each Vehicle Emissions Group







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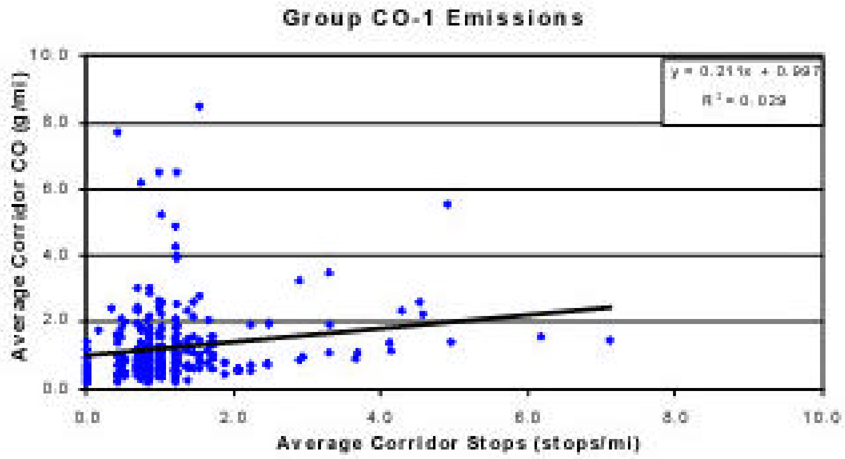
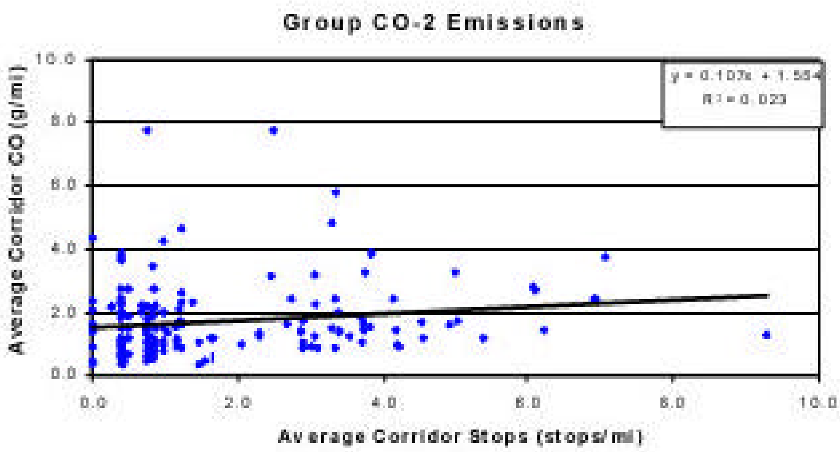
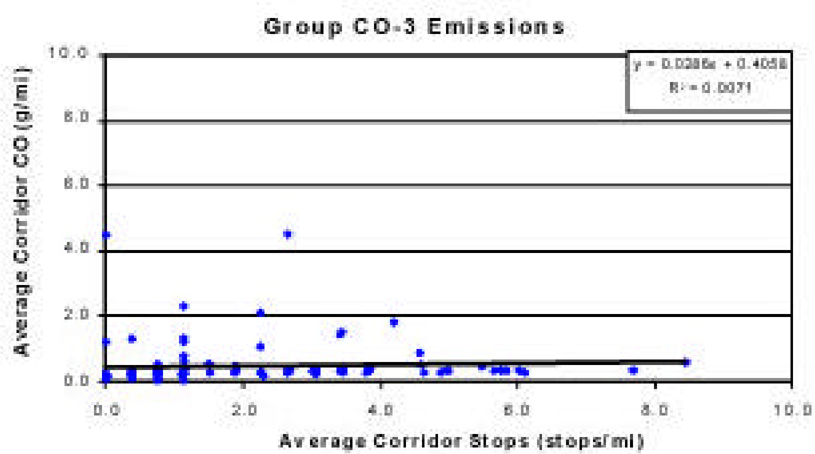


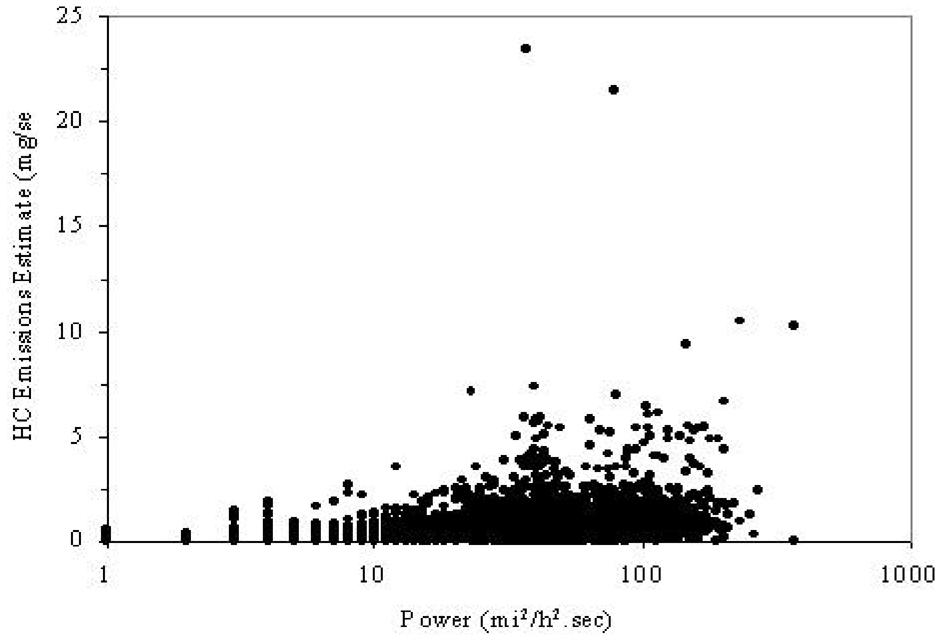


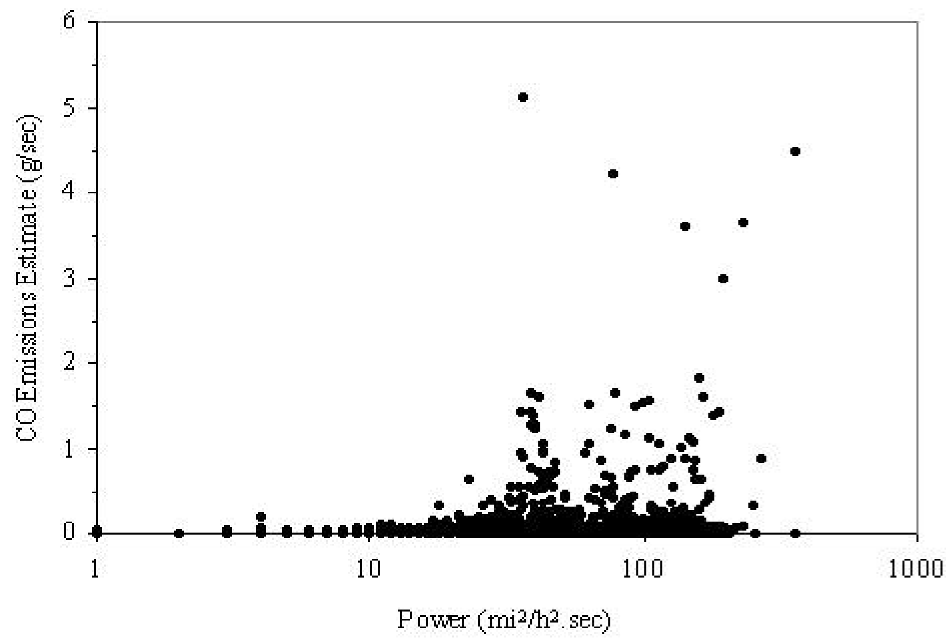


APPENDIX IV

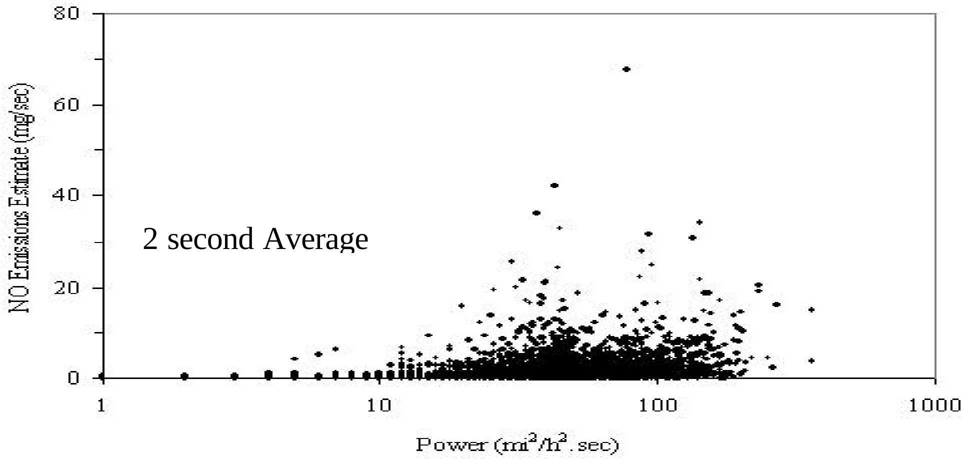
Correlation between CO, HC Emissions and Power Demand

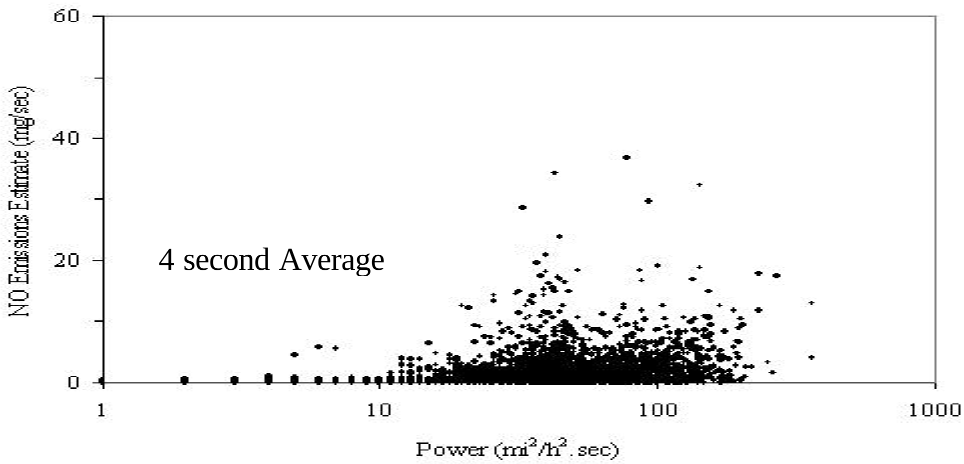
Appendix IV. Pollutants versus Power Demand

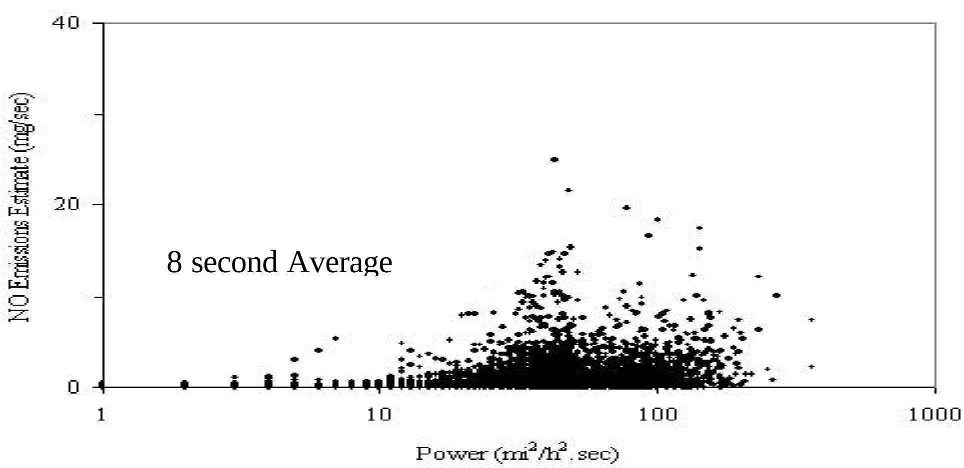




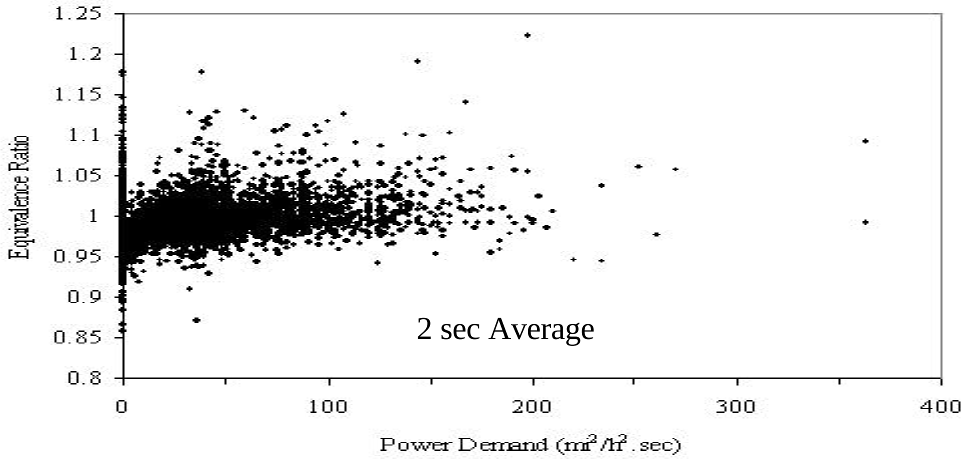
Appendix IV. Average NO versus Power Demand

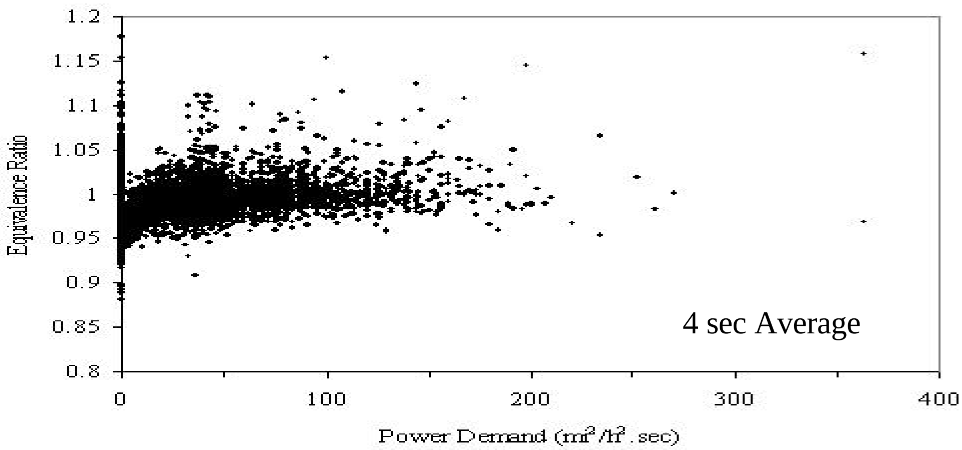


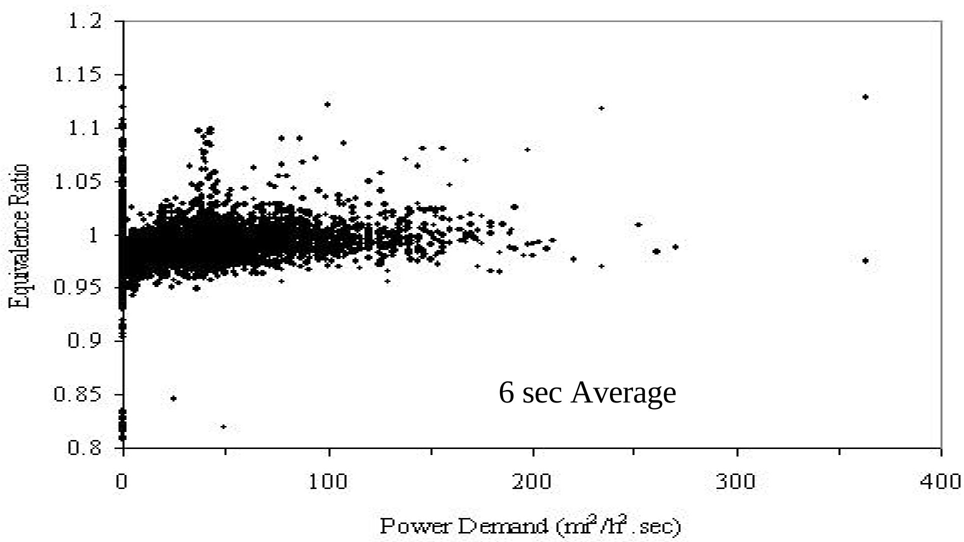




Appendix IV. Average NO versus Power Demand





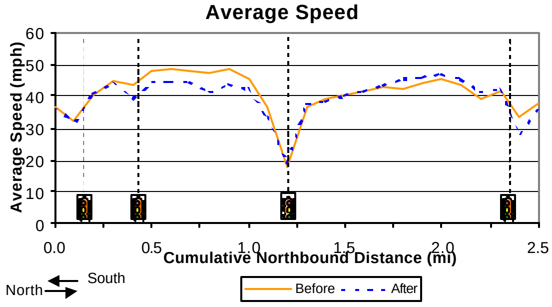


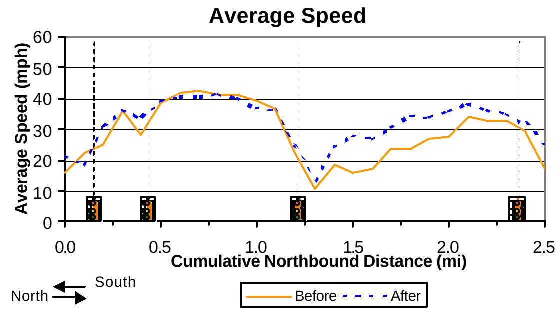
APPENDIX V

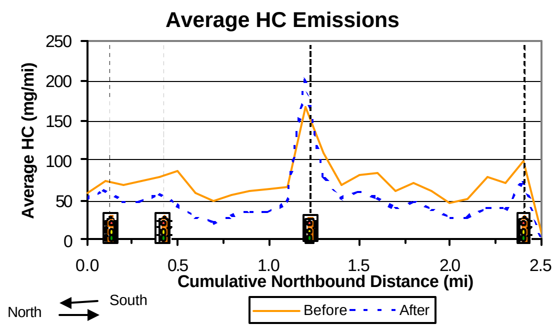
- Spatial Analysis Graphs for Ford Taurus PM on Chapel Hill Road
- Spatial Analysis Graphs for Chevrolet Venture PM on Chapel Hill Road
- CDFs for Hotspots for Chapel Hill Road
- Spatial Analysis Graphs for Ford Taurus PM on Walnut Street
- Spatial Analysis Graphs for Oldsmobile Cutlass AM on Walnut Street
- CDFs for Hotspots for Walnut Street

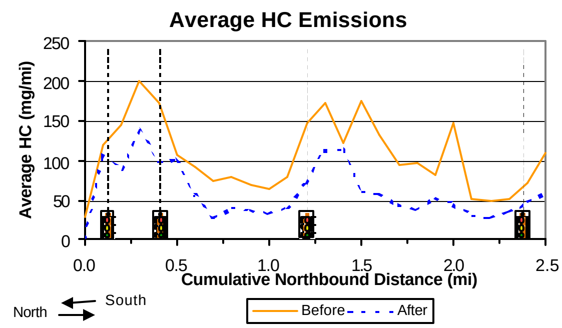
Appendix V. Spatial Analysis for Ford Taurus PM Runs on Chapel Hill Road

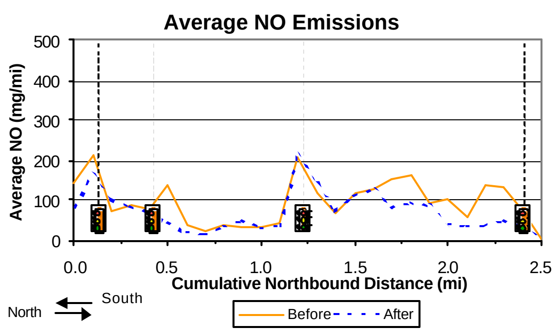
North Runs | *South Runs*

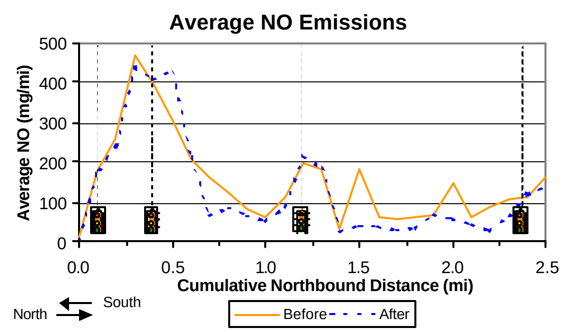


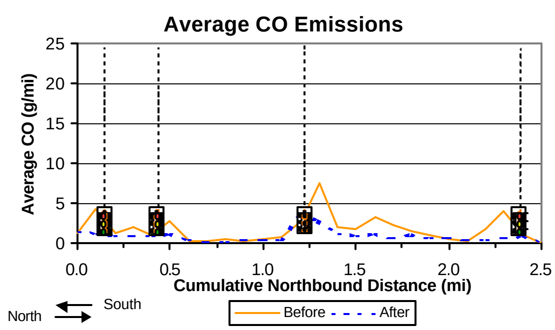


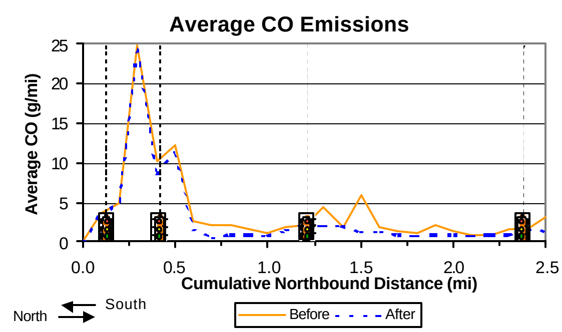






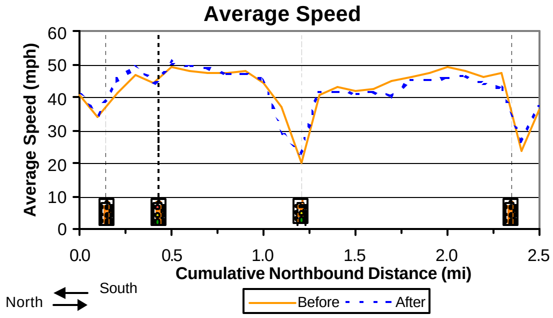


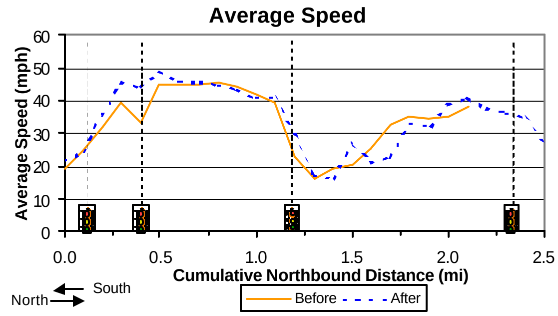


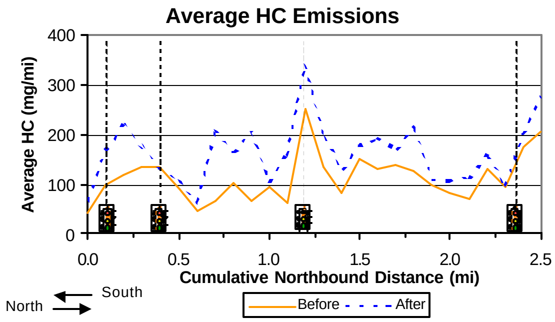


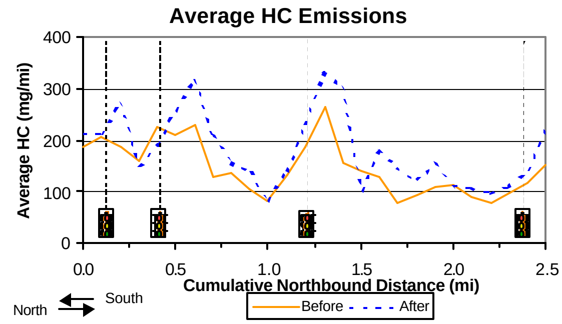
Appendix V. Spatial Analysis for Chevrolet Venture PM Runs on Chapel Hill Road

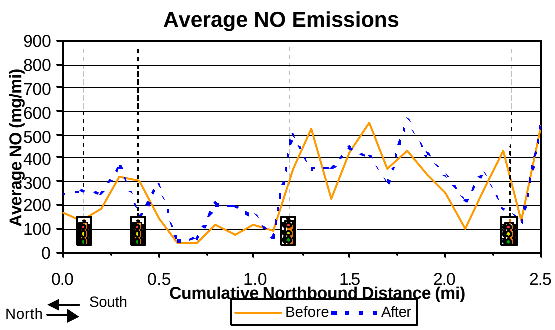
North Runs *South Runs*

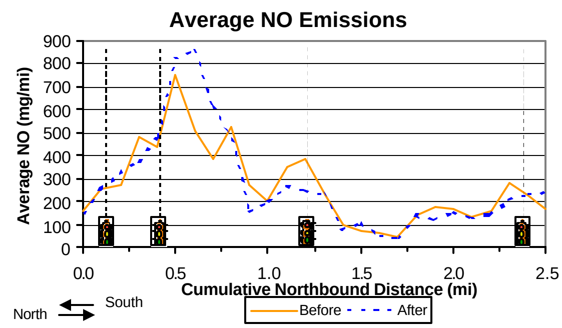


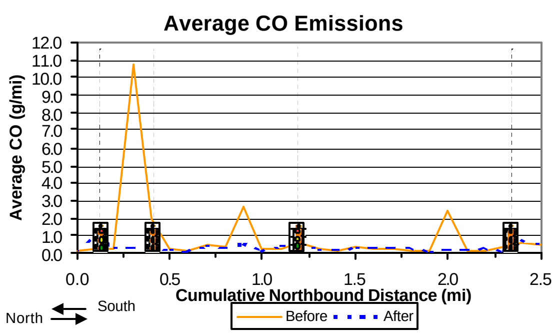


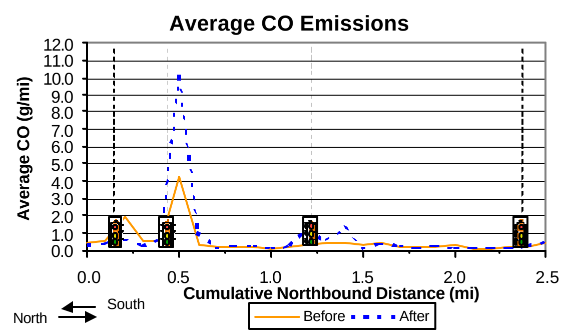




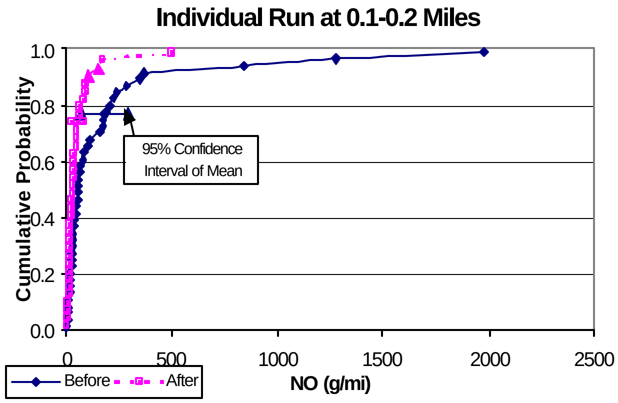


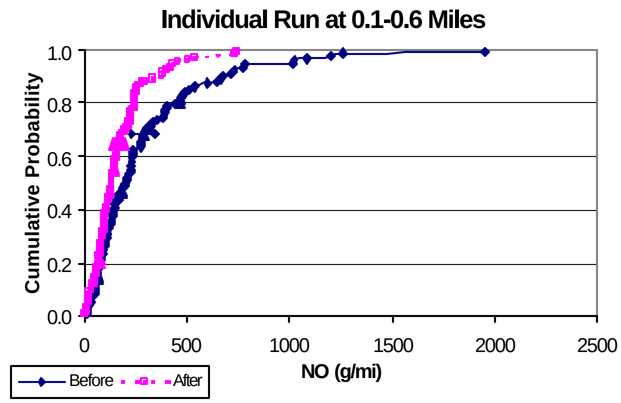


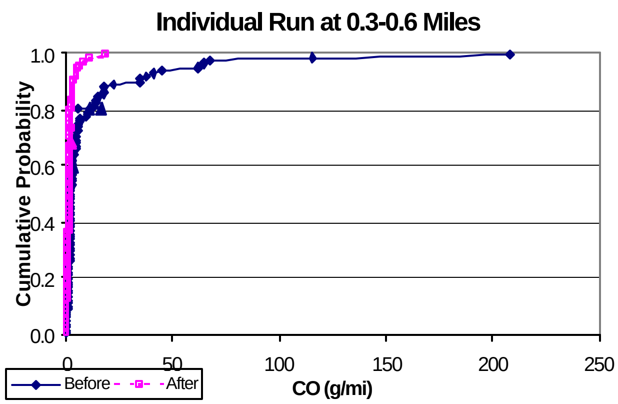


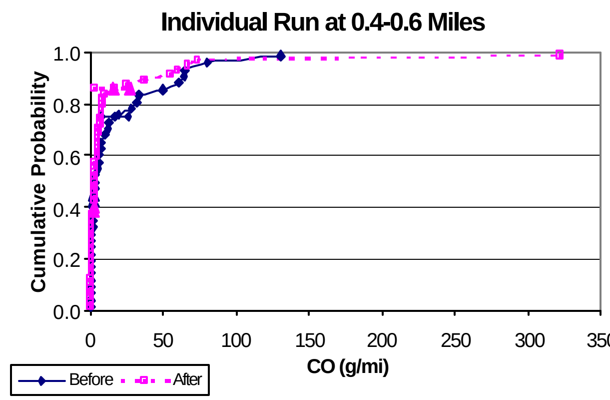


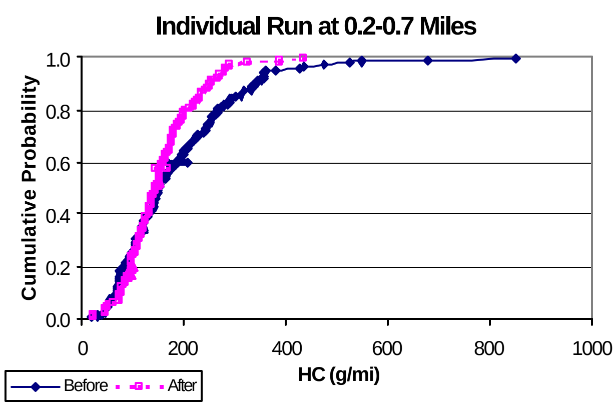
Appendix V. CDFs for Hotspots for Chapel Hill Road

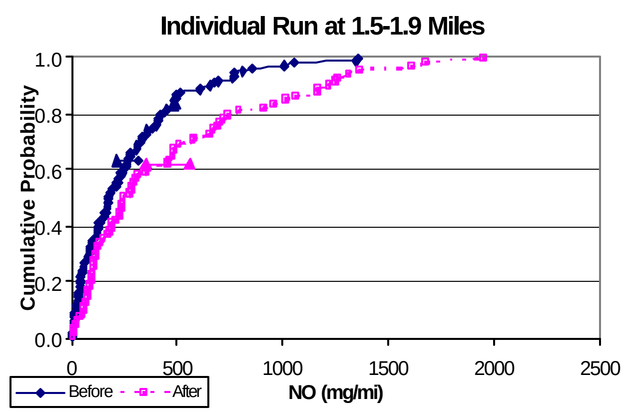




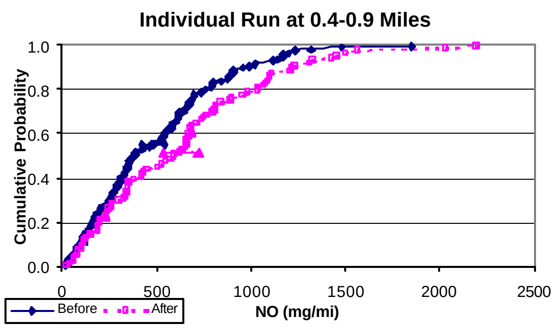


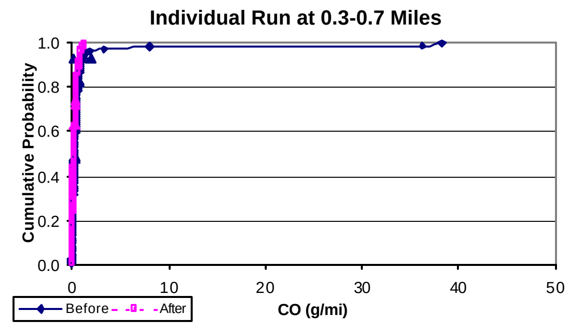


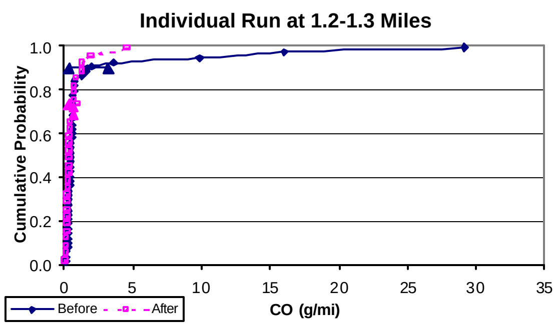


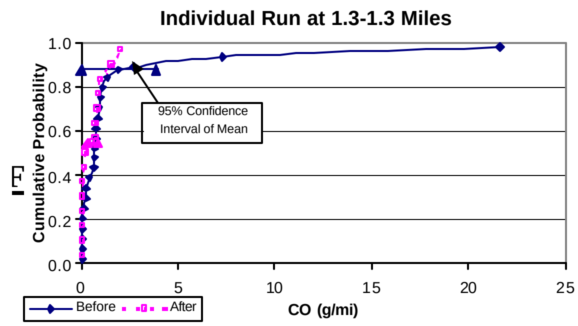


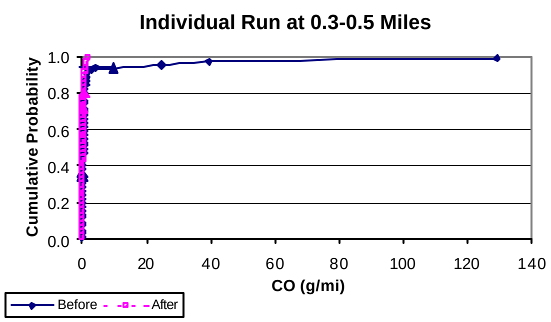
Appendix V. CDFs for Hotspots for Chapel Hill Road

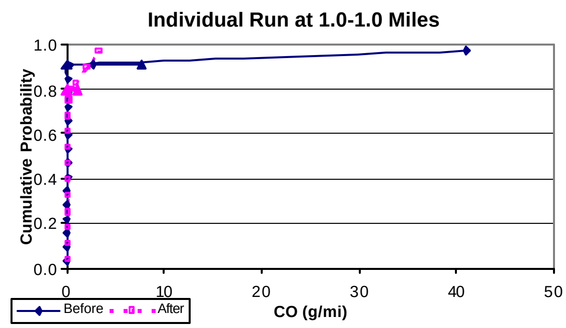


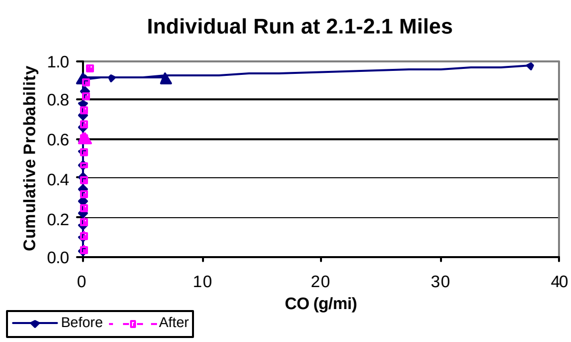






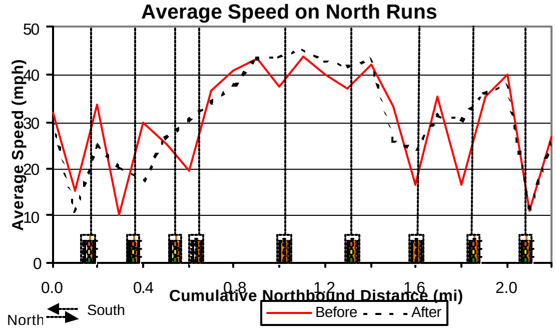




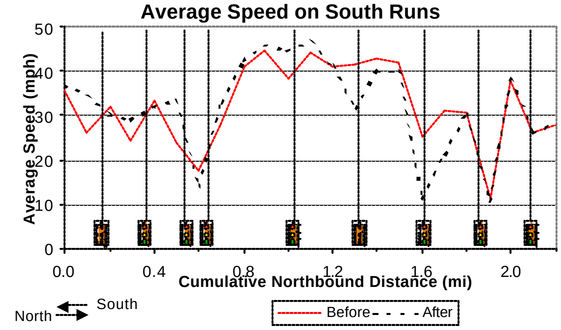


Appendix V. Spatial Analysis for Ford Taurus PM Runs on Walnut Street

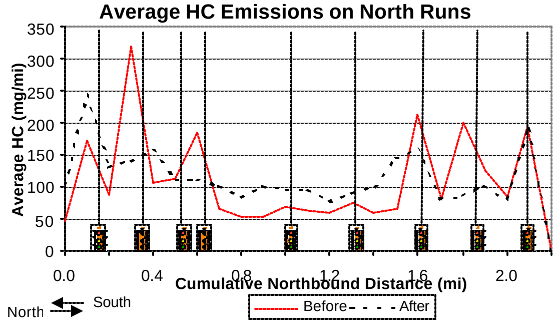
Average Speed on North Runs



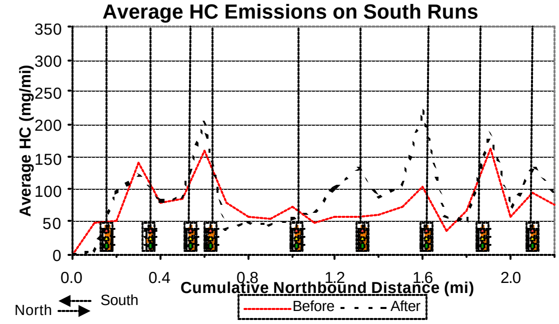
Average Speed on South Runs



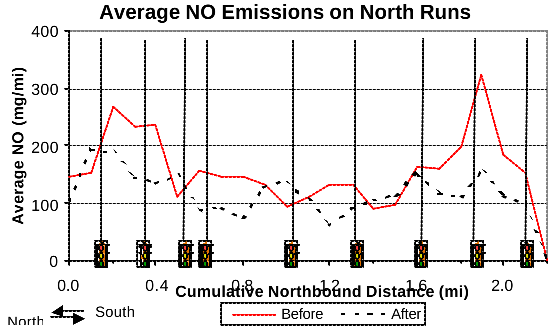
Average HC Emissions on North Runs



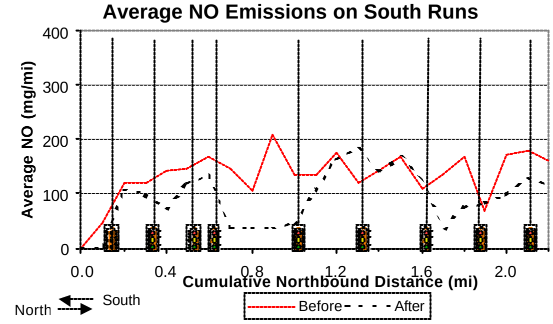
Average HC Emissions on South Runs



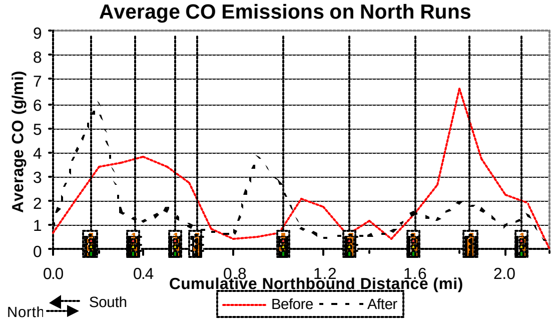
Average NO Emissions on North Runs



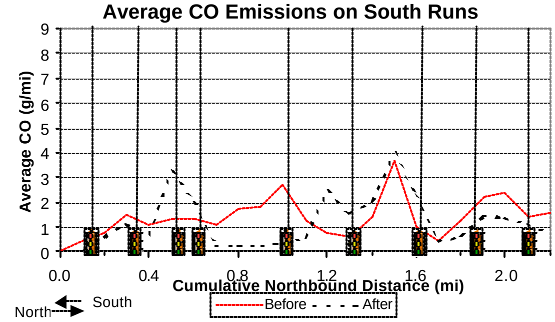
Average NO Emissions on South Runs



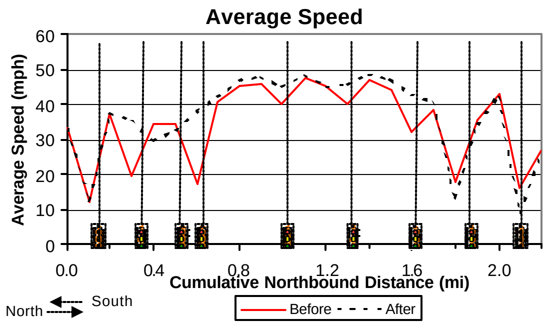
Average CO Emissions on North Runs

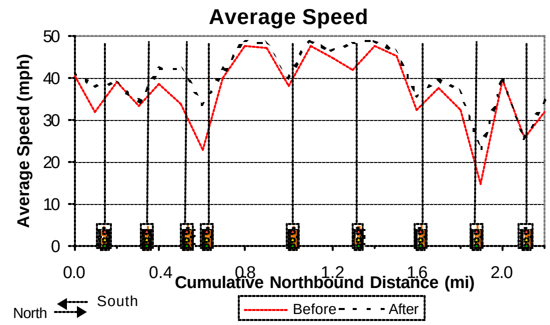


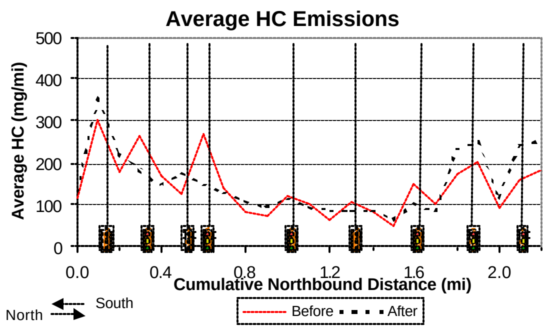
Average CO Emissions on South Runs

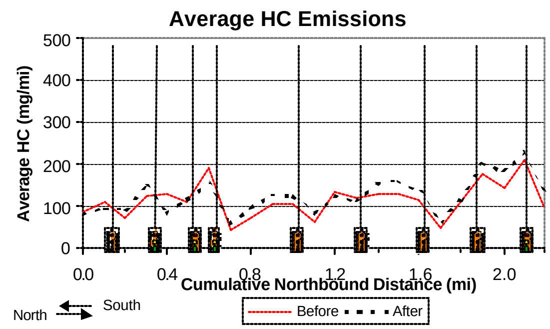


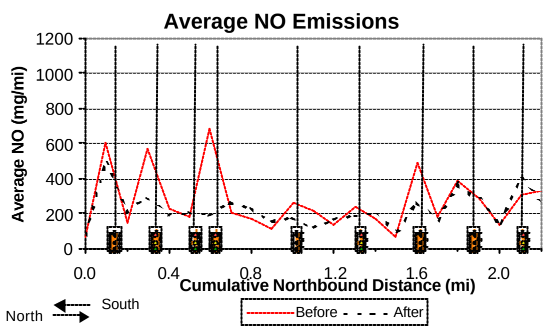
Appendix V. Spatial Analysis for Oldsmobile Cutlass AM Runs on Walnut Street

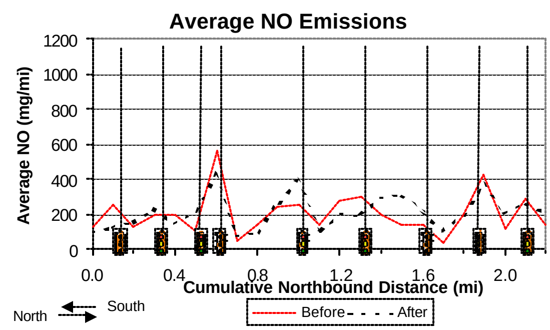


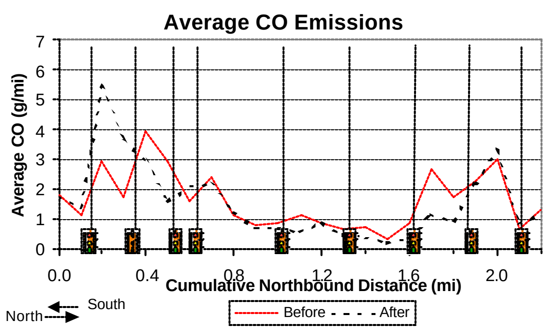


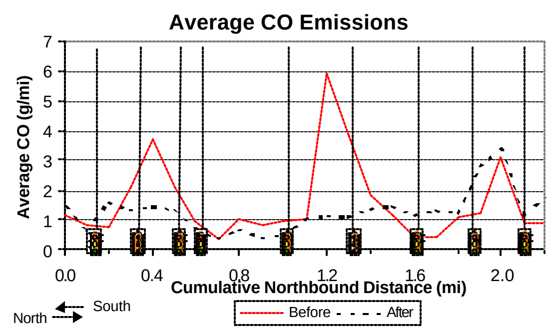




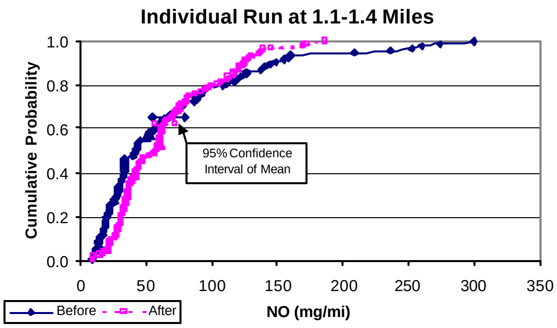


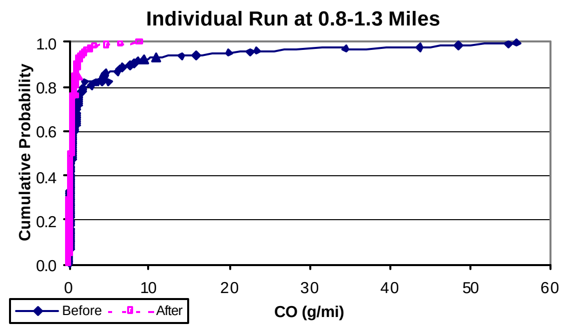


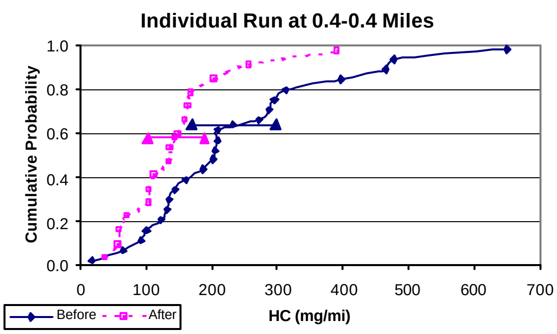


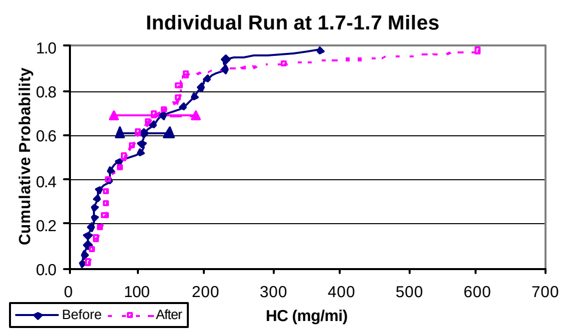


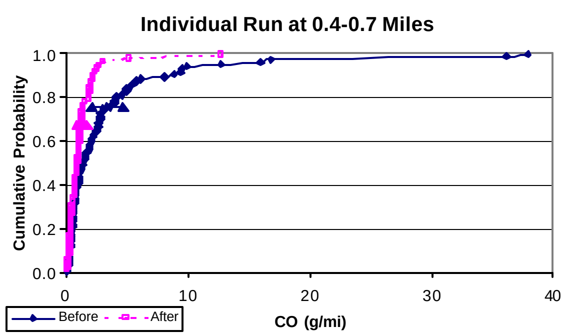
Appendix V. CDFs for Hotspots for Walnut Street

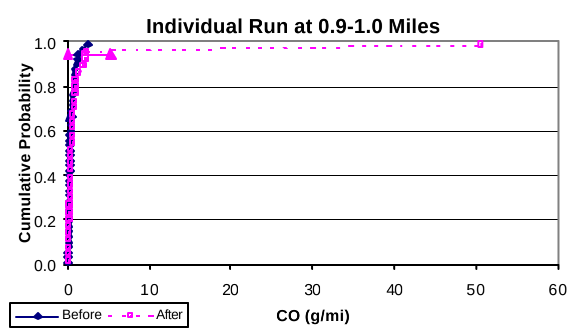


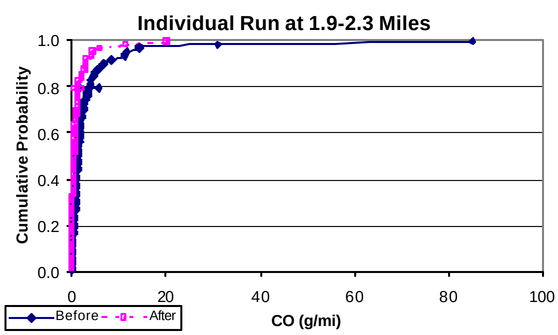


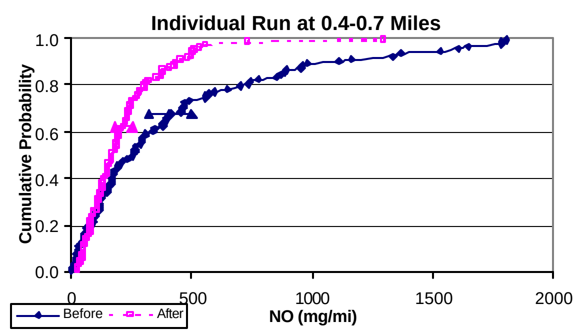












Appendix V. CDFs for Hotspots for Walnut Street