Use of On-Board Tailpipe Emissions Measurements for Development of Mobile Source Emission Factors

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ABSTRACT

Advances in technology in the last few years have resulted in the availability of a variety of equipment for on-board measurement of highway vehicle tailpipe emissions during actual driving. As an example, NC State has recently completed a two-year study of the effect of changes in traffic signal timing and coordination based upon before and after measurements of vehicle emissions on selected corridors. This paper focuses on the key facets of experimental design for an on-road emissions measurement study using portable instruments and how the experimental design can be developed for various study objectives. Key elements of study design include vehicle selection, driver selection, route selection, instrument deployment, scheduling, and measurement of observable but not controllable factors that might influence emissions. The data collected from on-board instruments can facilitate the development of micro-scale, meso-scale, and macro-scale emission factors and emission inventories. Results from work at NC State are used to illustrate the major elements of study design and the potential uses of data. For example, speed and emission traces were used to identify emissions hotspots. Measured data were analyzed to estimate emission rates for different driving modes (e.g., idle, acceleration, cruise, and deceleration). Measured data were used to develop average emissions estimates for roadway segments or routes. Lessons learned from experience and recommendations for future work are provided.

Keywords: On-road data collection, vehicle emissions, emissions inventory

INTRODUCTION

In order to better monitor and control air pollution it is essential to accurately identify the emission sources and determine their emissions. As of 1999, the transportation sector, including on-road and non-road vehicles, was estimated by the U.S. Environmental Protection Agency (EPA) to contribute 47 percent of hydrocarbon (HC) emissions, 55 percent of nitrogen oxides (NO_X) emissions, 77 percent of carbon monoxide (CO) emissions, and 25 percent of particulate matter (PM) emissions to the national emission inventory.[1] The contribution of on-road 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 estimates are obtained by using the MOBILE emission factor model and are subject to uncertainties inherent in this model.[2-3]

Currently, data used in the mobile emission factor models are based upon dynamometer testing. Dynamometer testing is a method where emissions from vehicles are measured under laboratory conditions during a driving cycle that simulates vehicle road operation.[2] 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.[4] Different driving cycles are used to represent driving under different conditions. Dynamometer tests typically suffer from well-known shortcomings associated with non-representativeness of actual driving conditions.[2, 5-7] For example, many tests under-represent short-term events that cause high emissions even for a properly functioning vehicle, such as high accelerations. Driver behavior can affect the duration of both cold starts and of events leading to high-emissions enrichment operation, which in turn have substantial effects on emissions regardless of the total number of vehicle miles traveled.

Dynamometer tests are often used in regulatory procedures to check compliance of new vehicles with emission standards or to inspect in-use vehicles. The data obtained from driving cycles are also used to develop emission estimation models, such as EMFAC7F, MOBILE6, Georgia Tech's MEASURE, and UC Riverside's modal emissions models.[8-10]

Remote sensing (RS) is another method for measuring vehicle emissions. RS uses infrared (IR) and, in some cases, ultraviolet (UV) spectroscopy to measure the concentrations of pollutants in exhaust emissions as an on-road vehicle passes a sensor on the roadway. There are several applications of remote sensing in mobile emissions determination. These 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.[8] 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 disadvantage of remote sensing is that it only gives an instantaneous estimate of emissions at a specific location. There are constraints on the siting of remote sensing devices (RSDs) that make it impractical to use remote sensing as a means for measuring vehicle emissions at many locations of practical interest, such as close to intersections or across multiple lanes of heavy traffic. Furthermore, remote sensing is more or less a fair weather technology.[8]

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.[11-17] 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 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. 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.[5, 11-13] In other studies, researchers have measured engine parameters only.[7,18-20] 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.[21] Private companies such as Clean Air Technologies International Inc., and Sensors, Inc., have developed versions of on-board instruments that are commercially available.[17,22]

In this work, an empirical approach to measurement of real-world, on-road vehicle emissions is emphasized. The specific method employed here, based upon instrumentation of individual vehicles and measurement of tailpipe emissions, offers the benefit of providing second-by-second vehicle activity and emissions data, which enables characterization of emissions at any time or location during a route.

The main objectives of this paper are to: (1) describe the on-board emission measurement systems; (2) present the types of data and inferences that can be obtained from on-board emissions measurement systems; and (3) present the methodology developed for estimating emission factors for vehicles using on-board data.

DATA

The on-board data presented in this paper were collected in two separate studies. First study was conducted by the researchers at North Carolina State University (NCSU) and sponsored by the North Carolina Department of Transportation (NCDOT) via the Center for Transportation and the Environment. The project, titled "Emissions Reduction through Better Traffic Management: An Empirical Evaluation Based upon On-Road Measurements," focused on evaluating strategies aimed at preventing motor vehicle air pollutant emissions through better traffic management. The project started in April of1999 and continued through December of 2001, during which time researchers at NCSU collected data for over 1,200 one-way trips with more than 20 Light-Duty Gasoline Vehicles (LDGV) and 10 drivers, representing 160 hours of data, and 4,000 vehicle-miles traveled. Data were collected at four different sites in Research Triangle Park and Cary, North Carolina. Details of this study can be found elsewhere.[15]

The second study was conducted at NCSU for EPA's Office of Transportation and Air Quality (OTAQ). The project, titled "Recommended Strategy for On-Board Emission Data Analysis and Collection for the New Generation Model," aimed at developing strategies for the New Generation Model (NGM) for vehicle emissions. The NGM recently renamed to "Multi-Scale Motor Vehicle and Equipment Emissions System" (MOVES), is the anticipated successor to Mobile6. On-board emissions data for this study was provided by OTAQ, including second-by-second data for 12 different Light-Duty Gasoline Vehicles (LDGV), 12 different Heavy-Duty Diesel Vehicles (HDDV), and 3 different Nonroad vehicles. Details on this study can be found elsewhere.[17]

INSTRUMENTATION

The on-board data for the NCDOT-sponsored project were collected by researchers at NCSU using the OEM-2100^{TM} manufactured by Clean Air Technologies International, Inc. Data used for the OTAQ-sponsored project were provided by EPA. In this section, data from the NCDOT-sponsored study will be used as an example.

The OEM-2100^{TM} system is comprised of a five-gas analyzer, an engine diagnostic scanner, and an on-board computer. The five-gas analyzer measures the volume percentage of CO, CO_2, HC, NO_x, and O_2 in the vehicle exhaust. Simultaneously, the engine scanner is connected to the On-Board Diagnostics (OBD) link of the vehicle from which engine and vehicle data are downloaded during vehicle operation. Field data collection activities include the use of the OEM-2100^{TM} as well as supplemental equipment. Road grade was measured with a digital level on the study corridors at one-tenth mile increments. Key characteristics of the study corridors, such as roadway geometry (e.g., number of lanes), speed limits, and traffic control device locations (e.g., traffic signals) were recorded. A laptop computer was used to record temperature and humidity, and information regarding each vehicle tested such as year, make, model, VIN, engine size, and other characteristics. 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. Details regarding the instrumentation can be found elsewhere.[16-17]

EXPERIMENTAL DESIGN

The design of an on-road data collection effort involves selection of vehicles and drivers, and deployment of vehicle/driver combinations during different time periods on selected routes. The criteria for selection of drivers, vehicles, routes, and deployment times depend upon the objective of the study. Possible objectives for these kinds of studies include: (1) evaluation of emissions benefits of a transportation improvement, which requires before and after studies on a specific route or facility; (2) estimation of on-road emissions on specific facility types, which requires a large vehicle fleet deployed on representative facility links (e.g., freeway, arterial, secondary roads); (3) estimation of emissions benefits of alternative routing, which requires measurement of alternative routes between a fixed origin and destination; (4) estimation of area-wide fleet average emissions, which requires a representative vehicle sample on a representative sample of trips in a given geographic area; and (5) evaluation of driver behavior, which requires measurements with multiple drivers using the same vehicles and routes.

The example case study presented in this paper is based upon measurements on selected corridors that is consistent with a study objective of estimating area-wide emission factors for selected vehicles.

Vehicle Selection

As part of on-board data collection efforts at NCSU, data were collected for LDGVs with engine sizes from approximately 1.6 liters to 5.4 liters. The data for the OTAQ-sponsored project included LDGV, HDDV, and Nonroad vehicles. These vehicles included LDGVs ranging from 1.9 liters to 3.1 liters in engine size with both automatic and manual transmission systems; 8.5 liter engine size transit buses for HDDV; and a bulldozer, a compactor, and a scraper for nonroad vehicles. For the case study, data collected for LDGV will be presented.

Driver Selection

Driver behavior is one of the possible considerations that might be important in explaining variability in vehicle emissions. Studies aiming to analyze the effect of driver behavior on vehicle emissions may involve data collection on the same routes and with the same vehicles using multiple drivers.

Route Selection

On-board data collection is very flexible in terms of site selection compared to other measurement methods such as remote sensing. Selection of sites for on-board data collection depends on the objectives of the study. For example, to evaluate the effect of a TCM or roadway improvement, one would perform a "before and after study" on a short route that includes the location of the TCM or roadway improvement. To evaluate the effects of alternate routings, one would perform a study of emissions during trips from the origin to the destination for each alternative route. As another example one might need to estimate area-wide fleet average emissions. This requires a representative vehicle sample on a representative sample of trips in a given geographic area on selected routes.

Some of the example results presented in this paper, were collected on a heavily traveled corridor in Cary, NC. The rest of the example data were collected on several different routes in Ann Arbor, Michigan.

INSTRUMENT DEPLOYMENT

As an example, deployment of the OEM-2100^{TM} is described. The OEM-2100^{TM} is portable and can be installed in approximately 15 minutes in a light duty vehicle. The OEM-2100^{TM} has three connections with the vehicle: (1) a power cable typically connected to the cigarette lighter; (2) an engine data link connected to the OBD data port; and (3) an emissions sampling probe inserted into the tailpipe. The connections are fully reversible and do not require any modifications to the vehicle. The OEM-2100^{TM} is typically placed on the front passenger seat. Details of instrument deployment are given elsewhere.[15]

RESULTS AND DISCUSSIONS

To illustrate the type of data that were collected with an on-board instrument and the insights they provided, an example of an individual one-way vehicle trip for a 1996 Oldsmobile Cutlass on October 31, 2000 is presented. Figure 1 shows vehicle speed versus elapsed time of the trip. The figure is labeled with the location of the vehicle at specific times. The trip took place on Walnut Street. The trip began south of Dillard Drive and ended a short distance north of Cary Towne Boulevard. There is notation in the figure indicating when the vehicle crossed the center of the intersection, such as at Nottingham Drive. The travel time on the corridor was approximately 8.5 minutes. The instantaneous speed ranged from zero to approximately 50 mph, and the average speed was 17 mph. The longest waiting times occurred in the queue at the intersection with Mall Access.

An example of an emission trace for a pollutant is shown in Figure 2 for CO. The CO emission rate exceeded 0.29 grams per second only twice during the trip, and emissions exceeded 1 gram per second only one time. The largest peak in the emission rate occurred at the same time as the acceleration from zero to approximately 50 mph as the vehicle cleared the intersection with Dillard

Drive. The second largest peak in CO emissions also coincides with an acceleration event that occurs when clearing the intersection with Cary Towne Boulevard. In both of these cases, the increase in CO emissions corresponds to significant acceleration events. The CO emission rate remained below 0.29 grams for the rest of the trip, where cruising or low acceleration events occurred. These data suggest that the CO emission rates during idling or cruising are comparatively low compared to CO emissions during high acceleration.

In general, the time traces for all four measured pollutants, including HC, NO, and CO_2 (not shown here but documented in elsewhere[15,17]) indicate that there is a relatively large contribution to total emissions from short-term events that occur within the trip. These short-term events cause hotspots that might have emissions significantly higher than rest of the trip. This implies that efforts to reduce on-road emissions should be aimed at understanding and mitigating these hotspots. In particular, it may not be necessary to reduce vehicle miles traveled in order to reduce emissions; instead, it may be necessary to prevent hotspots.

EMISSION FACTOR ESTIMATION

In this section vehicle emission factor estimation via data collected from on-board instrumentation will be presented. The methodology developed for vehicle emissions modeling will be explained briefly. Details of these analyses can be found elsewhere.15,17

There are three different levels for vehicle emission factor estimation as suggested by NRC and EPA.2,23 These levels are: micro-scale; meso-scale; and macro-scale. Micro-scale analysis refers to estimation of emissions for specific corridors and intersections for project level and hot-spot analyses.23 The temporal profile of vehicle activity and emissions provides important insights regarding potential factors that can explain variation in vehicle emissions, and, in particular, explain high emissions events or “hot spots.” The examples given in Figures 1 and 2 show this kind of analysis.

Meso-scale analysis refers to analysis at regional and sub-regional (corridor) levels as stated by NRC.2 These analyses should be for fine resolution estimation of emissions using vehicle-operating conditions as input parameters. It should be noted that there might be some overlap between meso-scale and micro-scale analyses.23 Meso-scale analyses would allow development of accurate assessments of TCMs and Transportation Improvement Plans (TIPs). One method that enables such results is modal analysis. The details of this type of analysis will be presented later in this paper.

Macro-scale refers to analysis over a large regional area (e.g., county, state, and nation), for which emissions are estimated using aggregated analysis techniques.2,23 As a general rule, it is preferred to obtain macro-scale estimates based upon aggregation of data from a finer resolution scale. With finer resolution data, there is always the option of partitioning or analyzing the data in ways to take into account key explanatory micro-scale or meso-scale variables that might affect macro-scale emissions, or that might allow the same data and model to be used for multiple purposes in analyzing problems at all three scales. For example, because real world emissions are often highly influenced by localized high emission rates, macro-scale emissions may be influenced by peak measures of vehicle equivalence ratio, fuel use, or power demand, rather than average values of these. Some variables, such as ambient temperature, do not fluctuate substantially during a typical trip and therefore are more naturally treated as trip-average or macroscale variables.

In this study, a combined approach is taken for emission factor development. In this approach vehicle emissions were analyzed at all three scales: macro, meso and micro. The second-by-second data obtained from on-board instruments are micro-scale. By aggregating the data, it is possible to do both meso- and macro-scale analyses. In the next section, an example for meso-scale analysis is presented.

Figure 1. Vehicle speed versus elapsed time of the trip.

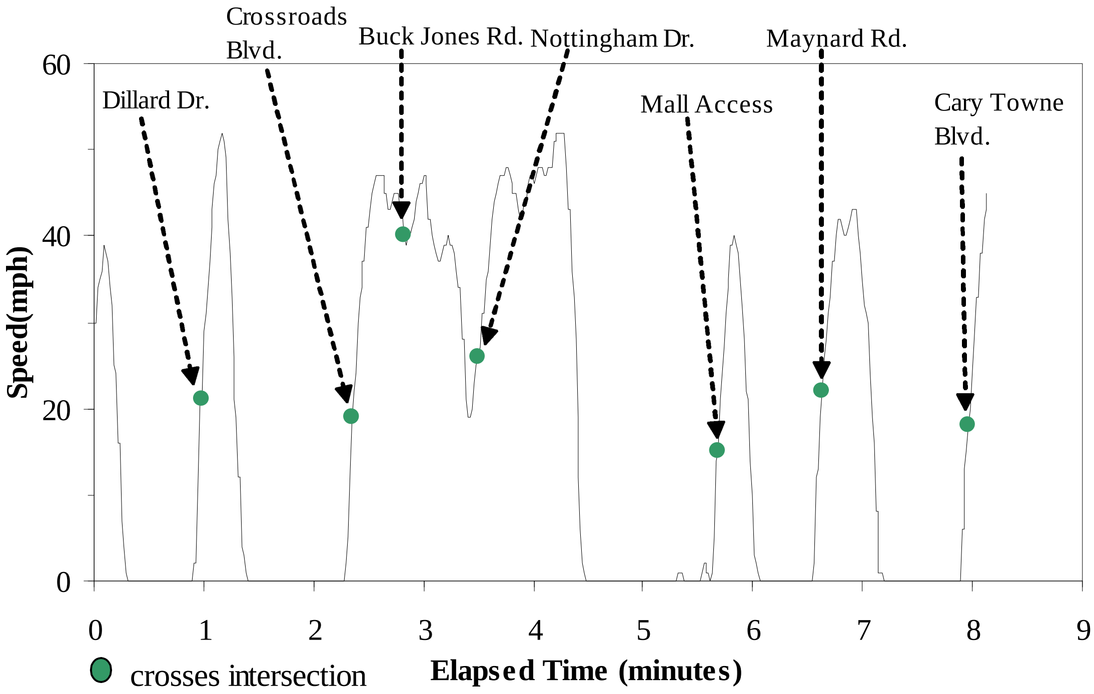
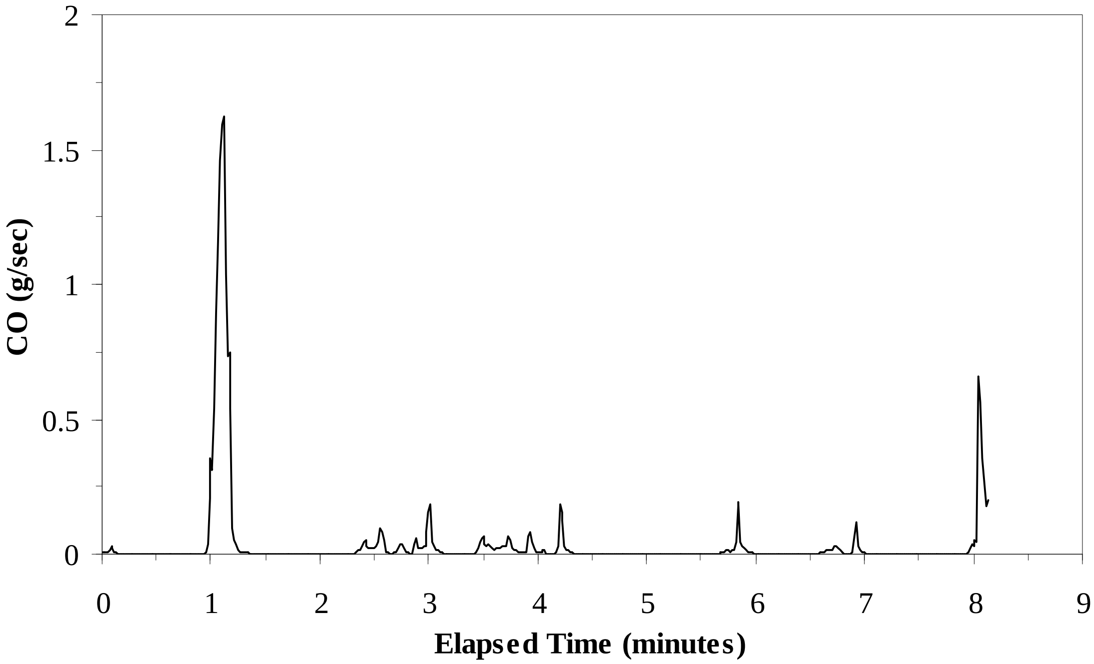


Figure 2. Vehicle CO emissions versus elapsed time of the trip.



Modal Analysis

Average emissions of vehicles are different in different operating modes 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.[9-10, 13, 15-17] For example, driving can be divided into four modes: (1) acceleration; (2) cruise; (3) deceleration; and (4) idle.

The defining characteristics of a driving mode are somewhat arbitrary. A *priori* assumptions based upon vehicle's speed and acceleration have been used in this work to determine the operating mode of the vehicle during hot-stabilized operation. Details of this methodology are explained elsewhere.[15-17] Cold start was defined as a mode based upon the duration of the cold start.[17]

The driving mode for each second of a trip is determined with the help of a program written in Microsoft Visual Basic. The program calculates the total emissions for the trip. In order to determine whether modal analysis has explanatory value or not, average modal emission rates were estimated for each trip. The average of the estimates for each mode was calculated based upon all vehicles and trips in the database. A comparison of the average modal emission rates for each of four pollutants is shown for an example dataset in Figure 3, along with estimates of the 95 percent confidence intervals on the trip mean emission rates. The dataset used for this example consists of 12 different LDGVs and 51 trips. The modes shown are cold start, and the four hot stabilized modes of idle, acceleration, deceleration, and cruise. The cold start mode includes all vehicle activity that took place during the cold start. Cold start determination was conducted using non-linear statistical model, and is explained in detail elsewhere.[17]

It is clear from Figure 3 that the average emission rate during cold start is approximately comparable to the average hot stabilized acceleration emission rate. For example, for CO, the average cold start and hot-stabilized acceleration emission rates are not statistically significantly different from each other. These two rates are also nearly the same for NO. For HC the average cold start emission rate is substantially higher than that for hot stabilized acceleration. The results for CO_2 are somewhat different in that the cold start emission rate is less than the acceleration emission rate and is approximately comparable to the cruising emission rate.

Setting aside the cold start mode, and focusing only on the four hot stabilized modes, the comparisons reveal similar trends among all four pollutants and are similar to the findings obtained with different vehicles in a previous study by NCSU.[15] The emissions during the acceleration mode are significantly higher than for any other driving mode for hot-stabilized emissions for all four of the pollutants measured. Conversely, the emission rate during idling is the lowest of the four modes for all four pollutants. The cruising emission rate is typically slightly higher than the deceleration emission rate.

In order to check whether average modal emission rates are statistically significantly different from each other, pairwise t-tests were estimated. Results of the t-tests are presented in Table 1 in terms of p-values. P-values less than 0.05 indicate that the particular pair has statistically significant differences in average estimates. For example, the t-test between idle and acceleration modes for HC emissions gave a p-value of 0, indicating that average HC emissions are different for these two modes. Out of 24 possible pairwise comparisons excluding cold start mode, only one of them gave p-values higher than 0.05, indicating that average emissions rates for this pair is not statistically different from each other. This one case occurred between deceleration and idle modes for HC emissions.

The modal emissions analysis results suggest that the *a priori* modal definitions assumed here are reasonable. These modal definitions allow some explanation of differences in emissions based upon driving mode, as revealed by the fact that, in most cases, the average modal emission rates differ from each other. The analysis also indicates that the average acceleration emission rates for CO and NO are more than a factor of 10 higher than the average idling emission rates, and that the average acceleration emission rates for CO_2 and HC are approximately a factor of five higher than the average idling emission rates. These findings are very similar to previous study by NCSU for a different set of LDGVs.[15] These substantial differences in emission rate have important implications for traffic and air quality management. It should be noted that CO_2 emissions are highly correlated with and are a good surrogate for fuel consumption.

Vehicle Emissions Modeling

Modal definitions have a power to explain variability in emissions since average emission rates for different modes are found to be statistically significant from each other. A further step was taken to improve driving modes for hot stabilized emissions so that emissions within each mode are more

Figure 3. Average Modal Emission Rates for All Trips for LDGV.

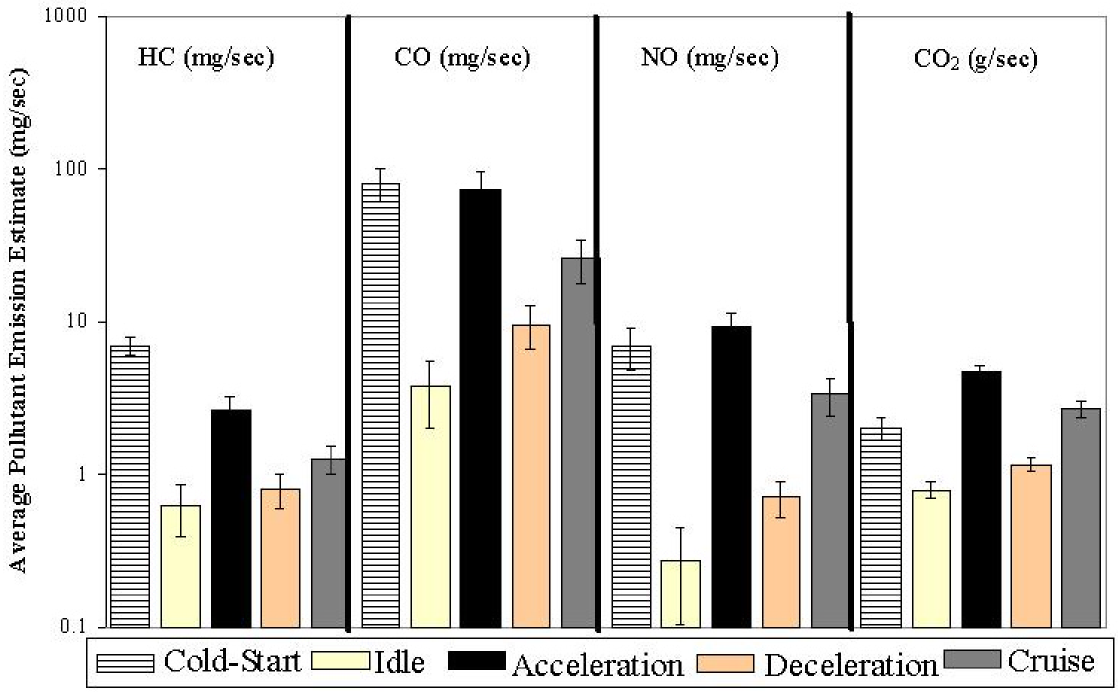


Table 1. Result of Pairwise Comparison for Modal Average Estimates in terms of p-value.

P-Values for T-test for Significance in Difference in Averages					
	Modes	Idle	Acceleration	Deceleration	Cruise
HC	Cold-Start	0.000	0.000	0.000	0.000
	Idle		0.000	0.270	0.001
	Acceleration			0.000	0.000
	Deceleration				0.014
CO	Cold-Start	0.000	0.608	0.000	0.000
	Idle		0.000	0.001	0.000
	Acceleration			0.000	0.001
	Deceleration				0.001
NO	Cold-Start	0.000	0.140	0.000	0.004
	Idle		0.000	0.001	0.000
	Acceleration			0.000	0.000
	Deceleration				0.000
CO_2	Cold-Start	0.000	0.000	0.000	0.003
	Idle		0.000	0.000	0.000
	Acceleration			0.000	0.000
	Deceleration				0.000

homogeneous. In order to improve driving modes, Hierarchical Tree-Based Regression (HTBR) was utilized. HTBR is a statistical method that cane be considered as a forward step-wise variable selection method. Detailed information on this method can be found elsewhere.[10,17]

Emissions data in each mode were analyzed using HTBR with respect to several explanatory variables. These variables were: speed; acceleration; power demand (i.e., surrogate for power utilized by vehicle and estimated using speed and acceleration); road grade; and vehicle engine size. HTBR analysis

Figure 4. Observed versus Predicted Trip Averages for HC Emissions

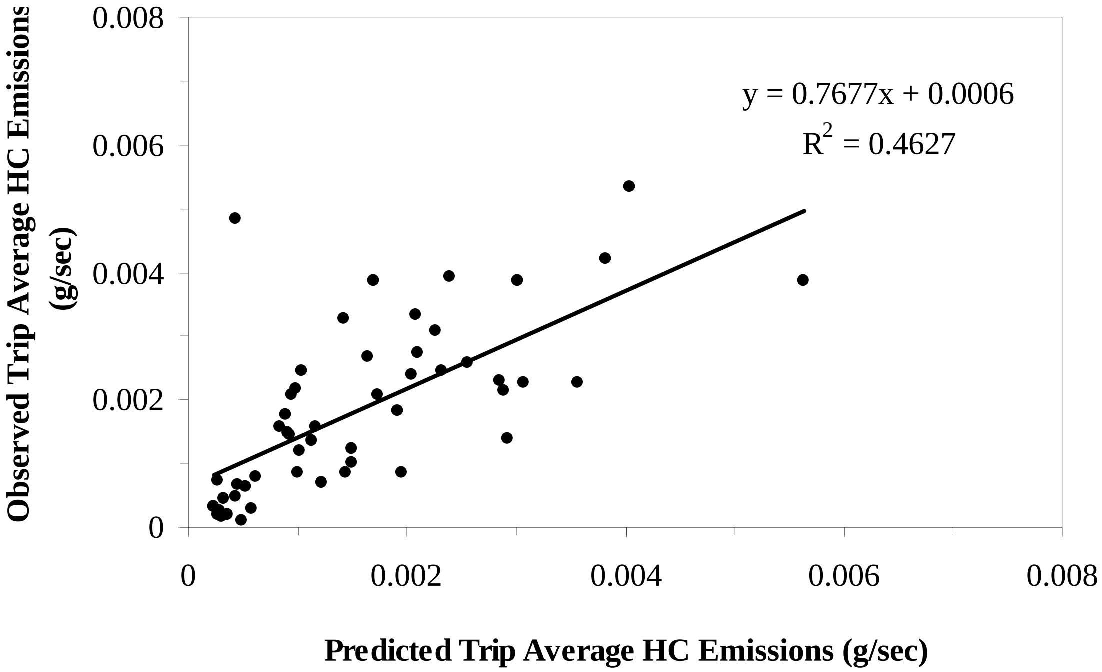
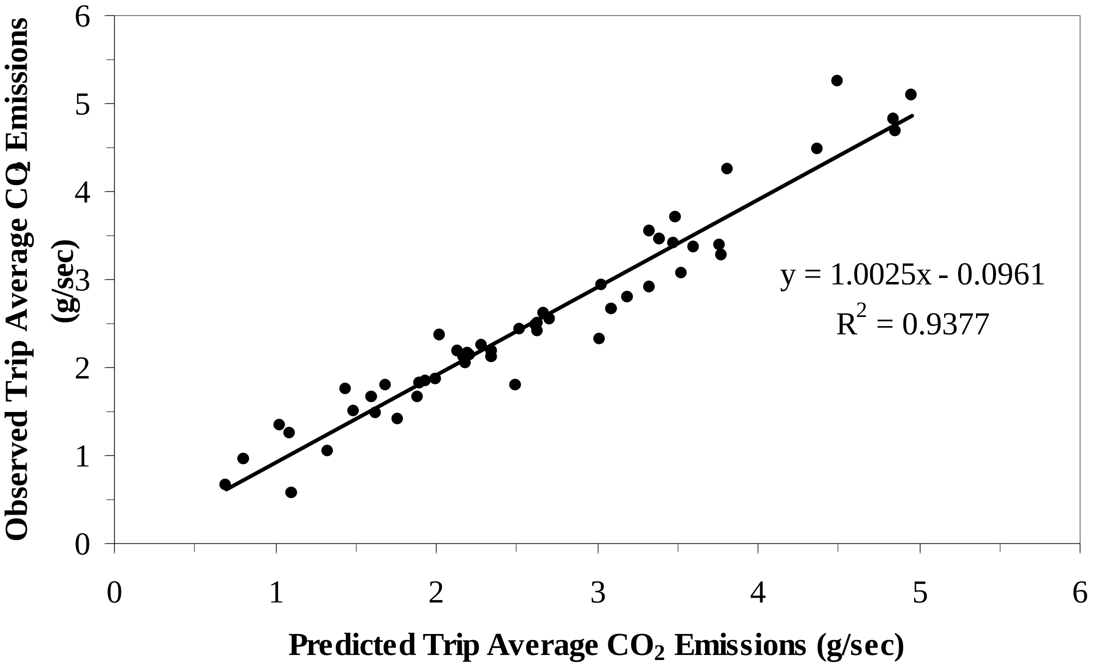


Figure 5. Observed versus Predicted Trip Averages for CO_2 Emissions



was conducted separately for HC, CO, and NO emissions. For CO_2 emissions, the original modes were considered to be adequate for their explanatory power.

It was found that power demand can be used to improve driving modes for HC, CO, and NO emissions. For example, for the acceleration mode, a cut off point of 100 mi^2/h^2sec can be used. Data in acceleration mode where power demand is greater than this cut off point was identified as “high acceleration” mode, and data having power demand lower than the cut off point was identified as “low acceleration” mode.

After developing modal definitions, Ordinary Least Squares (OLS) regressions were fit to the second-by-second data in each mode using explanatory variables. These explanatory variables were: speed; acceleration; power demand; engine size; ambient humidity; ambient temperature; altitude; and road grade. Using a stepwise regression technique in SAS, regressions were fit for each mode and for each pollutant separately. Details of this analysis are given elsewhere.[17]

In order to model emissions during cold-start, a different approach was taken. For cold-start emissions, data are consecutive and have autocorrelation.[17] A regression with time series errors technique was used to model cold-start emissions. This method removes the autocorrelation in the data before fitting a regression so that it prevents bias in regression estimations. Details of this analysis are given elsewhere.[17]

The overall models developed for each pollutant are based upon estimation of emissions (average g/sec) at a meso-scale for each of the five modes (cold start, idle, acceleration, deceleration and cruise). In all cases, except for CO_2, the modes were further divided based upon power demand, such as for acceleration and cruise. OLS regression equations were used to provide a microscale second-by-second predictive capability within the modes. Cold start was treated differently because of the autocorrelation of emissions within this mode.

After developing the model, in order to determine whether the overall model is good or not, trip-average emissions estimations from the observed data were compared to model predictions for the same trips using parity plots. Examples of parity plots are given for HC and CO_2 emissions in Figures 4 and 5 respectively. There are 51 points in these figures representing average emissions for each trip.

The performance of the model can be evaluated in terms of precision and accuracy. The R^2 value is an indication of precision. Higher R^2 values imply a higher degree of precision and less unexplained variability in model predictions. The slope of the trend line for the observed versus predicted values is an indication of accuracy. A slope of one indicates an accurate prediction, in that the average prediction of the model corresponds to an average observation. The R^2 value for Figure 4 is 0.46, and the slope of the trend line is 0.77. These results indicate that the model can explain approximately half of the variability in the data, and that there is some bias in the model predictions. The bias can be corrected using the slope and intercept from the trend line to convert a model prediction to more closely to match the observed emissions.

A similar comparison for CO_2 emissions is shown in Figure 5. The R^2 for the regression between the predicted and observed values is 0.94. While the R^2 of the trend lines for CO, NO, and HC are typically approximately 0.4 to 0.45, the much larger R^2 of 0.94 for CO_2 illustrates that it may be possible to obtain precise estimates of CO_2 emissions even though predictions for the other pollutants may be less precise.

It should be noted that the methodology developed in this study was based upon data collected only with on-board instruments. In a preliminary analysis, methods for estimating modal emissions from driving cycle data have been identified.[17]

CONCLUSIONS

On-board emissions measurement of tailpipe emissions for on-road and in-use vehicles is a preferred approach over the use of laboratory dynamometer based methods or remote sensing. On-board emissions measurement enables collection of data at any time and location, thereby resulting in a more accurate and representative emissions data base than can be obtained with current alternative methods.

NCSU has successfully demonstrated an overall methodology for on-board measurement of tailpipe emissions for on-road vehicles, including experimental design, instrument deployment, field data collection, data reduction, and data analysis.

Data obtained from on-board emissions measurement demonstrate that emissions during a trip or segment of a trip are influenced by short-term high emissions events referred to here as "hotspots." Hotspots are typically associated with rapid accelerations, such as occurring at a signalized intersection when the signal phase changes to green. Analysis of second-by-second data motivated the development of driving modes for purposes of meso-scale analysis of on-board data.

Data for selected light duty vehicles were analyzed to estimate average emissions on a grams per second basis for cold start and for four hot stabilized driving modes: idle, acceleration, cruise, and deceleration. For each of four pollutants, these five driving mode definitions were found to be statistically significantly different from each other in most pairwise comparisons among the modes. Furthermore, the average emission rate during acceleration was shown to be approximately five to ten times larger than the average emission rate during idling. Thus, the modal definitions are useful because they are statistically significant and they capture a significant portion of the variability in emission rates.

A conceptual approach to developing a vehicle emission factor model was illustrated using selected light duty gasoline vehicles. The approach involved dividing second-by-second on-board data into bins representing each of the five driving modes, and then developing regression models from which to estimate emissions within a mode on a second-by-second basis. The conceptual model was applied to estimate trip emissions for selected vehicles and the results were compared with measured emissions. The precision and accuracy of the models was characterized. The models were found to perform well. The precision and accuracy of the model can be used to support assessment of uncertainty in the model predictions.

The cold start, acceleration, and cruise modes typically contribute far more to total trip emissions than do the idle and deceleration modes. A key implication for traffic and air quality managers is that it is important to development strategies aimed at reducing the frequency and duration of high emissions events. This could be accomplished, for example, not by modifying how many miles people drive, but by modifying *how* people drive. Approaches for modifying driving behavior could include improved roadway facility design, improved signal timing and coordination, and message systems to provide feedback to drivers. Data regarding the relationship between traffic facility design and management in comparison to emissions are needed in order to identify and recommend improved design and management approaches.

This paper demonstrates that the meso-scale based modal emissions estimation method can be supplemented with micro-scale regression analysis techniques to enable a multi-scale capability to predict vehicle emissions. Although the focus of this paper was with respect to on-road vehicles, similar approaches were demonstrated for nonroad vehicles. Modal based modeling approaches are recommended for MOVES. Such approaches should be combined with techniques for quantifying uncertainty in predictions and for making use of a variety of data sources. To support MOVES, adequate resources should be devoted to properly designing and executing field studies of on-road or in-use emissions, analyzing the data, developing the model, documenting the model, and obtaining review of the model.

ACKNOWLEDGEMENTS

The authors acknowledge the support of the North Carolina Department of Transportation (NCDOT), via the Center for Transportation and the Environment, and the Office of Transportation and Air Quality (OTAQ) of the U.S. Environmental Protection Agency, which funded portions of this work. This report has not been subject to any EPA review. The opinions, findings, and conclusions expressed

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