ABSTRACT

UNAL, ALPER. On-board Measurement and Analysis of On-Road Vehicle Emissions (Under the direction of Dr. Chris Frey)

Recent developments in on-board instrumentation enable measurement of vehicle activity and emissions under real-world conditions as opposed to laboratory tests. On-board instrumentation of vehicles during on-road operation enables data collection under real-world conditions at any location traveled by the vehicle and under any weather conditions. Variability in vehicle emissions as a result of variation in vehicle operation, roadway characteristics, or other factors can be represented and analyzed more reliably than with other measurement methods.

The primary purpose of this dissertation is to develop methodologies for on-board vehicle activity and emissions data collection and data screening. Successful application of the developed methodology resulted at data collected in two signalized corridors in Cary, North Carolina. Eight gasoline fueled light-duty vehicles and four drivers were tested, resulting in a total of 824 one-way runs representing approximately 1,000 vehicle-hours and 2,020 vehicle-miles of simultaneous second-by-second vehicle activity and emissions data. Exploratory analysis of these data revealed that emissions are different under different vehicle operation conditions. *A priori* modal definitions were developed based upon vehicle speed and acceleration. It was found that modal definitions yield statistically significantly different emission rates for idle, acceleration, cruise, and deceleration. The average emission rate on a mass per time basis for acceleration was found to be typically a factor of five greater than the idle emission rate for HC and CO_2, and a factor of ten or more for NO and CO. A key implication of this finding is that

methods for reducing real-world on-road emissions should involve measures that reduce the frequency and duration of episodic events, such as high accelerations, that lead to short periods of high emissions.

A secondary, but equally important, purpose was to utilize vehicle activity and emissions data collected to tackle real-world problems related to vehicle emissions. One of these problems is to investigate emissions hotspots along roadways. Methods were developed to identify hotspot locations and applied to two example case studies to illustrate the types of insights obtained from this analysis. For the example case studies, emissions associated with a single signalized intersection contributed substantially to total emissions for a particular corridor. Based upon statistical and graphical analysis, hotspots were attributed most typically to stop-and-go traffic conditions which result in sudden changes in speed and accelerations.

The sensitivity of different emissions factor estimation methods (i.e., distance-based, time-based, and fuel-based) was investigated with respect to vehicle operation modes. It was found that time- and distance-based emission factor estimation methods are sensitive to different vehicle operation modes. For fuel-based method NO emission, are sensitive to mode, however, CO and HC emissions are less sensitive to mode. Fuel consumption was also found to be sensitive to vehicle operation modes.

The effect of changes in signal timing and coordination on vehicle emissions was also investigated. Methods were developed to analyze and interpret real-world on-road tailpipe emissions data regarding before and after comparisons associated with a change in traffic conditions. For the example case study it was found that coordinated signal timing improved traffic flow on Walnut Street, which lead to a reduction in vehicle emissions. For Chapel Hill Road, emissions of NO, CO, and HC were lower in the uncongested case compared to the congested case. It was found that differences in emissions were highly associated with differences in quantitative measures of traffic flow such as average speed, average control delay, and average number of stops per mile.

On-Board Measurement and Analysis of On-Road Vehicle Emissions

by

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To my wonderful wife, Gozde Unal, who made all of this possible, with her endless love and encouragement

BIOGRAPHY

Alper Unal completed his high school education at TED Ankara Koleji, Ankara, in 1992, and received his Bachelor of Science degree in Environmental Engineering with Honors from Middle East Technical University, Ankara, Turkey, in 1996. He started his graduate studies at North Carolina State University, Raleigh, in 1997, and worked on measurement and analysis of vehicle emissions using Remote Sensing Device (RSD). He earned his Master of Science degree in Civil Engineering from the North Carolina State University, Raleigh, in 1999. Since August 1999, he continued his graduate studies in the Civil Engineering Department at North Carolina State University, Raleigh, NC, and worked as a research assistant at the Computational Laboratory for Energy, Air, and Risk (CLEAR) group, pursuing his Ph.D. degree. This thesis completes the requirements for this degree.

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PART I

INTRODUCTION

1.0 INTRODUCTION

Motor vehicles constitute major emission sources for several air pollutants, including nitrogen oxides (NO_X), carbon monoxide (CO), particulate matter (PM), and hydrocarbons (HCs). These pollutants have significant adverse effects on human beings and the environment.

Vehicle emissions cause near-term problems associated with health effects. For example, hydrocarbons and nitrogen oxides are the precursors of ozone, which have effects ranging from short term consequences such as chest pain, decreased lung function, and increased susceptibility to respiratory infection, to possible long-term consequences, such as premature lung aging and chronic respiratory illnesses (NRC, 2000; EPA 1993).

High amounts of carbon monoxide can lead to CO poisoning and can impair visual perception, and manual dexterity. Infants, elderly persons, individuals with heart disease, and individual with respiratory diseases are particularly sensitive to CO (EPA, 1993). Other pollutants emitted by vehicles are known to contribute to ill health, acid deposition, smog, and green house problem (NRC, 2000).

At the Federal and state level, regulations have been developed placing limits on the allowable emission rate of emissions sources including highway vehicles. In spite of efforts for controlling emissions, about 121 million people lived in counties that violated one or more of the National Ambient Air Quality Standards (NAAQS) in the year 1999 (EPA, 2001a). Transportation sector, including on-road and non-road vehicles, are estimated, based upon emission inventories prepared by the U.S. Environmental Protection Agency (EPA), to contribute 47 percent of total HC emissions, 55 percent of total NO_x emissions, 77 percent of total CO emissions, and 25 percent of total PM emissions in 1999 (EPA, 2001a). 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 regulatory vehicle emission factor estimation model, MOBILE, and are subject to types of uncertainties that this model carries (NRC, 2000; Kini and Frey, 1997).

In a recent National Research Council (NRC) study to review Mobile model, it has been found that it has serious limitations to answer the demands of a wide range of application in vehicle emissions field, which varies from national vehicle emissions and fuel standards to local travel demand and congestion mitigation measures. NRC study made several critical recommendations in order to improve vehicle emissions estimation (NRC, 2000). One of the key suggestions by the NRC study is to develop a new emissions estimation method which allow for prediction of emissions over a broad range of spatial and temporal scales. This could be possible with real-world data rather than data collected under laboratory conditions.

Another key suggestion by NRC is to utilize improved science and technology to improve vehicle emissions estimation. As stated by EPA (2001b) recent emergence of on-board emissions devices, which enable data collection under real-world conditions, will revolutionize vehicle emissions data collection. Variability in vehicle emissions as a result of variation in vehicle operation, roadway characteristics, or other factors can be represented and analyzed more reliably with on-board emission devices than with the other methods, such as laboratory dynamometer tests which are basis for MOBILE model. This is because measurements are obtained during real-world driving conditions, eliminating the concern about non-representativeness. It is indicated by the EPA that on-board emission devices will be the focus of EPA's emission factor testing program and will provide significant changes in vehicle emissions modeling (EPA, 2001b).

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 (Cicero-Fernandez and Long, 1997; Gierczak *et al.*, 1994; Tong *et al.*, 2000; Rouphail *et al.*, 2001; Frey *et al.*, 2001, Frey *et al.*, 2002a; Frey *et al.*, 2002b). On-board emissions measurement has not been widely used in the past because it has been prohibitively expensive. However, in the last few years, efforts have been underway to develop lower-cost instruments capable of measuring both vehicle activity and emissions (Scarbro, 2000; Vojtisek-Lom and Cobb, 1997; Wilson, 2002; Butler, 2002; Oestergaard, 2002).

The first contribution of this dissertation is to utilize on-board instruments to collect vehicle activity and emissions data under real-world conditions. This study is unique since it is one of the first studies where on-board measurement device was utilized to measure vehicle activity and emissions data under real-world conditions. Another key feature of this study is to utilize on-board emissions data to tackle real-world problems related to vehicle emissions. In other words, the main contributions of this dissertation are the development of new methodologies: (i) to assess the effect of traffic parameters on vehicle emissions; (ii) to investigate of emissions hotspots along roadways; and (iii) evaluate the sensitivity of different emission factor estimation methods to vehicle operation conditions. All these contributions are unique since they are conducted with data collected under real-world conditions in contrast to methods that utilize simulations or laboratory data.

The remainder of this chapter outlines the objectives of this dissertation, gives an overview of the research and presents the organization of the dissertation.

1.1 OBJECTIVES

The primary objectives of this dissertation are as follows:

1. To develop methodologies for on-board vehicle activity and emissions data collection. These efforts include development of experimental design as well as data collection procedures. Development of a joint emission and traffic parameters, data screening and reduction are also part of this effort.

2. To investigate sensitivity of different vehicle emission factor estimation methods to vehicle operation conditions based upon real-world emissions data.

3. To investigate hotspots along roadways where high values of emissions are observed. Investigation of parameters that have significant effects on hotspots is also part of this effort.

4. To assess the feasibility of on-board emission measurement system for estimating traffic signal impacts on emissions. This objective also includes evaluating the effect of traffic signal timing and coordination with respect to vehicle emissions on selected corridors.

1.2 OVERVIEW OF RESEARCH

The research of this dissertation focused on two main parts: developing methodology for real-world vehicle activity and emission data collection and application of real-world on-board data to different problems in vehicle emissions field.

The data collection and analysis for this dissertation was part of a research project entitled, "Emissions Reduction Through Better Traffic Management." The project began in April 1999 and ended in December 2001. The project was authorized by the North Carolina Department of Transportation (NCDOT) and the Center for Transportation and the Environment (CTE) and was conducted by North Carolina State University (NCSU).

This dissertation features novel methodological contributions regarding on-board vehicle activity and emissions measurements. Part III of this dissertation deals with development of experimental design, data collection, screening, and reduction procedures. The methodology developed in Part III is utilized to process the collected data for further analysis. Effects of different drivers and engine parameters are investigated in this section. Modal analysis of vehicle emissions is also explained in this section. Modal analysis techniques developed in this study are being investigated by the author and the researchers at North Carolina State University for a project supported by EPA for possible uses in the new vehicle emissions estimation model, named as Multi-Scale Motor Vehicle and Equipment Emission System (MOVES) (Frey et al., 2002a, Frey et al., 2002b).

Part IV of this dissertation investigates the sensitivity of different emission factor estimation methods with respect to vehicle operation conditions. This section will answer a very important question related to vehicle emissions factor estimation method. Modal analysis will be utilized for comparison of different emission factor estimation methods.

Part V of this dissertation demonstrates the methodology for emissions hotspots determination using on-board data. Spatial analysis of vehicle emissions will be given in this section where multivariate statistical methods such as Principal Component Regression are applied.

Part VI demonstrates the use of on-board instrumentation for determining the effect of traffic parameters on vehicle emissions. Effect of traffic signal coordination and timing on vehicle emissions on selected corridors will be presented in this section.

1.3 ORGANIZATION

This dissertation will first present background information and literature review on vehicle emissions, which is given in Part II of this dissertation. Four manuscripts that the author has submitted or plans to submit for publication in peer-reviewed journals comprise Parts III through VI of this dissertation. More detail is available in project reports prepared for NCDOT (Frey *et al.*, 2001) and USEPA (Frey *et al.*, 2002b).

The paper given in Part III of this dissertation provides a discussion on the methodological aspects of on-board vehicle emissions data collection. The manuscript given in Part IV of this dissertation demonstrated the methodology in evaluating emissions hotspots along roadways based upon real-world vehicle emissions and activity data.

The manuscript presented in Part V investigates sensitivity of different emission factor estimation methods with respect to vehicle operation parameters. Part VI of this dissertation demonstrated effect of traffic parameters with respect to vehicle emissions based upon the real-world data collected on selected corridors. Finally, the conclusions of this study and the recommendations for future studies are presented in Part VII.

Alper Unal is the first author of all but the first paper. In the first paper, Alper Unal contributed substantially and significantly to data collection and analysis, including deployment of the OEM-2100TM, development of data processing tools, quantification of modal emission rates, statistical analysis of data, analysis of CO emissions with respect to equivalence ratio, and comparison of drivers.

Each part of this manuscript has its own list of references cited.

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PART II

BACKGROUND ON VEHICLE EMISSIONS

This section summarizes a literature review that was performed of the relevant research related to vehicle emissions. First background information on vehicle emissions formation is given. Then brief information on regulations related to vehicle emissions is presented. Finally general approaches used in vehicle emissions measurement and modeling are described.

2.1 INTRODUCTION

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 121 million people lived in counties that violated one or more of the NAAQS in the year 1999 (EPA, 2001). Transportation sector, including on-road and non-road vehicles, are estimated, based upon emission inventories prepared by the U.S. Environmental Protection Agency, to contribute 47 percent of total HC emissions, 55 percent of total NO_x emissions, 77 percent of total CO emissions, and 25 percent of total PM emissions in 1999 (EPA, 2001). 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 MOBILE6 elsewhere. 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 MOBILE6, 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; Rouphail *et al.*, 2000).

Driving cycle-based models do not consider the differences in engine load while calculating the emission factor (Hallmark *et al.*, 2000). 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; Rouphail *et al.*, 2000; Frey *et al.*, 2001; Frey *et al.*, 2002; 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, 1997). 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 was 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). Recently, private companies such as Clean Air Technologies International Inc., Sensors Inc., Ford Motor

Company, and Horiba have developed commercial versions of on-board instruments (Vojtisek-Lom and Cobb, 1997; Wilson, 2002; Butler, 2002; Oestergaard, 2002).

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, named as Multi-Scale Motor Vehicle and Equipment Emission System (MOVES). 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 MOVES (Frey *et al.*, 2002).

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PART III

ON-ROAD MEASUREMENT OF VEHICLE TAILPIPE EMISSIONS USING A PORTABLE INSTRUMENT

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On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument

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ABSTRACT

A study design procedure was developed and demonstrated for the deployment of portable on-board tailpipe emissions measurement systems for selected gasoline and E85 fueled highway vehicles. Data collection, reduction, and analysis protocols were developed to assure data quality and to provide insights regarding quantification of real-world intra-vehicle variability in emissions. On-board systems provide representative real-world emissions measurements; however, on-board field studies are challenged by the observable but uncontrollable nature of traffic flow and ambient conditions. By characterizing intra-vehicle variability based upon repeated data collection runs with the same driver/vehicle/route combinations, this study establishes the ability to develop stable modal emissions rates for idle, acceleration, cruise, and deceleration even in the face of uncontrollable external factors. For example, a consistent finding is that average emissions during acceleration are typically five times greater than during idle for hydrocarbons and CO_2, and ten times greater for NO and CO. The role of equivalence ratio and fuel flow with respect to emissions is quantified using on-board data. A statistical method for comparing on-road emissions of different drivers is presented. On-board data demonstrate the importance of accounting for the episodic nature of real-world emissions in order to help develop appropriate traffic and air quality management strategies.

IMPLICATIONS

Real-world vehicle emissions are episodic in nature. On-board data enables quantification of high emissions episodes with respect to location as well as with respect to micro-scale trip characteristics, based upon representative on-road data. Idle emission rates were found to be low compared to acceleration and cruise emission rates, and high emissions episodes were often associated with acceleration. An implication of this work is that *how* a vehicle is driven, not necessarily how many miles are driven, is important. Insights such as this can be used to design Transportation Control Measures (TCMs) and Transportation Improvement Plans (TIPs) that effectively reduce emissions.

1.0 INTRODUCTION

Motor vehicle emissions contribute substantially to national and local emission inventories for hydrocarbons (HC), nitrogen oxides (NOx), and carbon monoxide (CO).1,2,3 The typical approach for estimating vehicle emissions is to use area-wide driving cycle-based models such as Mobile5b, Mobile6, and EMFAC. The tailpipe emissions data for these models are typically based upon average emissions per mile over standard driving cycles as measured in the laboratory using a dynamometer. Idle emissions are typically extrapolated from a g/mi basis based upon driving cycles with low average speeds to a g/sec basis, but are not estimated based upon measurement of actual idling. Second-by-second data collected in the laboratory and on the road demonstrate that vehicle emissions are episodic in nature, in which average emissions for a trip are often dominated by short-term events. Thus, while driving cycle-based models are useful for developing area-wide emission inventories, these models lack the temporal and spatial resolution to properly characterize the episodic microscale nature of vehicle emissions. The latter is a critical need in order to identify and develop effect traffic management strategies that will result in real-world emissions reductions. Furthermore, the standard driving cycles may not adequately represent real world driving for a particular location because of failure to represent the influence of real world traffic flow. Therefore, it is important to develop and deploy methods for obtaining real-world, on-road microscale measurements of vehicle emissions during actual and typical vehicle use.

In this work, an empirical approach to measurement of real-world, on-road vehicle emissions is emphasized. Instrumentation of individual vehicles to measure tailpipe emissions offers the benefit of providing second-by-second vehicle activity and emissions data, enabling characterization of emissions at any time or location during a route. With on-road data of high temporal and spatial resolution, it will be possible in the future to accurately evaluate the local effect of changes in traffic flow that might result from improved signalization or roadway design.

The main objectives of this paper are to document: (1) the on-board emission measurement system; (2) key considerations in experimental design for on-road data collection; (2) data collection procedures; (4) the approach for preparation of a joint emissions and traffic parameter database; (5) data reduction and analysis; and (6) exemplary case studies of data and insights. The case studies highlight: (1) the episodic nature of vehicle activity and emissions data; (2) variability and uncertainty in modal NO, HC, CO, and CO2 emissions; (3) the relationship between equivalence ratio and CO emissions; and (4) a comparison of emissions based upon two different drivers. The use of on-board measurements for transportation and air quality management applications is discussed.

The Role of On-Board Instrumentation

There are three typical vehicle tailpipe emission measurement methods: (1) dynamometer tests; (2) remote sensing; and (3) on-board instrumentation. Dynamometer testing involves measurement of vehicles using standardized driving cycles, typically under controlled ambient conditions. 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.[2,3] The data obtained from driving cycles are also used to develop emission estimation models, such as EMFAC7F, MOBILE6, MEASURE, and CMEM.[4-6] A key concern with such tests is that they may not represent real-world on-road driving in a given geographic area.[2, 4]

Remote sensing devices uses infrared (IR) and, in some cases, ultraviolet (UV) spectroscopy to measure the concentrations of pollutants in exhaust emissions. An advantage of remote sensing is that it is possible to measure a large number of on-road vehicles (e.g., thousands per day). A disadvantage of remote sensing is that it only gives an instantaneous estimate of emissions at a specific location on a concentration or fuel basis. 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 a fair weather technology.[4]

On-board instrumentation of vehicles during on-road operation enables data collection under real-world conditions at any location traveled by the vehicle and under any weather conditions.[7-13] In the past, on-board instrumentation was not widely used because it was prohibitively expensive. Therefore, on-board emissions measurement studies have typically focused on a very small number of vehicles.[7-9,14] In some studies, researchers have measured engine parameters only.[15-17] However, in recent years portable instruments have become available. For example, the U.S. Environmental Protection Agency (EPA) is developing an on-board measurement system, Real-time On-road Vehicle Emissions Reporter (ROVER), for both light and heavy duty vehicles.[18] Clean Air Technologies International Inc. (CATI), Sensors Inc., Ford Motor Company, and Horiba are among those who have developed portable on-board instruments.[19-22]

2.0 INSTRUMENTATION

The instrument used for on-board data collection in this study is the OEM-2100™ manufactured by CATI. The 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, 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 may be downloaded during vehicle operation. Model year 1990 and later vehicles have OBD connections. In 1996, OBD-II was introduced and includes a standardized data link. Eight OBD parameters are collected by the OEM-2100™: 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.[19]

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.[23] Three light-duty gasoline vehicles were tested by NYDEC using the I/M 240 and NYCC driving cycles. Two light-duty vehicles were tested by EPA using the FTP, US06, NYCC, and FWY-HI driving cycles. The results showed high correlation coefficients (R^2), ranging from 0.90 to 0.99, between the OEM-2100™ measurements and laboratory measurements for CO, CO_2, NO, and HC. The measurements of CO, NO, and CO_2 were accurate. The measurements of HC are biased low because the on-board instrument uses NDIR, the same technology typically used in RSDs, which is well-known to respond only partially to a typical hydrocarbon speciation profile of vehicle exhaust.[4]

During data collection, the OEM-2100™ was calibrated on a routine basis using a calibration gas composed of 4.03 percent CO, 12 percent CO_2, 1,190 ppm HC (as C_3H_8), and 2,026 ppm NO. The calibration process was repeated approximately every 3 months. The instrument is very stable and holds a calibration for a long time. For example, just prior to calibration, the instrument was used to measure the calibration gas, and the errors were typically on the order of plus or minus 5 percent or less, compared to a typical error of approximately plus or minus 2 percent immediately after calibration.

During on-road data collection, the instrument automatically "zeros" on a periodic basis in order to prevent drift. Zeroing is done by measuring ambient air. 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 20.9 volume percent and 0.03 volume percent, respectively.

Supplemental data were collected using other instruments. 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 field data file using a program written in Microsoft Visual Basic. Temperature and humidity were recorded at the beginning of each data collection run. Time stamps were recorded for each significant traffic event using a laptop computer, including stopping at a signalized intersection, passing through the center of a signalized intersection, and stopping or slowing significantly at a mid-block location due to a turning vehicle or incident. Vehicle specifications, driver identity, and weather conditions were also recorded using the laptop computer.

3.0 EXPERIMENTAL DESIGN

An on-board on-road study is an observational, as opposed to a controlled, study. The on- road operation of a vehicle is subject to uncontrollable variability in ambient and traffic conditions. The opportunities for desired ambient, traffic, and roadway characteristics are influenced by the scheduling and routing of the data collection activities. However, it is not possible to completely eliminate variability in ambient and traffic conditions. Therefore, it important to have a baseline characterization of the intra-vehicle variability in measurements for similar ambient and traffic conditions, in order to determine whether it is possible to estimate meaningful emission rates based upon on-board data.

The design of an on-road data collection effort involves selection of vehicles, drivers, routes, scheduling, and number of replications. The study design depends upon the study objectives. For example, possible objectives include: (1) evaluation of emissions benefits of a transportation improvement or installation of a transportation control measure (TCM), 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.

In this case, the main objective is to develop a baseline insight regarding the variability in emissions measurements from one run to another under similar conditions and regarding key factors that influence vehicle emissions. Therefore, the study design involves deployment of a small number of vehicles and drivers on a small number of routes and for selected times of day (i.e. weekday morning and afternoon peak travel periods). The study design features two primary drivers, both of who operated two primary vehicles on each of two corridors. The largest number of driver/vehicle/route data collection runs were made with primary drivers and vehicles in order to characterize intra-vehicle variability and to compare emissions of the same vehicle with two different drivers. Data collection was supplemented with secondary vehicles, which were driven by the primary drivers in some cases and by secondary drivers in other cases. The purpose of this portion of data collection was to evaluate the robustness of the data analysis methodology and emission factor results when applied to different vehicles and drivers. In addition, there was an opportunity during the study to collect data on a third corridor with two Flexible Fuel Vehicles (FFVs) that were fueled with E85, a blend of 85 percent ethanol and 15 percent gasoline. These data were collected in order to evaluate the robustness of the data analysis method applied to different fuels.

On-board data collection is very flexible in terms of site selection compared to other measurement methods such as remote sensing. The site selected for the primary example case study, Chapel Hill Road, is a heavily traveled corridor during morning and evening rush hours and is representative of rush-hour commuting between Cary, NC and Research Triangle Park, NC. Data were also collected on Walnut Street, in Cary, NC, and on NC 54 in RTP. All three corridors are primary arterials with heavy traffic flow during peak travel times. The road grades on these corridors are modest, typically ranging well within plus or minus five percent.

Instrument Deployment

The OEM-2100™ can be installed in approximately 15 minutes in a light duty vehicle. The equipment has a width of 53 cm, height of 41 cm and depth of 31 cm. It weighs approximately 30 kg. The instrument has three connections with the vehicle: (1) a power cable typically connected to the cigarette lighter or an independent battery; (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. A hose for obtaining reference air for zeroing purposes is routed outside, typically via the front passenger window.

The engine scanner can interface in two ways for most vehicles. The preferred interface is "vehicle-specific", in which the user enters vehicle specific information (e.g., manufacturer, VIN) and in which the engine scanner is able to sample OBD data with a frequency of less than once per second. For 1996 and more recent vehicles, an alternative "generic OBD II" interface can be used if for some reason the vehicle-specific interface fails. With the OBD-II interface, OBD data are sampled approximately only every three seconds. Thus, the vehicle-specific setup is preferred if possible.

The gas analyzer goes through a procedure to warm up and stabilize, which initially involves a relatively high frequency of zeroing and which typically takes approximately 45 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 or separate battery power while the vehicle is cold. The instrument has its own internal battery with enough capacity to maintain the instrument voltage during ignition if power is obtained from the vehicle's battery. Therefore, it is possible to maintain power to the equipment during a cold-start of the vehicle. However, because the focus of this study was on hot stabilized vehicle operation on primary arterials during peak travel periods, cold starts were not measured.

4.0 DATA PROCESSING

Figure 1 illustrates the key steps in data processing. Each run of data collected by the OEM-2100™ is summarized in a tab-delimited format in the "emissions" file, and then converted to spreadsheet format (Microsoft Excel™). 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. Both of these data files are downloaded to a PC in the laboratory. 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.

For quality assurance purposes, the combined data set for a vehicle run is screened to check for errors or possible problems. The most common encountered problems were:

Laptop Computer Errors: Possible problems include not synchronizing the laptop and OEM-2100™ clocks, the laptop battery running out before data collection is complete, or not pressing the timestamp keys at the proper place.

Engine Analyzer Errors: On occasion, communication between the vehicle's on-board computer and the engine scanner may be lost, such as because of a loose cable, leading to loss of data.

Gas Analyzer Errors: If an automatic 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 at a constant value during a run, most likely because of an error in the gas analyzer computer interface.

The data file for each run is checked for these 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. On average, 90 percent of attempted data collection runs resulted in a quality assured data file. Problems with the laptop computer, gas analyzer, and engine scanner, in decreasing importance, were the main factors regarding loss of data. The data collection protocol was modified over time to reduce the frequency of these types of errors. For example, ensuring that the laptop battery was fully charged, that cable connections were secure, that instrument readings were reasonable prior to each run, and that zeroing has taken place prior to a data collection run help reduce the frequency of data quality problems.

5.0 RESULTS FROM DATA COLLECTION AND ANALYSIS

Data collection and analysis focused on four main objectives: (1) characterizing the episodic nature of microscale events during a trip; (2) quantifying variability and uncertainty associated with a modal approach to analyzing emissions; (3) quantifying the relationship of CO emissions to engine operation (i.e. equivalence ratio); and (4) comparing emissions based upon two different drivers.

5.1 Time Traces and Emissions Episodes

An example of time traces of vehicle speed, emissions of CO, NO, HC, and CO_2, and fuel consumption is given in Figure 2. The travel time on the corridor was approximately 14 minutes. The instantaneous speed ranged from zero to approximately 45 mph, and the average speed was 10 mph. The longest waiting times occurred in the queue before Morrisville Parkway intersection. 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. 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. 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 20 mph. These data suggest that the CO emission rate during idling or crawling is low compared to the CO emission rate during acceleration.

The emission rate for NO remains below 0.2 mg/sec for approximately 85 percent 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 sensitive to the higher speed travel toward the end of the trip, with several large peaks in emission rate occurring during the last two 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 similar to each other. Because the emissions of CO and HC are low compared to the CO_2 emissions, over 99.8 percent of the carbon in the fuel is estimated to be emitted as CO_2. Therefore, CO_2 emissions 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 significant 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. The results for the example of Figure 2 are similar to the time traces of many other trips.

5.2 Modal Emissions Analysis Results

Analysis of emissions with respect to driving modes, also referred to as modal emissions, has been done in several recent studies.[11, 13, 24] In this work, the second-by-second emissions data were divided into these four modes of idle, acceleration, deceleration, and cruise, and the average emissions rates for each mode were calculated.

A priori modal definitions were developed for this study. The idle mode is defined as zero speed and zero acceleration. For acceleration mode, the vehicle speed must be greater than zero and the acceleration must at least 2 mph/s. However, in some cases, a vehicle may accelerate slowly. Therefore, an acceleration rate averaging at least one mph/sec for three seconds or more is also classified as 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.

A Visual Basic program was written that calculates the driving mode for each second of data, determines the average value of emissions for each of the driving modes, and calculates total emissions for the trip. In order to illustrate the types of results obtained from modal analysis of the emissions data, example results are developed based upon 141 one-way trips obtained using a 1999 Ford Taurus on Chapel Hill Road between August and October of 2000. The vehicle has a 3.0 liter engine and an automatic transmission, and was fueled with retail gasoline.

One of the key objectives of this work is to understand the variability in emissions from one trip to another. To illustrate the variability, an Empirical Cumulative Distribution Function (ECDF) of average acceleration mode CO emissions for each of the 141 one-way trips is shown in Figure 3. The individual trip acceleration mode emission rate for CO, on a mg/sec basis, varies over two orders-of-magnitude, from approximately 2 mg/sec to approximately 400 mg/sec, and the average is 44 mg/sec. Because the distribution of data is positively skewed, the mean occurs at the 75th percentile of the distribution for inter-trip variability. The 95 percent confidence interval of the mean is 33 mg/sec to 55 mg/sec.

As detailed elsewhere, Analysis of Variance (ANOVA), non-parametric regression, statistical multi-comparisons of means, and comparisons of ECDFs were used to help identify possible explanations for the inter-run variability in emission rates.[11] Factors such as time of day and direction of travel (which are surrogates for traffic flow), average speed, ambient temperature and relative humidity were found to be significant in at least some cases. No clear significant relationship between emissions and road grade was found, indicating that the road grades on the selected corridors were either not steep and/or long enough to be important.

A comparison of the average modal emission rate for each of four pollutants is shown in Figure 4 for the Ford Taurus deployed on Chapel Hill Road, along with estimates of the 95 percent confidence intervals of the mean emission rates. For each pollutant, based upon pairwise t-tests, the mean of each mode was found to be statistically significantly different from the mean of each of the other three modes at a

0.05 significance level. The mean emission rates are highest for acceleration and decrease in order from cruise to deceleration to idle.

Similar results were obtained for other vehicles tested during our study. Tables 1 presents the average modal NO, HC, CO, and CO_2 emission rates, and 95 percent confidence intervals of the averages, for 10 vehicles tested on three different sites: Chapel Hill Road; Walnut Street; and NC-54. These vehicles are: four different 1999 Ford Tauruses; two different 1996 Oldsmobile Cutlasses; 1998 Chevrolet Venture minivan; 1998 Toyota Camry; 1997 Dodge Caravan; and 1997 Jeep Cherokee. Two of the 1999 Ford Tauruses, driven on NC-54, were FFVs fueled with E85. All vehicles had automatic transmission except for the Camry, which had a 5-speed manual transmission.

The average emission rate for acceleration mode is the highest for all pollutants for all vehicles. The cruise mode has the second highest emission rate for all vehicles. In almost all of the cases, deceleration is the third highest emission rate, and idle emission rate is the lowest. The exceptions are that the Oldsmobile Cutlasses on both Walnut Street and Chapel Hill Road have higher NO emission rates for idle than for deceleration. Although the average CO idle emission rate for the Chevrolet Venture on Chapel Hill Road (Table 4) appears to be higher than that for deceleration, these two emission rates are not statistically significantly different. Similarly, although the average CO_2 idle emission rate appears to be higher than that for deceleration for the Toyota Camry on Walnut Street, these two emission rates are not significantly different from each other.

In order to test whether average modal rates are statistically significantly different from each other, pairwise t-tests were conducted. Out of 264 possible pairwise tests, (representing 11 vehicle-corridor combinations, 4 pollutants, and 6 pairwise comparisons per pollutant), 247 of them, or 94 percent, are statistically significantly different from each other. It should be noted that out of 17 insignificant cases, 15 were for data sets with less than or equal to 32 data points and 11 of them involved comparisons of deceleration and idle. Since the statistical significance test is sensitive to sample size, it is likely that with more data, there would be fewer cases of insignificant comparisons.

Because the average modal emission rates are significantly different from each other for each pollutant in the vast majority of cases considered, the *a priori* modal definitions assumed here are shown to be useful in representing some of the variability in emissions as a function of different types of driving activity. Typically, the average acceleration emission rates for CO and NO are typically more than a factor of 10 greater than the average idle emission rates. Similarly, the average acceleration emission rates for CO_2 and HC are typically a factor of five higher than the average idle emission rates.

Because acceleration and cruise emission modes typically contribute most of the total trip emissions, statistical comparisons between vehicles were based primarily upon statistical t-test comparisons of the averages of these two modes. The observed data indicate that the two gasoline Tauruses had similar CO and CO_2 emissions but the HC and NO emissions differed by approximately 30 percent. These differences could be a combination of inter-vehicle differences as well as differences in roadway and activity patterns on the two corridors. The same Caravan was deployed on both Walnut Street and Chapel Hill Road and had similar NO, HC, and CO emission rates, but appeared to have slightly better fuel economy, reflected by slightly lower CO_2 emissions, on Chapel Hill Road. The two E85-fueled Tauruses on NC 54 had similar emissions of all pollutants. The E85-fueled Tauruses had higher NO and lower HC emissions, but similar

CO and CO_2 emissions, compared to the two gasoline-fueled Tauruses; however, the E85 vehicles were operated on a different corridor than the gasoline fueled vehicles. The two Cutlasses, operated on two different corridors, had generally similar NO, HC, and CO_2 emissions; the CO emissions were similar except for the acceleration mode. It is likely that the difference is because of a small number of command enrichment events that may have occurred on one corridor but not the other. The two minivans in the sample, the Venture and Caravan, had different emission rates except for HC. The one SUV in the sample, the Jeep Cherokee, had emissions similar to the minivans. The SUV had higher NO and HC emissions, similar CO_2 emissions, and lower CO emissions, compared to the sedans. The latter may be because the SUV did not have as high of a frequency of command enrichment as the sedans. Overall, it is clear that there is inter-vehicle variability in emissions. However, the same or similar vehicle tested on different corridors typically had similar emission rates. Because of the intra-vehicle variability in emission rates from one run to another, it is important to use a statistical method for making the comparisons.

5.3 Equivalence Ratio Analysis Results

The preceding case studies have focused on analyses of emissions with respect to easily observable vehicle activity measures, such as speed and acceleration. OBD data can also be used to develop explanations for variation in emissions based upon engine data. For example, the equivalence ratio is considered an important parameter that can help explain variation in CO emissions.[5,25] As noted above, similar vehicles had different CO emission rates on different corridors, which may be attributable to differences in fuel-rich operation. The equivalence ratio is defined as the ratio of the actual fuel-to-air mass ratio in the engine divided by the stoichiometric fuel-to-air mass ratio. 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 performance is required, such as during hard acceleration, the engine will operate in a fuel-rich mode, referred to as "command enrichment," resulting in an equivalence ratio of greater than one.

A program was written in Visual Basic that calculates the equivalence ratio using the fuel and air data reported by the OEM-2100™. 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. These 72 trips were made during a two week time period in late August and early September of 2000. In Figure 5, grams of CO emitted per gram of fuel consumed are plotted versus equivalence ratio. A total of 30,108 data points were used for this plot, representing over eight hours of data. High CO emission rates occur only when the vehicle is in enrichment. When the vehicle is operating fuel lean or near stoichiometric, CO emissions tend to be comparatively lower. For example, the emission rates are less than 0.13 g CO/g fuel consumed when the equivalence ratio is one or lower, but are as high as 0.65 g CO/g fuel consumed at an equivalence ratio of 1.11. There are 12 data points with less than 0.05 g CO/g fuel although their equivalence ratios are estimated to be more than 1.05. The fuel consumption rate for these 12 data points was very low, and it is likely, therefore, that these data points do not represent true command enrichment but instead may represent transients as the vehicle was initiating or completing idling.

Although not shown here, analyses of on-board data were performed with respect to NO and HC emissions.[11] It was found that periods of highest NO and HC emissions were associated with high fuel flow rates, regardless of the equivalence ratio.

5.4 Comparison of Two Drivers

Differences in driving behavior are often hypothesized to produce differences in emissions.[15, 26, 27] In order to illustrate a method for comparing two different drivers, a dataset based upon 72 one-way trips obtained using the 1999 Ford Taurus on Chapel Road is used, including 31 trips made by Driver 1 and 41 trips made by Driver 2. ECDFs of average pollutant emission rates for each driver are shown in Figure 6 for NO, HC, and CO. The 95 percent confidence interval for the mean value of the distribution is also shown.

The mean emission rates for both drivers were found to be similar. Figure 6 indicates substantial overlap in the confidence intervals for the mean for each pollutant, which was confirmed by statistical t-tests. None of the means were significantly different at a 0.05 significance level. A Kolmogorov-Smirnov (K-S) test comparing the distributions for the two drivers also indicated that the distributions were not statistically significantly different at a 0.05 significance level; however, it should be noted that the application of the K-S test to compare two empirical distributions is an approximation. The range of variability in emissions from one run to another was similar for both drivers for all three pollutants. Although not shown, similar results were obtained for CO_2. Thus, in this particular comparison, the two drivers were found to be similar to each other. This result indicates that it is possible to find drivers who have similar driving behavior. These results indicate that it is reasonable to combine data collected from Drivers 1 and 2 into a single database, thereby increasing sample size.

6.0 CONCLUSIONS

This paper documents key aspects of the data collection, screening, and analysis protocols associated with deployment of a portable on-board tailpipe emissions measurement system. Experience gained during field work and data processing 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, leading to improved data collection protocols. A high proportion (over 90 percent) of measurement attempts resulted in valid vehicle activity and emissions files.

On-board emissions measurement can be used to support a variety of study objectives. A key objective of this work was to gain insight into the intra-vehicle variability in emissions obtained from repeated runs with the same combinations of drivers and routes. Knowledge of intra-vehicle variability is critical to understanding the precision with which average emissions can be estimated in the face of uncontrollable variability in traffic and ambient conditions that is characteristic of a real-world on-road study. It is also critically important to establish methods for processing and analyzing on-board data. The modal definitions that were evaluated in this study have proven to yield statistically significantly different emission rates for idle, acceleration, cruise, and deceleration. Furthermore, the relative trends among these modal emission rates are generally similar among the ten vehicles tested. The average emission rate on a mass per time basis for acceleration is typically a factor of five greater than the idle emission rate for HC and CO_2, and a factor of ten or more greater for NO and CO. The statistical and practical robustness of the modal emission rates confirms that the *a priori* modal definitions employed in this work are useful in characterizing at least a portion of the intra-vehicle variability in emissions.

The example time traces of speed, emissions, and fuel use demonstrate that real-world vehicle emissions and fuel use are episodic in nature. A key implication is that methods for reducing real-world on-road emissions should involve TCMs and transportation improvement plans (TIPs) that reduce the frequency and duration of episodic events, such as high accelerations, that lead to short periods of high emissions. This can be done, for example, through improved traffic signalization or through better roadway facility design.

The observation that the emission rate during idling is the lowest compared to the other modes illustrates the critical importance of obtaining representative (accurate) real-world data. Idling emission rates have often been extrapolated based upon the MOBILE emission factor models. As a result, it is likely that idling emissions have been over-estimated in the past, leading perhaps to too much emphasis on idling as a contributor to total estimated emissions.

The ability to evaluate and confirm key hypotheses regarding factors affecting emissions is a means to increase confidence in the results obtained with portable on-board measurement systems. For example, as illustrated here, the relationship between CO emissions and equivalence ratio can be evaluated.

Other study objectives will motivate different combinations of and numbers of vehicles, drivers, routes, and schedules than used in this study. In addition to the challenges already discussed regarding the observational nature of on-board measurements, on-board emissions measurements have some limitations, such as: (1) only tailpipe emissions are addressed; (2) NDIR does not measure total hydrocarbons; and (3) additional instrumentation is required to measure emissions from non-OBD vehicles, such as for pre-1990 vehicles. The first limitation suggests a continuing need for measurement of evaporative emissions with other means. Over time, it is likely that instrumentation will improve to more accurately measure HC emissions. Many vendors already have developed capabilities to measure particulate matter emissions, with particular focus on diesel vehicles. Sensor arrays for measuring or estimating exhaust flow for non-OBD vehicles are available, including non-road vehicles.

This study has been successful in establishing data collection, reduction, and analysis protocols, and in providing key insights regarding how to quantify intra-vehicle variability in emissions. This work demonstrates the feasibility of using on-board emissions measurements to develop useful insights regarding the episodic nature of vehicle emissions, on-road emissions hotspots, intra-vehicle variability in emissions, and inter-vehicle variability in emissions. On-board emissions measurement is recommended as an important method for collecting real-world, representative activity and emissions data in order to improve the accuracy and applicability of emissions estimation methods at the micro-scale as well as for higher levels of temporal and spatial aggregation.

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Table 1. Summary of Modal NO, HC, CO, and CO_2 Emission Rates Based upon On-Board Tailpipe Emission Measurements of Ten Vehicles

Vehicle:		Ford Taurus 1		Oldsmobile Cutlass 1		Dodge Caravan		Ford Taurus 2	
Location:		Walnut Street		Walnut Street		Walnut Street		Chapel Hill Rd.	
Drivers:		Primary		Primary		Secondary		Primary	
	Driving Mode	μ	95 % CI	μ	95 % CI	μ	95 % CI	μ	95 % CI
NO (mg/sec)	Idle	0.06	0.06 - 0.07	1.1	1.0 - 1.2	0.09	0.06 - 0.11	0.06	0.04 - 0.07
	Accel.	1.4	1.3 - 1.6	3.2	3.0 - 3.4	6.7	5.9 - 7.6	1.9	1.7 – 2.1
	Decel.	0.52	0.45 - 0.58	0.38	0.35 - 0.40	0.46	0.39 - 0.53	0.26	0.21 - 0.31
	Cruise	1.1	0.96 - 1.2	1.5	1.4 - 1.6	2.5	2.2 - 2.8	0.72	0.64 – 0.81
HC (mg/sec)	Idle	0.25	0.22 - 0.27	0.42	0.40 - 0.43	0.36	0.30 - 0.42	0.19	0.17 - 0.22
	Accel.	1.0	0.94 - 1.1	1.8	1.8 - 1.9	2	1.8 - 2.3	0.8	0.74 – 0.86
	Decel.	0.36	0.33 - 0.40	0.44	0.42 - 0.46	0.38	0.33 - 0.43	0.27	0.23 - 0.30
	Cruise	0.6	0.55 - 0.65	0.96	0.92 – 1.0	1	0.90 - 1.1	0.42	0.38 - 0.46
CO (mg/sec)	Idle	1.5	1.7 - 1.7	0.69	0.64 - 0.74	1.1	0.69 - 1.6	1.3	1.1 - 1.5
	Accel.	23	19 – 26	19	16 – 22	11	8.9 - 13	44	33 – 55
	Decel.	5.5	4.2 - 6.9	3.8	3.4 - 4.2	1.5	1.2 - 1.7	5.2	1.9 – 8.5
	Cruise	11	9.0 – 13	14	13 – 15	4.5	3.9 - 5.1	9.8	8.0 – 12
CO_2 (g/sec)	Idle	1.7	1.6 - 1.8	1.1	1.1- 1.2	1	0.99 - 1.0	1.8	1.6 - 2.0
	Accel.	6.4	6.2 - 6.6	5.4	5.3 - 5.5	6.5	6.2 - 6.7	6	5.7 - 6.3
	Decel.	2.6	2.4 - 2.8	1.2	1.1 - 1.2	1.3	1.2 - 1.3	2.7	2.4 – 3.0
	Cruise	4.1	3.8 - 4.4	2.8	2.7 - 2.8	3.4	3.3 - 3.5	3.9	3.6 - 4.2

Notes: μ is the average. The same Dodge Caravan was tested on both Walnut Street and Chapel Hill Road. Four different Ford Tauruses and two difference Oldsmobile Cutlasses were tested.

(Continued)

Table 1. Continued.

Vehicle:		Chevrolet Venture		Oldsmobile Cutlass 2		Toyota Camry		Dodge Caravan	
Location:		Chapel Hill Rd.		Chapel Hill Rd.		Chapel Hill Rd.		Chapel Hill Rd.	
Drivers:		Primary		Primary		Secondary		Secondary	
	Driving Mode	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI
NO (mg/sec)	Idle	0.06	0.04 - 0.07	1.6	1.2 - 2.1	0.07	0.04 - 0.10	0.07	0.03 - 0.12
	Accel.	1.9	1.7 – 2.1	3.0	2.5 - 3.5	3.8	2.7 – 4.9	4.6	3.0 – 6.3
	Decel.	0.26	0.21 - 0.31	0.77	0.61 - 0.92	0.66	0.41 - 0.91	0.5	0.35 - 0.65
	Cruise	0.72	0.64 – 0.81	1.8	1.5 – 2.0	2.8	2.1 – 3.4	2.9	2.0 – 3.7
HC (mg/sec)	Idle	0.19	0.17 - 0.22	0.5	0.46 - 0.54	0.48	0.44 - 0.53	0.49	0.42 - 0.55
	Accel.	0.8	0.74 – 0.86	2	1.8 – 2.3	2	1.7 – 2.2	2	1.7 – 2.3
	Decel.	0.27	0.23 - 0.30	0.61	0.50 - 0.72	0.63	0.50 - 0.76	0.81	0.56 – 1.1
	Cruise	0.42	0.38 - 0.46	1.2	1.1 - 1.4	1.2	1.0 - 1.4	1.3	1.0 - 1.6
CO (mg/sec)	Idle	1.3	1.1 - 1.5	0.66	0.43 - 0.90	1.5	0.98 - 2.1	0.79	0.36 - 1.2
	Accel.	44	33 – 55	34	16 – 51	31	14 – 48	10	6.1 – 15
	Decel.	5.2	1.9 – 8.5	4.6	2.9 – 6.2	6.4	4.9 – 7.8	2.2	1.3 – 3.1
	Cruise	9.8	8.0 – 12	14	8.3 – 19	12	9.4 – 14	4.8	3.7 – 6.0
CO_2 (g/sec)	Idle	1.8	1.6 - 2.0	1.3	1.2 – 1.3	1.2	1.2 – 1.3	1.2	1.1 – 1.2
	Accel.	6	5.7 - 6.3	6.1	5.5 - 6.7	6	5.4 - 6.7	5.8	5.0 - 6.6
	Decel.	2.7	2.4 – 3.0	1.4	1.4 – 1.5	1.4	1.3 – 1.5	1.3	1.2 – 1.3
	Cruise	3.9	3.6 - 4.2	3.3	3.0 – 3.6	3.2	2.8 – 3.6	2.9	2.6 – 3.2

(Continued)

Table 1. Continued.

Vehicle:		Jeep Cherokee		Ford Taurus 3 (E85 fuel)		Ford Taurus 4 (E85 fuel)	
Location:		Chapel Hill Rd.		NC 54		NC 54	
Drivers:		Primary		Primary		Primary	
	Driving Mode	μ	95% CI	μ	95% CI	μ	95% CI
NO (mg/sec)	Idle	0.07	0.04 - 0.09	0.18	0.12 - 0.24	0.05	0.03 - 0.07
	Accel.	3.9	2.9 – 4.9	2.7	2.4 – 3.2	2.2	1.9 – 2.6
	Decel.	0.63	0.40 - 0.86	0.68	0.52 - 0.86	0.25	0.19 - 0.32
	Cruise	2.8	2.2 – 3.5	1.4	1.1 – 1.7	1.1	0.91 – 1.2
HC (mg/sec)	Idle	0.49	0.45 - 0.53	0.16	0.12 - 0.20	0.11	0.08 - 0.14
	Accel.	2	1.8 – 2.3	0.75	0.63 – 0.90	0.77	0.61 – 0.95
	Decel.	0.62	0.50 - 0.73	0.21	0.16 - 0.26	0.15	0.11 - 0.19
	Cruise	1.2	1.0 - 1.4	0.37	0.31 – 0.45	0.34	0.28 – 0.41
CO (mg/sec)	Idle	1.5	1.0 – 2.0	0.87	0.69 – 1.1	0.45	0.23 – 0.68
	Accel.	13	9.3 – 16	33	13 – 55	40	25 – 55
	Decel.	4.0	2.7 – 5.3	2	1.3 – 2.8	2.3	1.7 – 3.0
	Cruise	7.1	4.0 – 10	7.4	5.1 – 10	12	9.8 – 15
CO_2 (g/sec)	Idle	1.3	1.2 – 1.3	1.6	1.3 – 1.9	1.5	1.3 – 1.7
	Accel.	6.2	5.6 - 6.8	6.5	6.1 - 7.1	6.4	6.3 – 6.8
	Decel.	1.4	1.3 – 1.5	2.6	2.1 – 3.2	1.9	1.7 – 2.2
	Cruise	3.3	2.9 – 3.6	4.1	3.6 – 4.8	3.6	3.4 – 3.9

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

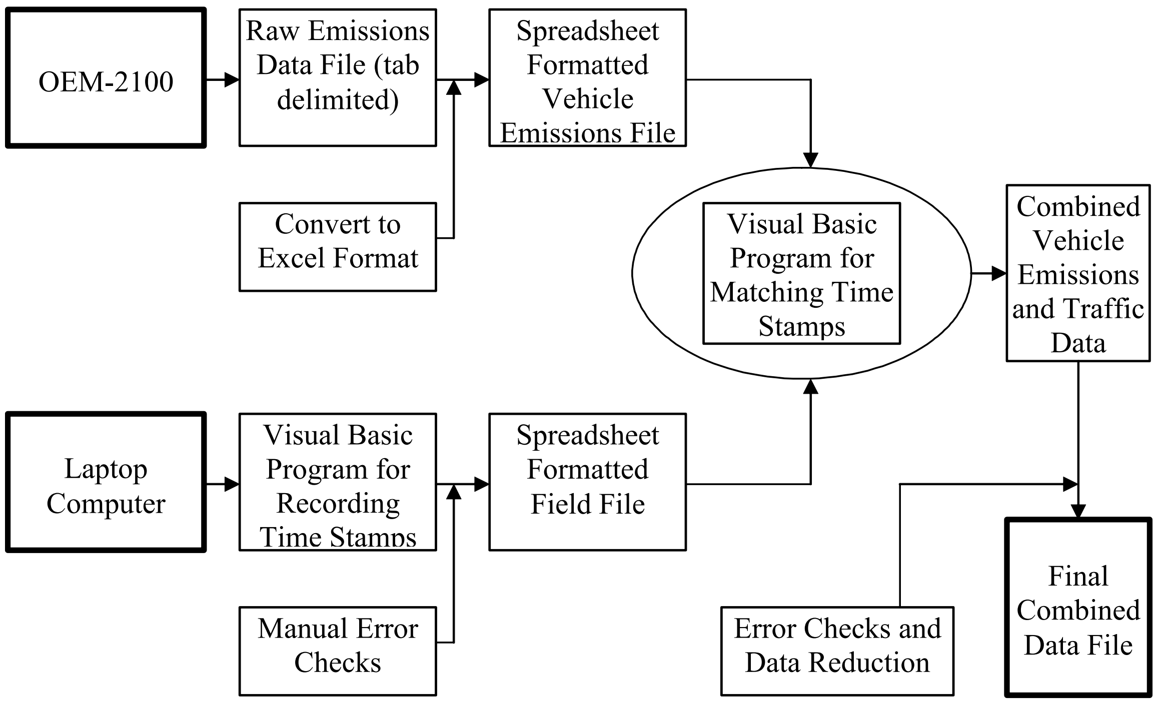


Figure 2. Time Traces of Vehicle Speed, Emissions, and Fuel Consumption for a 1999 Ford Taurus Driven on Chapel Hill Road on August 29, 2000.

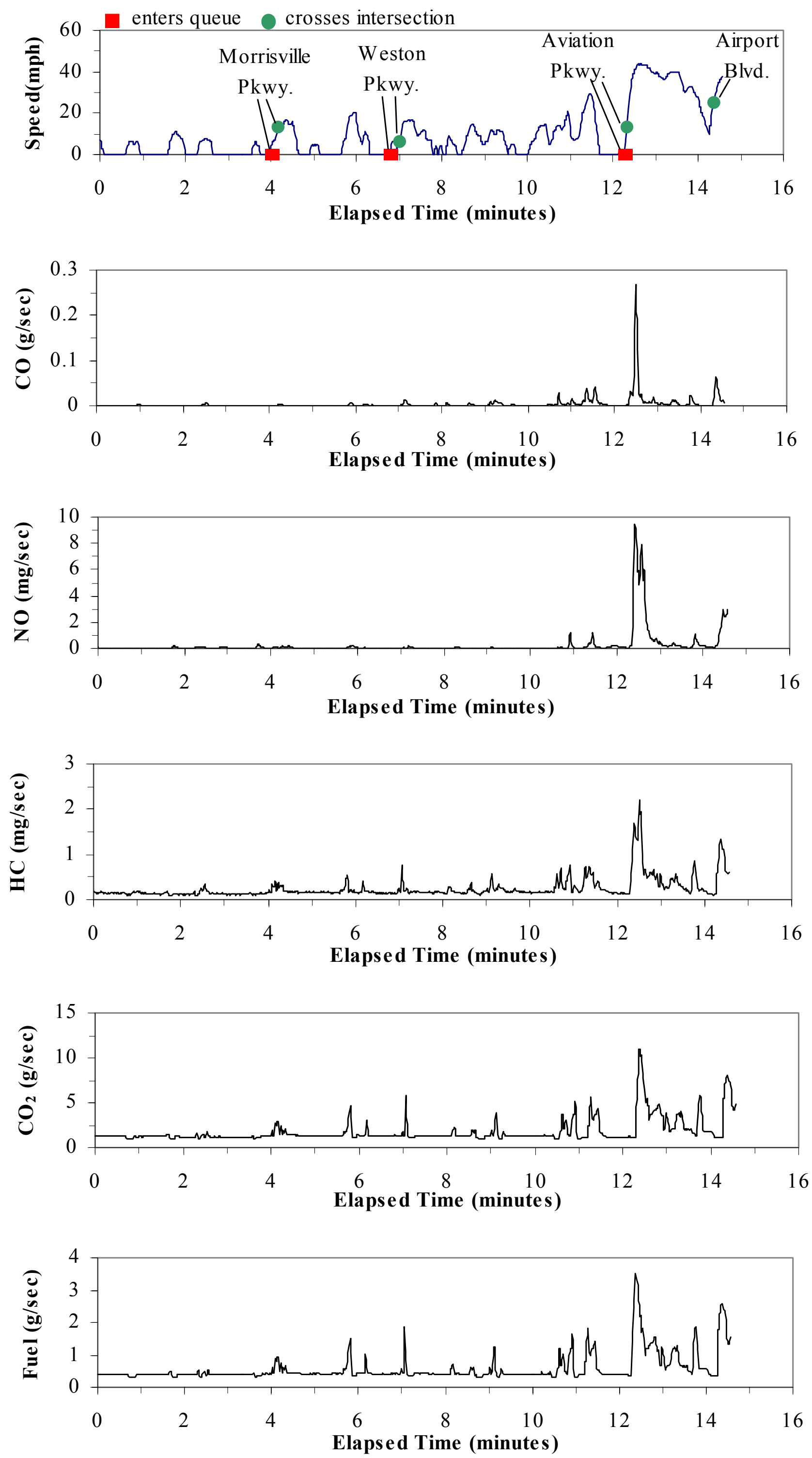


Figure 3. Cumulative Distribution of CO Emissions in Acceleration Mode for a 1999 Ford Taurus Operated on Chapel Hill Road, Based Upon 141 Trips

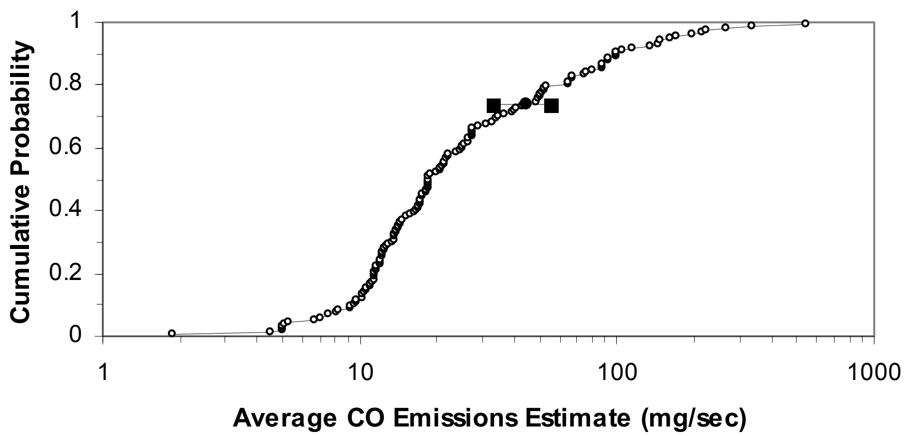


Figure 4. Average Modal Emissions for a 1999 Ford Taurus Operated on Chapel Hill Road Based Upon 141 Trips

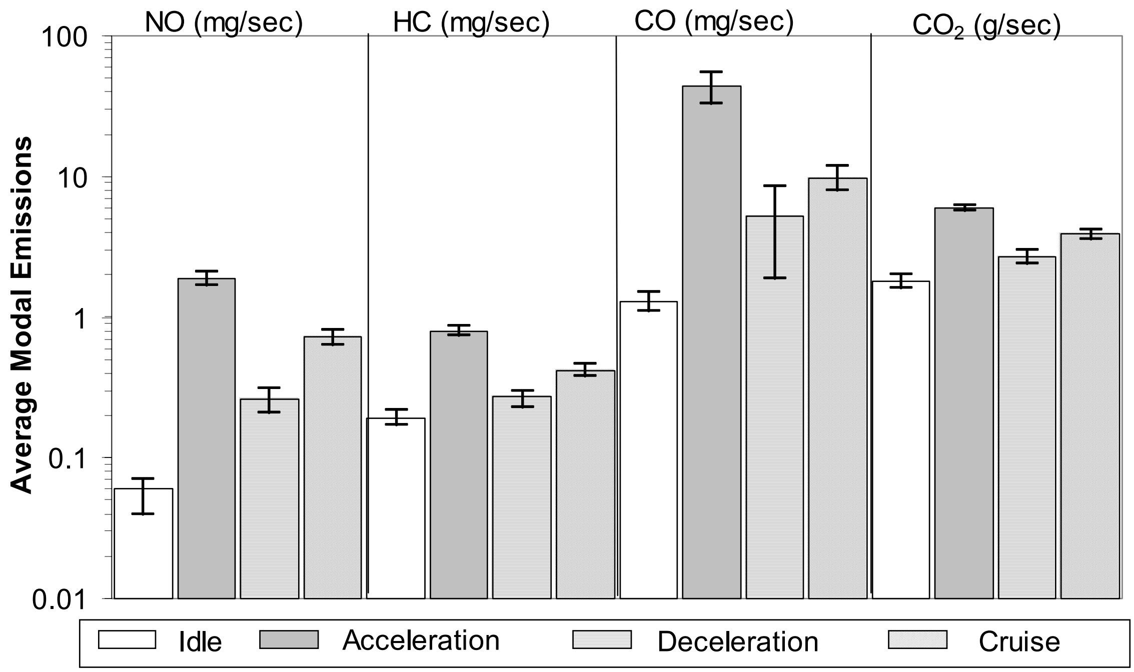


Figure 5. CO Emissions versus Equivalence Ratio for a 1999 Ford Taurus Operated on Chapel Hill Road

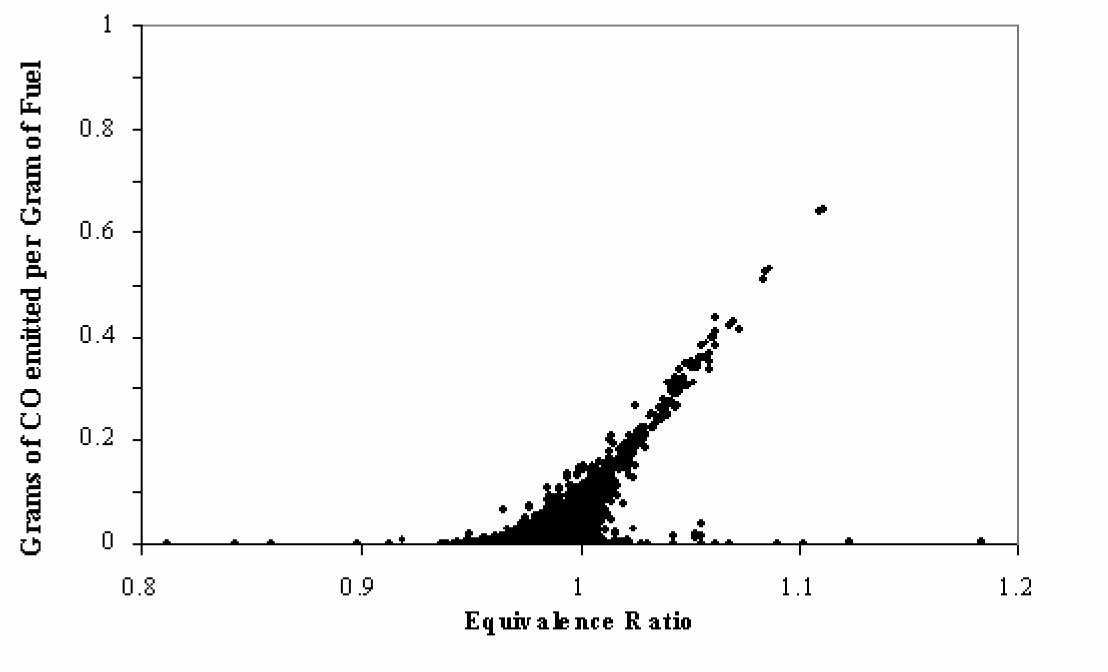
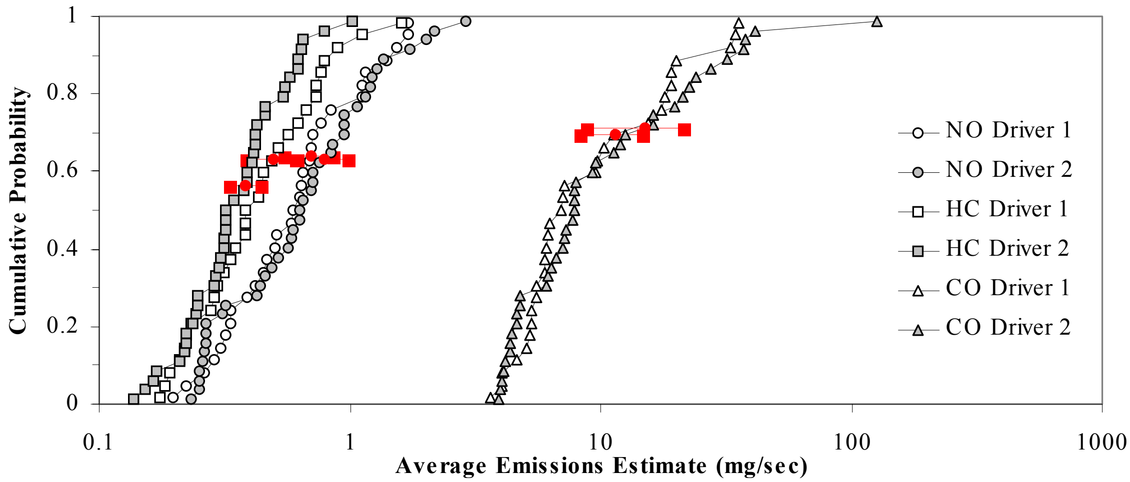


Figure 6. Cumulative Distributions for Average Pollutant Emissions Estimate for Two Different Drivers Operating 1999 Ford Taurus on Chapel Hill Road during August and September 2000 (n=31 for Driver 1 and n=41 for Driver 2)



PART IV
ANALYSIS OF EMISSION HOT SPOTS USING

ON-BOARD MEASUREMENTS

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ANALYSIS OF EMISSION HOT SPOTS USING ON-BOARD MEASUREMENTS

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ABSTRACT

The purpose of this study is to investigate high emissions hot spots along roadways based upon real-world, on-road vehicle emissions measurements. A portable instrument was used to measure on-road tailpipe emissions of carbon monoxide (CO), nitric oxide (NO), hydrocarbons (HC), and carbon dioxide (CO_2) on a second-by-second basis during actual driving. It was observed that the ratio of average emissions at hot spots to the average emissions observed during a trip was as high as 25 as in the case of CO emissions for one of the study corridors. This ratio was as high as five for NO and three for HC emissions. Some air toxics can be estimated as a percentage of HC emissions, therefore the spatial distribution of HC emissions is helpful to support exposure assessments. The relationships between hot spots and possible explanatory variables are investigated using graphical and statistical methods. The result of these analyses indicated that average speed, average acceleration, standard deviation of speed, percent of time spent in cruise mode, minimum speed, maximum acceleration, and maximum power have significant effects on vehicle emissions. Overall, it is found that stop-and-go traffic conditions which result in sudden changes in speed, and traffic patterns with high accelerations, generate hotspots.

1.0 INTRODUCTION

The purpose of this study is to investigate emission hotspots based upon real-world, on-road vehicle emissions measurements. Accurately identifying such hotspots can improve exposure assessment studies since vehicle emissions are known to be a major contributor to air pollution.[1] It should be noted that vehicle emissions estimates are typically obtained using the MOBILE emission factor model and are therefore subject to uncertainties inherent in this type of model.[2-3]

Transportation and air quality managers have the task of developing and evaluating Transportation Control Measurements (TCMs) and other types of Transportation Improvement Plans (TIPs). The benefits of many TCMs and TIPs accrue at the "micro" level, such as individual signalized intersections, traffic control devices, roadway facility improvements (e.g., ramps, roundabouts), improved incident response and management, and other strategies. It is important to be able to identify hotspots along routes in order to evaluate the air quality benefits of such projects.

Another example of the need for microscale emissions estimates is conformity analyses. Conformity is a determination that emissions from transportation plans, programs, and projects in a nonattainment area do not exceed mobile source emissions budgets established in the State Implementation Plans (SIP).[4] For example, CO nonattainment area must conduct project-level conformity analysis (“hotspot analysis”) for critical intersection and sites with violations or possible violations.[2] Highway emission factor models, such as Mobile6 or EMFAC7 series of models (based upon assumed standardized driving cycles measured over dynamometer tests) are typically but inappropriately utilized to estimate such emissions. Per the National Research Council (NRC) [2], Mobile-like models are not suited for conformity applications because they use a top-down procedure to estimate emissions. Thus, there is a need for appropriate microscale data (e.g., at the specific corridor or intersection level to properly support conformity analysis).

In this work, microscale emissions data were obtained based upon instrumentation of individual vehicles and measurement of on-road real-world tailpipe emissions. This approach offers the benefit of providing representative second-by-second vehicle activity and emissions data, which enables characterization of emissions at any time or location during a trip. With on-road data of high temporal and spatial resolution, it is then possible to evaluate the local effect of TCMs and TIPs, as well as to design and implement studies aimed at characterizing actual emissions. Furthermore, data such as these can be used to support development of new models that more properly account for mesoscale and microscale emissions. [5-8]

The main objectives of this paper are to: (1) describe the on-board emission measurement system used in this study; (2) summarize the experimental design for the on-road data collection and the data processing activities; (3) present the results of and exploratory analysis of the hotspot; and (4) investigate factors that contribute to hotspots.

2.0 REVIEW OF EMISSION MEASUREMENT METHODS

The use of instrumented vehicles is gaining in popularity with the development of an increasing number of portable on-board instruments. [5, 6, 9-14] The other two tailpipe emissions measurement methods most commonly used are dynamometer and remote sensing techniques. Dynamometer measurements involve replication of standard driving cycles in a laboratory setting, and as such may or may not be representative of actual on-road driving. [2, 15] Remote sensing enables collection of a snapshot of vehicle emissions at a specific location based upon a sample of typically one second or less of the plume of each passing vehicle. Thus, while remote sensing is a real-world technology, it is also a fair weather technology with significant siting limitations, such as difficulty in dealing with multiple lanes of traffic or slow moving vehicles. [2, 16, 17] Thus, neither dynamometer nor remote sensing measurements are ideally suited to identifying microscale hotspots in the real world. In contrast, with instrumented vehicles, it is possible to measure emissions at any location traveled by the vehicle under any ambient, traffic, and roadway conditions. [9-14]

3.0 METHOD FOR ON-BOARD MEASUREMENTS

The instrument used for on-board data collection was the OEM-2100™ manufactured by Clean Air Technologies International, Inc. The 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. The engine scanner collects from the On-Board Diagnostics (OBD) link of the vehicle engine and vehicle activity data. Eight OBD parameters are stored by the OEM-2100™. These include: 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 and reports emissions on a second-by-second basis.

The precision and accuracy of the OEM-2100™ was tested on a dynamometer 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.[18] OEM-2100™ has good precision, as reflected in R^2 values compared to the dynamometer of 0.90 to 0.99.

The OEM-2100™ is calibrated on a routine basis using a calibration gas. During data collection and operation of the instrument, the instrument automatically zeros on a periodic basis. Zeroing is a means of preventing drift in the measurements. Details regarding the operation of the instrumentation can be found elsewhere.[13]

Supplemental data were collected or recorded with other 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; information regarding each vehicle tested such as model year, make, model, VIN, engine size, odometer reading, and curb weight; and events recorded included the time at which the vehicle crossed the centerline of key intersections or entered queues.

4.0 EXPERIMENTAL DESIGN AND DATA PROCESSING

The main objective of this study is to investigate emission hotspots, therefore, study design involves deployment of a small number of vehicles and drivers on the selected corridors and collect as many runs as possible in order to have sufficient data.

The data for this study were collected in the summer and fall of 2000 on two arterials in Cary, North Carolina: Chapel Hill Road and Walnut Street. A total of 778 one-way runs representing 95 hours and 1,900 vehicle miles of travel were conducted involving three drivers and seven gasoline fueled light-duty vehicles. These vehicles were: two 1999 Ford Taurus sedans; two different 1996 Oldsmobile Cutlass sedans; 1998 Chevrolet Venture Minivan; 1997 Jeep Cherokee; and 1997 Dodge Caravan. Details on the experimental design can be found elsewhere.[13]

A substantial effort was devoted during the study to the development of data reduction and screening protocols in order to obtain an accurate database. Data collected from the OEM-2100^{TM}, from the laptop computer used in the field, and from other sources (e.g., measurement of road grade) were integrated into single combined vehicle emissions and traffic data file. The data were screened for errors that would impact the quality of the data. Errors that were encountered during data collection and methods for correction are explained elsewhere.[13-14]

5.0 EXPLORATORY ANALYSIS

The final combined database contains for second-by-second vehicle activity and emissions data. 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". A high emission event may be any event that produces high emissions. In contrast, a "hot spot" is a fixed location at which emissions tend to be consistently high because of the influence of roadway, traffic control, or other traffic flow characteristics at that location.

5.1 Single Run Analysis

To illustrate the type of data that were collected and the insights they provided, results for a single one-way vehicle trip on the Walnut Street site in a 1996 Oldsmobile Cutlass are presented. Figure 1 shows vehicle speed versus elapsed time of the trip and time at which various intersections were crossed on the Walnut Street site. The trip began south of Dillard Drive and ended a short distance north of Cary Towne Boulevard. The travel time on the corridor was approximately 8 minutes. The instantaneous speed ranged from zero to approximately 52 mph, and the average speed was 17 mph. The longest delays occurred at the intersection of Walnut and the Mall Access.

The CO emission trace (in grams per second) is shown in Figure 2. The CO emission rate exceeded 0.1 grams/second only six times during the trip, and emissions exceeded 0.2 grams per second only two times. The largest peak in the emission rate, 1.62 g/sec, occurred concurrently with the vehicle acceleration from zero to 50 mph downstream of Dillard Drive. In fact, most of the peaks in CO emission rates coincided with accelerations. Second highest CO emissions, 0.66 g/sec, occurred when the vehicle clears from Cary Towne Boulevard intersection. Although the average CO emissions for these two cases are 36 times higher than the average CO emissions in the rest of the trip (0.04 g/sec), they make up only seven percent of the trip time. These data suggest that CO emission rates are significantly higher for some events than others. Analysis of the speed trace in Figure 1, suggest that high emissions are caused due to high acceleration events. These data suggest that the CO emission rates during idling or crawling are comparatively low compared to CO emissions during acceleration.

Similarly the emission rate for NO in Figure 3 remains below 0.005 g/sec for approximately 90 percent of the trip. It increases by almost 10 times during acceleration through the Dillard Drive intersection. NO emissions appear to be sensitive to acceleration events at intersections.

The emission rate for HC in Figure 4 responds in a similar manner as CO. Peaks in HC emissions occur approximately at the same times as peaks in CO emissions. Similar to both CO and NO, the HC emission rates are highest during acceleration events.

The CO_2 emission trace in Figure 5 and the fuel consumption trace in Figure 6 are very similar to each other. Because CO and HC emissions are low compared to the CO_2 emissions, over 98 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 for all four measured pollutants 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 emission episodes that are significantly higher than those experienced in the rest of the trip. This implies that efforts to reduce on-road emissions should be aimed at understanding and mitigating these hotspots.

5.2 Multi-runs, Multi-Vehicle Analysis

This section focuses presents spatial distribution of emissions for the example vehicles. Vehicle position was estimated by integrating the speed trace and correcting for known positions, such as when the vehicle crossed specific intersections. [13]

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. The data within each bin were then utilized to estimate statistics such as the average, standard deviation, maximum and minimum for explanatory variables and emissions.

An example spatial analysis is presented based upon 24 runs with a 1999 Ford Taurus and 23 runs with a 1996 Oldsmobile Cutlass on Walnut Street during the weekday morning peak travel period. The average speed for both vehicles is shown in Figure 7, along with 95 percent confidence intervals for the averages. Similarly, the average emissions and 95 percent confidence intervals for the averages are shown for CO, NO, and HC in Figures 8, 9, and 10, respectively. Because the Cutlass typically has higher emissions than the Taurus, different vertical scales are used for each vehicle.

As seen in Figure 7, the average speed is consistently exceeds 35 mph between 0.7 and 1.6 miles, indicating close free-flow traffic conditions. There was a speed decrease from 30 mph to 15 mph at the 0.1-mile mark of the trip because of the first traffic signal (TS1). There are also significant drops in average speed at TS8 and TS9. Speed profiles are virtually identical for both the Ford Taurus and the Oldsmobile Cutlass.

Figure 7 and Figure 8 provide insight into the basic relationship between vehicle speed and emissions. The peaks in average CO emissions for both vehicles occurred for the most part when the vehicles accelerate. For example, in Figure 8, the largest peak in average CO emissions for the Taurus occurred at the 1.9-mile point which corresponds to an acceleration event, from approximately 9 mph to 32 mph. For Taurus average CO emissions are less than 1 g/sec, between 0.4 and 1.8 miles. However, for a very small part of the trip, at the 1.9-mile point, the average CO emissions were 3.4 g/sec, with a 95 percent confidence interval of 1.9 g/mi to 4.8 g/mi for Taurus. Average CO emissions at this point were more than seven times higher than the average CO emissions that occurred for the portions of the trip where free-flow conditions occurred. By definition the 1.9-mile point was a hotspot for this trip in terms of CO emissions for Ford Taurus. It should be noted that the confidence interval for the hotspot location does not overlap with the confidence interval of the average CO emissions for part of the trip where free-flow conditions occurs. This is an indication that the average CO emission at hotspot location is significantly higher than the average CO emissions at locations where free flow occurred at a significance level of 0.05. For the Oldsmobile Cutlass, qualitatively similar results were observed. The highest CO emission occurred at the 0.2 and 2.0 mile-points, the first having the higher emissions.

Figure 9 presents the average NO emissions profile for the same roadway section for both Ford Taurus and Oldsmobile Cutlass. For Taurus, the peak average NO emissions occurred at the 1.9-mile point for both vehicles, similar to the CO emissions pattern. Average NO emissions for this part of the trip were approximately four times higher than the part of the trip where free-flow conditions occurred (0.4 - 1.6 miles). Therefore, the 1.9-mile point was also a hotspot for NO emissions. For Oldsmobile Cutlass, the 0.1-mile point is also a hotspot. Similar to CO, average NO emissions at hotspot location is statistically significantly higher than average NO emissions where free flow conditions occurred.

Figure 10 presents the average HC emissions profile. Peak HC emissions occur at the 0.1, 1.8-mile, and 2.1-mile points of the trip for both vehicles, slightly different from the CO and NO emissions. Average HC emissions at these points were approximately three times higher than the part of the trip where there was a free-flow condition for traffic. These results indicate that the 0.1, 1.8, and 2.1-mile points were hotspots for HC emissions. Average HC emissions are not statistically different from each other at the two hotspot locations. However they are significantly higher than the average HC emissions where free flow conditions occurred.

Similar results were obtained with both the Ford Taurus and Oldsmobile Cutlass. Although the actual emission rates were different for the two vehicles, vehicles had their highest emission rates at approximately the same locations on the corridor.

6.0 FACTORS AFFECTING THE OCCURRENCE OF HOTSPOTS

In order to understand the factors affecting the occurrence of hotspots, statistical analysis was conducted to investigate potential explanatory variables. In the literature several factors that effect vehicle emissions are identified. Guensler [19] summarized these factors and divided them into four groups. These are: (i) vehicle parameters; (ii) vehicle operating conditions; (iii) vehicle operating environment; and (iv) fuel parameters.

Vehicle parameters are related to vehicle technology and include vehicle class, model year, vehicle mileage, fuel delivery system, emission control system, and on-board computer control system.[2, 16, 20, 21, 23] The starting mode of the vehicle (i.e, 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. [2, 15, 20, 22, 24, 25] Some of the fuel parameters include fuel type, oxygen content, fuel volatility, composition and hydrocarbon content.[2] Vehicle operating environment include such variables as humidity, ambient temperature, and road grade.[2, 9, 21]

Based upon data availability, a number of potential explanatory factors were investigated. Some parameters such as fuel type were not included in this study, since the same retail fuel was used during the measurements. In order to prevent possible confounding effects of vehicle make and model, data were analyzed separately for each vehicle.

Table 1 summarizes the explanatory variables used in this study. Each of these parameters is estimated for each 0.1 mile bin. As power surrogate, a method developed by Barth *et al.*[20] was used. Driving modes developed by Frey *et al.*[6] were utilized in this study in order to estimate the percent of time spent in different driving modes. Detailed information on these parameters is given elsewhere.[13]

Multivariate Statistical Analysis

Multiple regression analysis was utilized to identify those independent variables that have significant effects on hotspot identification. In multivariate statistics, correlations among the independent variables are not uncommon, and can cause multicollinearity in linear regression. When multicollinearity exists, it becomes difficult to accurately assess the significance of each of the explanatory variables.[26] One method to overcome multicollinearity is to standardize the independent variables by centering via mean and scaling via standard deviation. However, this may not be adequate if there is a high degree of multicollinearity. [26]

The use of Variance Inflation Factors (VIFs) or Condition Number (CN) are two approaches to identify multicollinearity. A simple rule of thumb is that any VIF which exceeds 30 is an indication of multicollinearity.[26] As an example the data collected for a 1999 Ford Taurus is presented in Figures 7 to 10. Regressing 25 standardized variables on HC gives VIFs in the range of hundreds, indicating that multicollinearity is a serious problem. Another indicator of multicollinearity is the Condition Number. A condition number greater than 100 implies severe multicollinearity.[26] For the example the condition number is 126, indicating a serious multicollinearity problem.

Principal Component Regression was used in order to overcome the problem of multicollinearity. In principal component regression, the first principal component analysis is conducted on the independent variables to get uncorrelated principal components. Then a regression fit to the dependent variable using the principal components. After obtaining the significant principal components for the regression, the coefficients and standard errors for the original variables are estimated using the coefficients and standard errors for the principal components.[26]

The first principal component is the weighted linear combination of variables that accounts for the largest amount of variance in the sample.[27] The second principal component is the weighted linear combination of the variables that are uncorrelated with the first principal component and accounts for the maximum amount of the remaining total variation in the data. Successive principal components progressively explain smaller portions of the total sample variance and are all uncorrelated with each other. This procedure produces a unique mathematical solution and transforms a set of correlated variables into a set of uncorrelated principal components. [26]

The number of principal components that adequately represent the variability in the full data set is assessed by examining the relative magnitude of the variances of the components. For the example dataset, 26.2 percent of the variability of the data is explained by the first principal component, and the second principal component explains 16.5 percent. Since the first ten principal components explain approximately 90 percent of the variability in the data, no further principal components were considered. After obtaining the principal components, the next step is to fit a regression to the principal components. Then the coefficients and the standard errors for the original variables are estimated using the significant principal components from the regression fit. This can be obtained by utilizing the fact that principal components are linear combinations of the original variables as suggested by Rawlings *et al.*[26]. Table 2 presents the coefficients and their standard errors, along with the estimated t-values for the original variables. It should be noted that the p-value for this fit is less than 0.0001 indicating that the model is statistically significant. The R^2 value for this fit is estimated at 0.48. In Table 2, it is observed from the t-values that out of 25 possible variables seven of them are significant at 0.05 level.

The coefficients of the significant variables indicate the response of HC emissions to each independent variable. For example, as average speed increases in a spatial bin by 1 mph, average HC emissions decrease by 0.04g/sec. Increases in average acceleration, maximum acceleration, maximum power, and standard deviation of speed result in increases in HC emissions. However, increases in minimum speed and percent of time spent in cruise mode decreases average HC emissions. These findings suggest that HC emissions tend to be low when speed is uniform, whereas under conditions where sudden changes in speeds occur, HC emissions tend to be higher. It should be noted that standard deviation of speed in a way represents the traffic “friction”. When the standard deviation of speed in a spatial bin is small, it represents conditions where there is smooth flow. On the other hand, stop-and-go traffic generates a higher standard deviation of speed. In Table 2, it is shown that as standard deviation of speed increases HC emissions tend to increase. Minimum speed is also another indication of traffic condition. Minimum speed decreases when cruising decreases in stop-and-go traffic.

It should be noted that average speed can only explain small percentage of the variability in HC emissions. In order to what percentage of the variability is explained by average speed only, linear regression fit to HC emissions using average speed as the only independent variable for the same data as in Table 2. It is found that average speed is statistically significant with a coefficient of -0.03 and R^2 is found to be 0.08. This indicates that average speed can only explain 8 percent of the variability in HC emissions in this dataset.

Variables such as road grade, temperature and humidity had no significant effect on HC emissions. One reason is that data were collected within a short period of time which kept the ambient conditions, such as temperature and humidity, nearly constant. 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.

The principal component regression technique was applied to other test vehicles: two 1999 Ford Tauruses; two 1996 Oldsmobile Cutlasses; a 1998 Chevrolet Venture; a 1997 Dodge Caravan; and a 1997 Jeep Cherokee. Table 3 summarizes the significant variables for these datasets for HC emissions. In Table 3, coefficients for significant variables are also listed along with the R^2 values for each of those regression equations.

In Table 3, seven variables were identified as significant for HC emissions. These were: average speed; average acceleration; standard deviation of speed; percent of time spent in cruise mode; minimum speed; maximum acceleration; and maximum power. HC emissions tend to increase as average acceleration, standard deviation of speed, maximum acceleration, and maximum power increases. HC emissions tend to decrease as average speed, percent of time spent in cruise mode, and minimum speed increases. The findings are similar to the results presented in Table 2, which indicate that emissions are lower when vehicle travels smoothly compared to stop-and-go traffic.

Similar results were obtained for other pollutants. For all pollutants average speed, average acceleration, standard deviation of speed, percent of time spent in cruise mode, minimum speed, maximum acceleration, and maximum power were found to be significant in almost all of the vehicles tested. The relation of these variables with emissions is also similar for all pollutants. Emissions tend to increase when average acceleration, standard deviation of speed, maximum acceleration, or maximum power increases, and tend to decrease when percent of time spent in cruise mode increases.

In summary emissions tend to decrease when traffic conditions are smoother compared to stop-and-go traffic. The significant parameters found in this study are responsible for hotspot occurrence.

7.0 DISCUSSION

The analysis conducted in this study clearly indicated that data collected using an on-board instrument for CO, NO, and HC emissions can reveal locations where hotspots occur. Although air toxics emissions were not measured in this study, it has been observed by other researchers that, emission rates of some air toxics can be estimated as a fraction of total hydrocarbon emissions. Therefore, with knowledge of the spatial distribution of tailpipe hydrocarbon emissions, it is possible to make an estimate of the spatial distribution of tailpipe air toxics emissions in some cases. Although there are uncertainties associated with this approach, the analysis suggests that approximately half of the variability in emissions of selected air toxics is explained by variability in the total hydrocarbon emission rate.[27] Therefore, the use of hydrocarbon hotspots data as surrogate for air toxics emissions hotspots may be useful. The measurement of on-road hotspots is important to the development of realistic and accurate spatially and temporally distributed emissions estimate for use in exposure and risk assessment.

8.0 CONCLUSIONS AND RECOMMENDATIONS

This paper has successfully demonstrated a method that can assist in determining hotspots along roadways for gasoline-fueled light duty vehicles. The method was applied to an example case study to illustrate the types of insights obtained from measured tailpipe emissions data.

The case study for spatial distribution of emissions demonstrated that emissions associated with a single signalized intersection contributed substantially to total emissions for a particular corridor. This work involved an empirical approach to measurement of microscale events was employed. No modeling was involved.

In the examples presented in this paper, it was observed that average emissions in hotspot locations were found to be as much as seven times higher than the average emissions at locations where free-flow traffic conditions occur for NO emissions for Oldsmobile Cutlass. For Ford Taurus this ratio is 14. For HC emissions average emissions in hotspot locations were found to be five times higher than the average emissions at locations with traffic-flow conditions for both vehicles. For CO, this ratio is as high as 25 for both vehicles. For the example case study, although the actual emission rates were different for the two vehicles tested, vehicles had their highest emission rates at approximately the same locations on the corridor. Furthermore, the hotspot locations for different pollutants are very similar.

Multivariate statistical methods were applied to investigate parameters that have significant effects on emissions. Principal component regressions techniques were utilized successfully to overcome the problem of multicollinearity. The result of these analyses indicated that variables related to vehicle operation variables such as average speed, average acceleration, standard deviation of speed, percent of time spent in cruise mode, minimum speed, maximum acceleration, and maximum power have significant effects on vehicle emissions. Interestingly these variables are also indicators of traffic flow conditions. Overall, it is found that stop-and-go traffic conditions which result in sudden changes in speed and high accelerations generate hotspots. The effect of some variables, such as road grade and ambient conditions (e.g., temperature and humidity) could not be tested since the data were limited. Future studies should more thoroughly explore these possible explanatory variables, as well as others, such as fuel type, ambient temperature, and catalyst temperature.

This paper provides empirical insight regarding factors contributing to hotspots on signalized primary arterial roadways. This information is important with respect to accurate spatial estimation of emissions to support exposure and risk assessments for small geographic scales. Although this study focused primarily upon the role of signalized intersections in creating hotspots, the study design can be adapted to collect real-world data for other hypothesized hotspots, such as at freeway acceleration ramps, merges after toll booths, and others. Moreover, although the data collected were only for CO, NO, and HC, other work suggests that HC emission may be a useful surrogate from which to estimate emissions of some air toxics. Therefore, the type of data collected in this study could be used to support emissions and exposure assessments for a variety of pollutants. The study addresses tailpipe emissions. Evaporation emissions are not measured by the on-board system. Therefore, supplemental data regarding evaporative emissions are needed.

The findings from the example case study are specific to the conditions of the case study, including the specific vehicles used and the conditions under which they operated. It is important not to extrapolate these findings without additional data and verification. Thus, the findings from the case study are suggestive of insights that are likely to be obtained from other work, but they are not definitive without data from additional vehicles, roadways, and drivers.

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9.0 REFERENCES

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Figure 1. Example of Speed versus Time Trace – Walnut Street

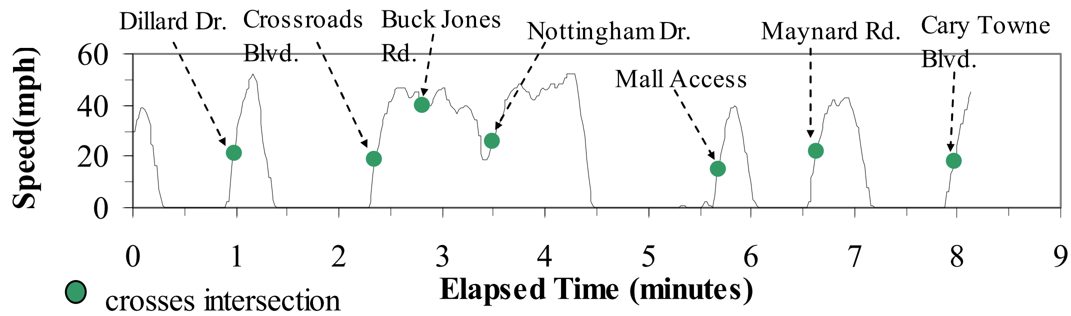

Figure 2. Example of CO Emissions versus Time Trace – Walnut Street

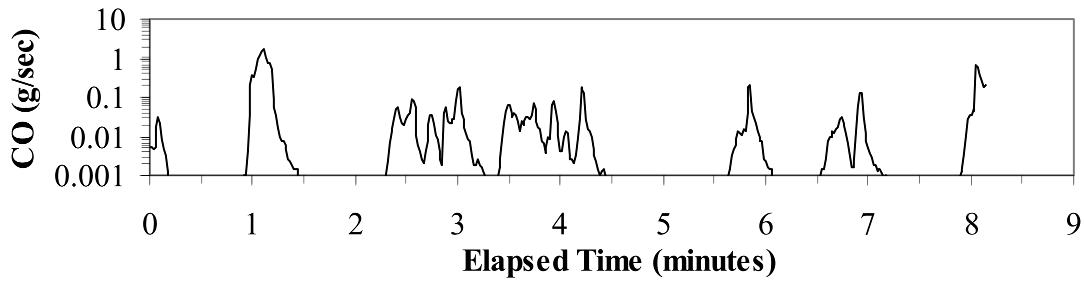

Figure 3. Example of NO Emissions versus Time Trace – Walnut Street

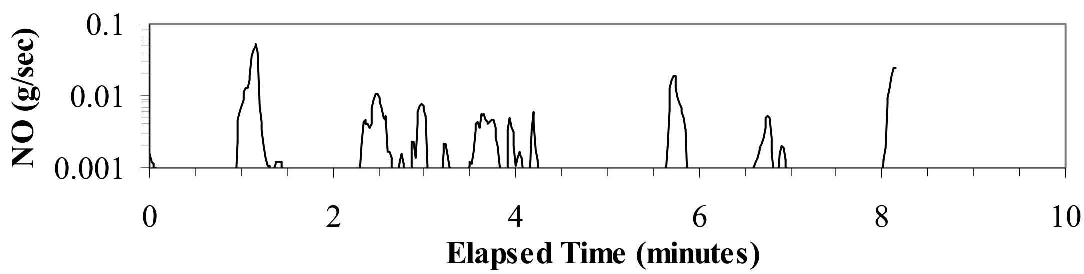

Figure 4. Example of HC Emissions versus Time Trace – Walnut Street

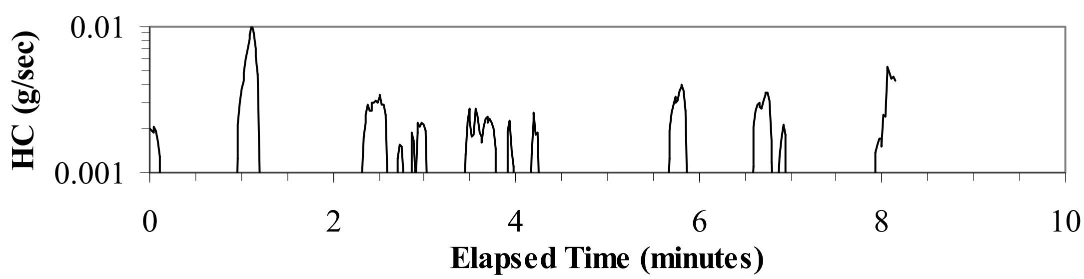

Figure 5. Example of CO_2 Emissions versus Time Trace – Walnut Street

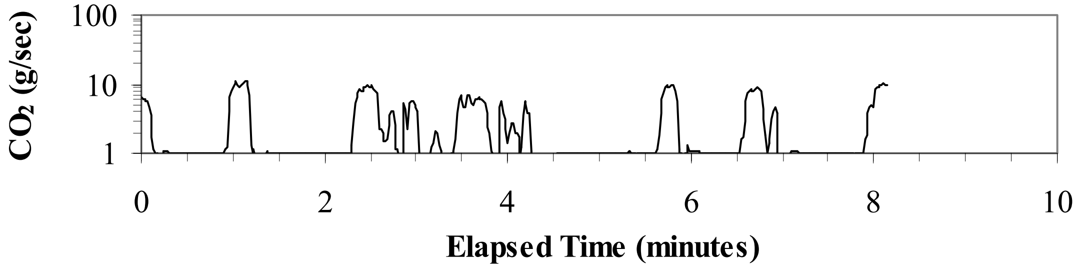

Figure 6. Example of Fuel Consumption versus Time Trace – Walnut Street

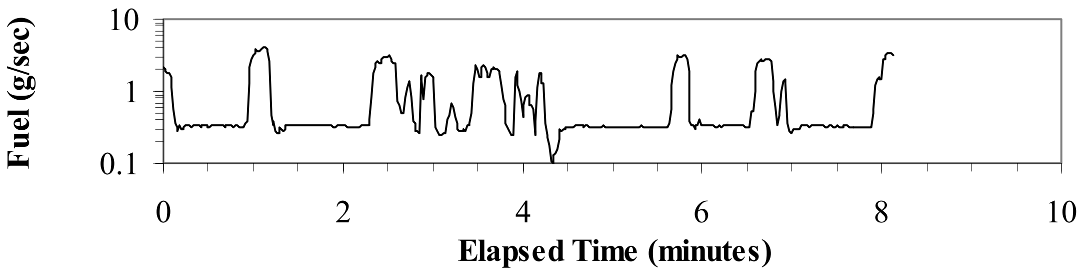

Figure 7. Spatial Distribution of Speed on the Walnut Street Corridor

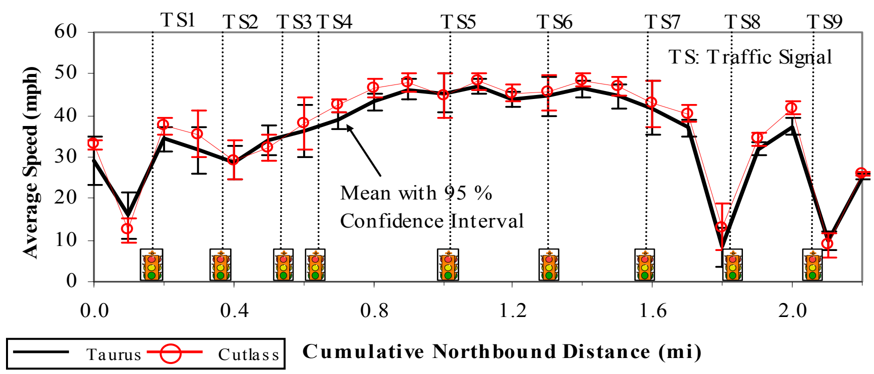

Figure 8. Spatial Distribution of CO Emissions on the Walnut Street Corridor

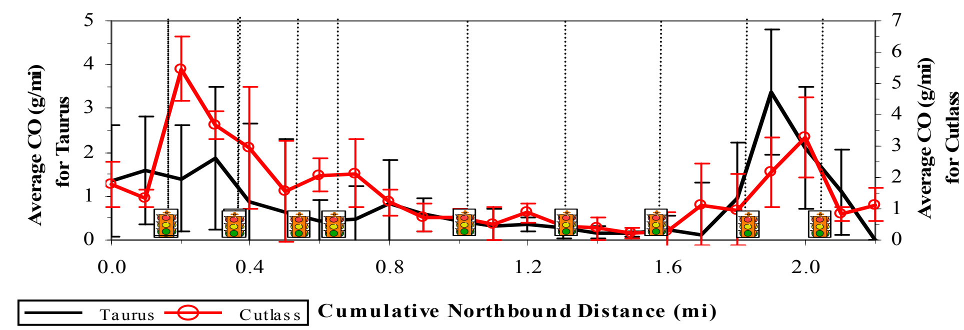

Figure 9. Spatial Distribution of NO Emissions on the Walnut Street Corridor

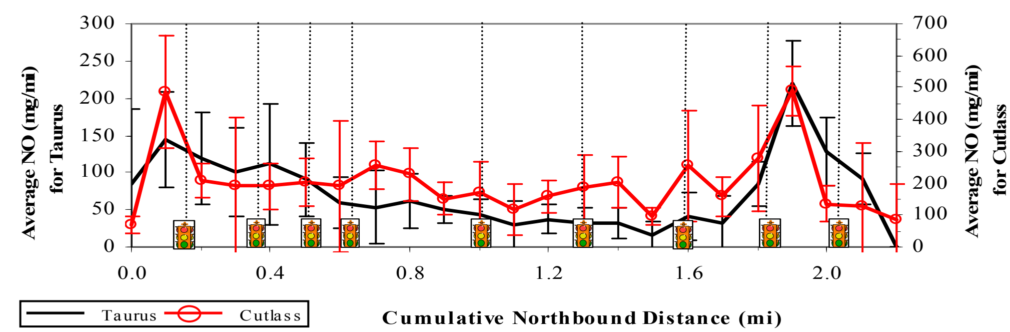

Figure 10. Spatial Distribution of HC Emissions on the Walnut Street Corridor

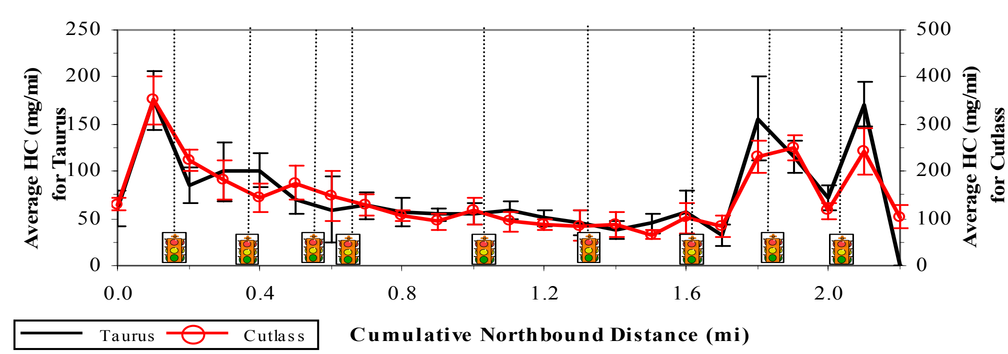

Table 1. Potential Explanatory Variables

Variable	Definition	Statistics	Unit
Congestion 1	1 if Northbound AM 0 otherwise	NA	NA
Congestion 2	1 if Northbound PM 0 otherwise	NA	NA
Congestion 3	1 if Southbound AM 0 otherwise	NA	NA
Driver	1 if Driver 0 otherwise	NA	NA
Coordination	1 if Before Coordination 0 if After Coordination	NA	NA
AC	1 if A/C is on 0 if A/C is off	NA	NA
Temperature	--	Mean	^{0}F
Humidity	--	Mean	%
Speed	--	Mean, Minimum, Maximum, Standard Deviation	mph
Acceleration	--	Mean, Minimum, Maximum, Standard Deviation	mph/sec
Power	$Speed \times Acceleration$	Mean, Minimum, Maximum, Standard Deviation	$mi^2/h^2.sec$
Grade	--	Mean	%
Time Spent in Idle Mode	Frey *et al.* 2001	NA	%
Time Spent in Acceleration Mode	Frey *et al.* 2001	NA	%
Time Spent in Deceleration Mode	Frey *et al.* 2001	NA	%
Time Spent in Cruise Mode	Frey *et al.* 2001	NA	%

Table 2. Regression Output for Average HC Emissions (gram/mi) and Explanatory Variables*

Parameter	**Coefficient**	**Standard Error**	**T-Value**
Congestion 1	-0.02	0.12	0.14
Congestion 2	0.04	0.16	0.23
Congestion 3	-0.01	0.11	0.11
Driver	-0.03	0.066	0.52
Coordination	-0.03	0.13	0.28
AC	-0.03	0.088	0.31
Temperature (^{0}F)	-0.02	0.078	0.30
Humidity (%)	-0.03	0.25	0.14
Average Speed (mph)	-0.04	0.019	**1.9**
Average Acceleration (mph/sec)	0.03	0.017	**1.8**
Average Power (mi^2/h^2.sec)	0.00	0.025	0.14
Std. Deviation of Speed (mph)	0.02	0.0093	**2.3**
Std. Deviation of Acceleration (mph/sec)	0.01	0.024	0.32
Std. Deviation of Power (mi^2/h^2.sec)	0.01	0.024	0.56
Average Grade (%)	-0.05	0.17	0.28
Time Spent in Idle Mode (%)	0.05	0.076	0.62
Time Spent in Acceleration Mode (%)	0.01	0.020	0.39
Time Spent in Deceleration Mode (%)	-0.03	0.070	0.48
Time Spent in Cruise Mode (%)	-0.01	0.0068	**1.8**
Maximum Speed (mph)	-0.02	0.059	0.33
Maximum Acceleration (mph/sec)	0.04	0.018	**2.4**
Maximum Power (mi^2/h^2.sec)	0.03	0.015	**2.0**
Minimum Speed (mph)	-0.03	0.0091	**3.1**
Minimum Acceleration (mph/sec)	-0.01	0.016	0.43
Minimum Power (mi^2/h^2.sec)	0.01	0.25	0.05

* All values are computed over a 0.1 mile length of road.

Table 3. Significant Variables and coefficient estimates for HC Emissions (gram/mi)

Significant Variable	1999 Ford Taurus[1]	1996 Oldsmobile Cutlass[1]	1999 Ford Taurus[2]	1998 Chevrolet Venture[2]	1996 Oldsmobile Cutlass[2]	1997 Jeep Cherokee[2]	1997 Dodge Caravan
Average Speed	-0.036	-0.036	-0.043	-0.047	-0.032	-0.048	
Average Accel.	0.029	0.040	0.035	0.044	0.033	0.039	
StdDev. Speed	0.022	0.022	0.019		0.017	0.013	
% in Cruise	-0.012	-0.014	-0.014	-0.011			-0.027
Min Speed	-0.028	-0.026	-0.037	-0.040	-0.027	-0.039	
Max Accel.	0.043	0.049	0.046	0.045	0.040	0.051	0.031
Max Power	0.031	0.038	0.026	0.020	0.027	0.035	
$\mathbf{R^2}$	0.41	0.67	0.48	0.41	0.40	0.57	0.27

1: Data Collected on Walnut Street.

2: Data collected on Chapel Hill Road.

PART V
COMPARISON OF VEHICLE EMISSION FACTOR UNITS BASED UPON REAL-WORLD MEASUREMENTS WITH PORTABLE INSTRUMENT

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Comparison of Vehicle Emission Factor Units based upon Real-World Measurements with Portable Instrument

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ABSTRACT

1.0 INTRODUCTION

Accurate emission inventories are needed to understand and control air pollution problems. 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). An accurate vehicle emission inventory is therefore essential for a correct understanding of air pollution.

At present vehicle emission inventory is estimated using driving cycle-based models which combine grams-per-mile emissions factors with activity data, expressed as vehicle miles traveled (VMT). The two highway vehicle emission factor models used for regulatory purposes in the U.S. are EMFAC2000 in California and Mobile6 elsewhere (2).

In a recent National Research Council (NRC) study (2) to review the Mobile model, it has been found that the model has serious limitations to answer the demands of a wide range of application in vehicle emissions field, which varies from national vehicle emissions and fuel standards to local travel demand and congestion mitigation measures. NRC study made several critical recommendations in order to improve vehicle emissions estimation (2). One of the key suggestions by the NRC study is to develop a new emissions estimation method which allow for prediction of emissions over a broad range of spatial and temporal scales (2). It is suggested by NRC that the improved model should include three different scales: macro-scale; meso-scale; and micro-scale. It is indicated by NRC that especially meso- and micro-scale modeling are in greater need of significant improvement. Emission estimation based upon vehicle operation modes are suggested in recent EPA studies for meso- and micro-scale modeling (4, 5).

With respect to modal modeling it is suggested by both NRC (2) and Singer and Harley (6) that using fuel-based emission factors where fuel consumption would be activity data, is less sensitive to the details of the vehicle's operation (i.e., speed and acceleration), and therefore this method is less susceptible to inaccuracies derived from the Mobile model's failure to represent realistic urban vehicle operation. It is also suggested by NRC (2) that fuel-based method is a promising one which might be used to reduce the uncertainties in emissions predictions.

There were some studies which involve use of remote sensing and tunnel measurements where fuel-based emissions were compared with travel-based emissions (7, 8). However, these studies were not complete since they did not possess the spatial and temporal resolution required to do an accurate comparison. As indicated by NRC (2), remote sensing only gives an instantaneous estimate of emissions and it reflects vehicles typically in a single mode of operation. 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 (9). As stated by NRC (2), RSDs does not provide an accurate measurement at low emissions levels as well. Tunnel studies suffer from similar problems. For example, as stated by NRC (2), tunnel data provide only a snapshot of vehicle emissions, and vehicle operation in tunnels tends to significantly deviate from average real-world conditions.

In this study, comparison of distance-based emission rates with fuel-based as well as with time-based emission rates will be given for dataset that were collected with on-board instrument under real-world conditions. Data collected with on-board instrument posses the spatial and temporal resolution required for the purposes of this study, since data are collected second-by-second under real-world conditions at any location traveled by the vehicle.

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 (10-15). Variability in vehicle emissions as a result of variation in vehicle operation, roadway characteristics, 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 (10-12, 16). In other studies, researchers have measured engine parameters only (17-19). 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, Real-time On-road Vehicle Emissions Reporter (ROVER), for both light and heavy duty vehicles (20). Recently, private companies such as Clean Air Technologies International Inc., Sensors Inc., Ford Motor Company, and Horiba have developed versions of on-board instruments that are commercially available (21-24).

The objectives of this study is to compare different emission factor units using vehicle emissions data collected using on-board instrument collected under real-world conditions. In particular, the main objectives of this paper are to: (1) describe the on-board emission measurement system used in this study; (2) present data that were collected using on-board emission measurement system; and (3) discuss comparison of emission factor units.

2.0 METHOD

2.1 Project Objectives

The results presented in this paper are part of a study conducted at North Carolina State University for a project, 99-8, sponsored by the North Carolina Department of Transportation 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 of 1999 and continued through December of 2001. In this study feasibility of using on-board emissions measurements to collect real-world on-road tailpipe emissions data for CO, NO, and HC was established. Measured emission rates (on a gram per second basis) were found to be highest during the acceleration driving mode. Another key finding is that measured emissions tend to increase with traffic congestion since there are more acceleration events. Signal improvements such as coordination and retiming were found to be associated with lower emissions on one of the data collection sites. The study also established a methodology for determining hotspots along roadways. Details of results found in this study can be found elsewhere (14, 15).

2.2 Instrumentation

The instrument used for on-board data collection was the OEM-2100™ manufactured by Clean Air Technologies International, Inc. The 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. The OEM provides a data stream of second-by-second engine and exhaust gas data. 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. The OEM has been compared by others with laboratory measurements and its precision and accuracy are good. Details regarding the instrument's precision and accuracy can be found elsewhere (14, 15).

Field data collection activities include the use of the OEM-2100™ as well as supplemental equipment. Road grade was measured with digital level 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. 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.

2.3 Experimental Design

The data used in this paper were collected on two arterials in Cary, North Carolina between the summer of 2000 and the winter of 2000. A total of 824 one-way runs representing 100 hours and 2,020 vehicle miles of travel were conducted involving four drivers and eight vehicles. These vehicles were: two different 1999 Ford Taurus sedan; two different 1996 Oldsmobile Cutlass; 1998 Chevrolet Venture Minivan; 1997 Jeep Cherokee; 1998 Toyota Camry; and 1997 Dodge Caravan. Two of the vehicles; 1998 Toyota Camry and 1997 Dodge Caravan were driven on both arterials. Details on experimental design can be found elsewhere (14).

3.0 EXPLORATORY ANALYSIS OF DATA

To illustrate the types of data available from on-board instrument and interpretation of results, an example case study is presented. One of the purposes of this section is to show variability in emissions as presented in different units. As an example, an individual one-way vehicle trip for a 1996 Oldsmobile Cutlass on October 20, 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 Crossroads Boulevard. The travel time on the corridor was approximately 8 minutes. The instantaneous speed ranged from zero to approximately 52 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 shown in grams/second. The CO emission rate exceeded 0.1 grams/second only six times during the trip, and emissions exceeded 0.2 grams per second only two times. The largest peak in the emission rate, 1.62 g/sec, occurred at the same time as the acceleration from zero to approximately 50 mph as the vehicle cleared the intersection with Dillard Drive. In fact, most of the peaks in CO emission rate tend to coincide with accelerations. Second highest CO emissions, 0.66 g/sec, occurred when the vehicle clears from Cary Towne Boulevard intersection. Although average CO emissions for these two cases are 36 times higher than average CO emissions that occurred for the rest of the trip, 0.04 g/sec, they make up only seven percent of the trip. These data suggest that time-based CO emission rates are significantly higher for some events than others. Analysis of speed trace in Figure 1, suggest that high emissions are caused due to high acceleration events.

Figure 3 shows CO emissions trace for distance-based unit. It should be noted that g/mi emission estimates for idling , where distance is zero , is set to zero for the sake of presentation. Trend for distance-based emissions is similar to time-based emissions. Highest CO emission, 124 g/mi, occurred as the vehicle cleared the intersection with Dillard Drive. Second highest emissions, 72 g/mi, occurred when the vehicle clears from Cary Towne Boulevard Intersection as in the case for time-based emissions. Average distance-based CO emissions for these two cases are 31 times higher than average CO emissions observed in the rest of the trip, which is 3.5 g/mi. This indicates that distance-based emission rates also sensitive to high acceleration events. However, there are slight differences between time-based and distance-based emission rates. For example, when the vehicle is decelerating at around 1.4th minute, time-based emission rate is small, less than 1 percent of the peak emission rate. However, at the same location distance-based emission rate is more pronounced, 6.7 g/mi, which is approximately 5 percent of the peak emission rate. This type of trend is observed when there is a deceleration event. This finding suggests that distance-based emission rates are more sensitive to deceleration events than time-based emission rates.

Figure 4 shows fuel-based CO emissions trace for the same trip. CO emission rate exceeded 200 grams/gallon only six times, during the trip. Emission exceeded 400 grams/gallon only two times. As in the case for time-based and distance-based emission traces, peaks for fuel-based emissions occurred when the vehicle clearing from intersections at Dillard Drive and Cary Towne Boulevard. Average fuel-based emission rate for these two events are more than 11 times higher than average fuel-based emission rate observed in the rest of the trip, which is 52 grams/gallon. This suggests that fuel-based emission rate is also sensitive to high acceleration events.

In general, the time traces indicate that there is a relatively large contribution to emissions from short-term events that occur within the trip for different emission factor units. Similar results are obtained for HC and NO emissions, although changes in emissions are less pronounced for fuel-based emissions. For CO_2, fuel-based emissions are almost constant throughout the trip, which is due to linear relationship between CO_2 emissions and fuel consumption.

3.1 Modal Analysis

The time traces suggest that emission rates differ during different types of driving. In particular, the largest emission rates appear to be associated with acceleration events. The analysis of emissions with respect to driving modes, also referred to as modal emissions, has been done in several recent studies (5, 12, 14, 25).

Researchers at NCSU divided emissions data into four modes: (1) acceleration; (2) cruise; (3) deceleration; and (4) idle. A priori assumptions were utilized to define these modes. Details of these definitions are explained elsewhere (14, 16).

In this study modal definitions developed by NCSU are utilized in order to investigate the sensitivity of different emission factor units to vehicle operation modes. As an example, we illustrate results for modal analysis of gram per second, gram per gallon, and gram per mile rates for CO, NO, HC, and CO_2 emissions as well as for fuel consumption rates for nine vehicles.

Table 1 presents the average emission and fuel consumption rates with Coefficient of Variation (CV) estimates data collected at two measurement sites in Cary, North Carolina. It should be noted that there is no idle emission rate for gram per mile emissions. Since fuel consumption rate for gram per gallon emission factor is a constant number, it is not reported in Table 1.

As observed in Table 1, acceleration emission rate for NO is significantly higher than for any other driving mode for gram per second and gram per mile emission factors. For gram per gallon emission factors, cruise mode has the highest rate for some vehicles. Acceleration emission rate is on the average more than 30 times higher than idle emission rate for gram per second emission factor. For gram per gallon NO emission rate for acceleration mode is ten times higher than idle mode for all vehicles tested. For gram per mile emission factor, deceleration mode has the lowest emissions for NO, which is six times lower than acceleration mode.

Cruise mode has the second highest emission rates after acceleration mode for gram per second and gram per mile. For gram per gallon acceleration mode has the second highest emissions. Deceleration mode has NO emissions lower than both acceleration and cruise modes. Idle has the lowest NO emission for gram per second and gram per gallon emission factor units. For visualization purposes, ratio of average NO emission rates in each mode with respect to idle, deceleration for gram per mile case, are also shown in Figure 5.

In order to test whether there is statistically significant differences between each modes pair-wise t-tests were conducted for the average emission rates for the modes. Table 2 summarizes the pairwise t-test results for all ten vehicles tested. Number of pair-wise t-tests which resulted in statistically significantly different emission rates among the modes are given in Table 2. For gram per second and gram per gallon there were 6 possible tests for each of the pollutants for each of the vehicle since there are four driving modes. For ten vehicles, totally there are 60 possible t-tests. For gram per mile there are three driving modes, in other words, three possible tests for each pollutant for each vehicle. For ten vehicles there are 30 possible pairwise t-tests. In Table 2 numbers in parenthesis give the percent of the data that is statistically significantly different in means. For example, for HC emissions, for gram per second emission factor, 55 out of 60 cases, or 92 percent, resulted in statistically significant different driving modes. It should be reminded that for gram per gallon fuel consumption rates were not estimated.

Overall, for gram per second more than 82 percent of the t-tests resulted in statistically significantly different modal rates. This number is more than 92 percent for NO, HC, and CO_2 emissions. For gram per mile, similar results are obtained, except for CO emissions where 73 percent of the t-tests resulted in statistically significantly different modes. For gram per gallon, statistically significant comparisons are less than 50 percent for HC and CO, whereas it is 88 percent for NO emissions. For CO_2 emissions 55 percent of the comparisons resulted in statistically significantly different average modal rates for gram per gallon emission factor unit. For fuel consumption rate, 97 percent of both gram per second and gram per mile data resulted in statistically significantly different modal rates.

3.2 Variability Analysis

In order to quantitatively determine the sensitivity of different emissions factor methods to different vehicle operation conditions, variability analysis is conducted. In this analysis total vehicle emissions were estimated using different emission factor methods. For this purpose four modal average rates were utilized. In order to estimate total emissions following equations were utilized for time-based, distance-based, and fuel-based methods respectively.

$$TE = \sum_{i=1}^{4} \left(\mathrm{ER}_i \times FT_i \right) \qquad (1)$$

$$TE = \sum_{i=1}^{4} \left(\mathrm{ER}_i \times DR_i \times FT_i \right) \qquad (2)$$

$$TE = \sum_{i=1}^{4} \left(\mathrm{ER}_i \times FR_i \times FT_i \right) \qquad (3)$$

Where,

TE = Total emissions (g)

ER_i = Emission rate for mode i (g/sec)

FT_i = Time spent in mode i (sec)

DR_i = Distance rate for mode i (mi/sec)

FR_i = Fuel rate in mode i (gallon/sec)

Using Equations 1 through 3, total pollutants emitted are estimated for different emissions factor estimation methods. It is also possible to estimate the variance of the total emissions estimate utilizing Taylor Series Expansion (26).

Data collected for five vehicles were utilized in this analysis in order to determine total emissions estimate and coefficient of variation (CV) estimates. Table 3 shows the total emissions estimate and CVs for three emission factor methods. Estimated total emissions are same for each emission factor method. However, CVs are different. For example, CVs for Ford Taurus for NO is 33 percent, 37.1 percent, and 36 percent for gram per second, gram per mile, and gram per gallon methods respectively. Overall, CV for gram per second is the smallest and gram per mile CV is the highest. CV for gram per gallon method is lower than gram per mile, however, generally, higher than CV for gram per second.

These numbers suggest that variability in total emissions estimate is slightly lower for gram per second estimate. Gram per gallon and gram per mile has more variability due to the fact that total emission estimation requires modal fuel rate and modal distance rate for these two methods. In gram per second method, on the other hand, there is no additional requirement for total emissions estimation.

4.0 DISCUSSIONS AND CONCLUSIONS

This paper focused on investigating the problem of sensitivity of different emission factor units to different vehicle operation modes. For this purpose, on-board measurement of on-road tailpipe emissions for gasoline-fueled light duty vehicles was successfully utilized.

The type of data provided by on-board emissions measurement cannot be replicated or accounted for in current generations of the highway vehicle emission factor model recommended for use by the U.S. Environmental Protection Agency. Both the Mobile5 and Mobile6 models are based upon average emissions for specified driving cycles. Therefore, these models cannot be used to estimate the effects of microscale events on emissions. Any traffic simulation models based upon output from the Mobile models will have the same inherent limitations of these models, which includes an inability to evaluate the effect of microscale events on emissions. In contrast, in this work, an empirical approach to evaluation of microscale events is employed. No modeling is involved. Other emissions measurement techniques, such as remote sensing and tunnel measurements, do not have the capability of getting data with such temporal and spatial resolution.

The example time traces of speed, emissions, and fuel use demonstrate that vehicle emission rates can be very low during a large portion of a trip, whether measured by time elapsed, distance traveled, or normalized with fuel consumption and that trip emissions can be dominated by a small number of short term events during the trip. It has been found for the example case study that, emission rates for the acceleration mode for gram per second, gram per mile, and gram per gallon emission factors are the highest. Average emission rates for cruising mode has been found to have the second highest emissions for all emission factor units. Deceleration and idling modes have the lowest emissions.

Based upon the insights obtained from time traces, modal analysis has been conducted. One of the important findings of the modal analysis is that gram per second and gram per mile modal emission rates are significantly different from each other for all pollutants. However, half of the gram per gallon modal emission rates are not different from each other for HC and CO2 emissions. For CO_2 this number is approximately 35 percent. On the other hand, approximately 90 percent of gram per gallon modal emission rates for NO are significantly different from each other.

Comparison among the modes indicate whether an average value of the modes can be utilized for prediction purposes or not. Under the conditions where there is no statistically significant difference among the means, using an average value would not cause uncertainty in the prediction. However, using an average value where there is statistical significant differences among the modes might cause an uncertainty in the model estimate. Under these conditions gram per gallon emission rates would behave better for HC, CO, and CO_2 emissions. For NO emissions gram per gallon emissions behave the same way other emissions factor methods. However, it should be noted that, when using gram per gallon modal rates, one would need fuel consumption rates disaggregated with respect to modes. It has been found in this study that fuel consumption rates are also sensitive to driving modes. Modal fuel consumption rates, both for gram per second and gram per mile, are statistically significantly different from each other 97 percent of the time. Therefore, in estimating total grams of pollutant emitted, there would be an extra uncertainty due to fuel consumption rate. For gram per second and gram per mile methods this is not the case.

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Figures and Tables

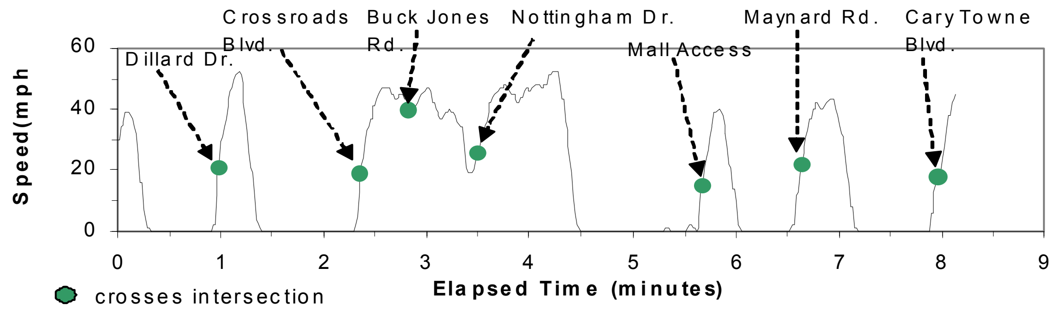


Figure 1. Vehicle speed versus elapsed time of the trip

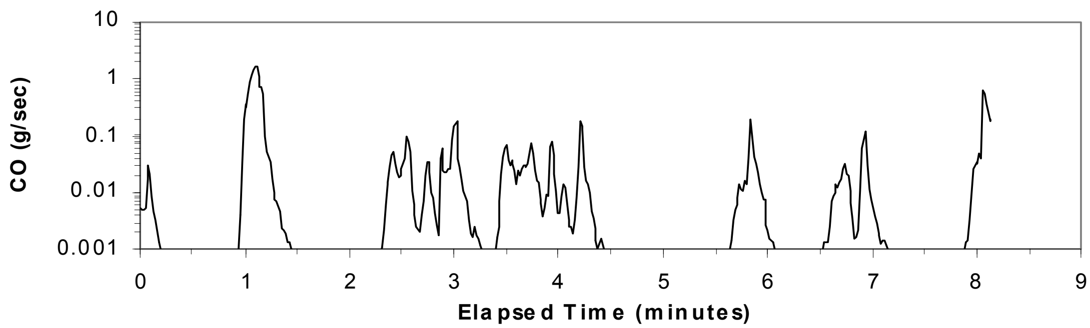


Figure 2. Vehicle CO emissions (g/sec) versus elapsed time of the trip

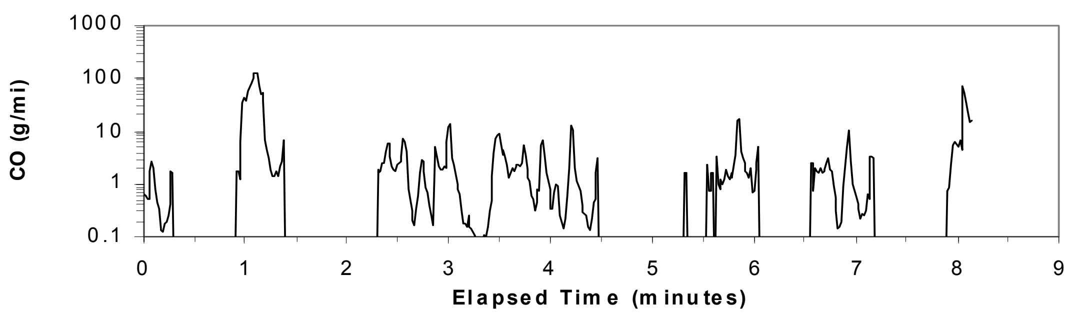


Figure 3. Vehicle CO emissions (g/mi) versus elapsed time of the trip

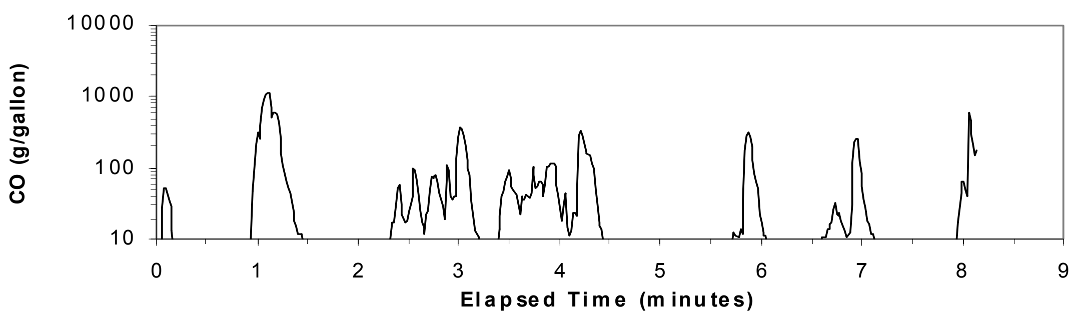


Figure 4. Vehicle CO emissions (g/gallon) versus elapsed time of the trip

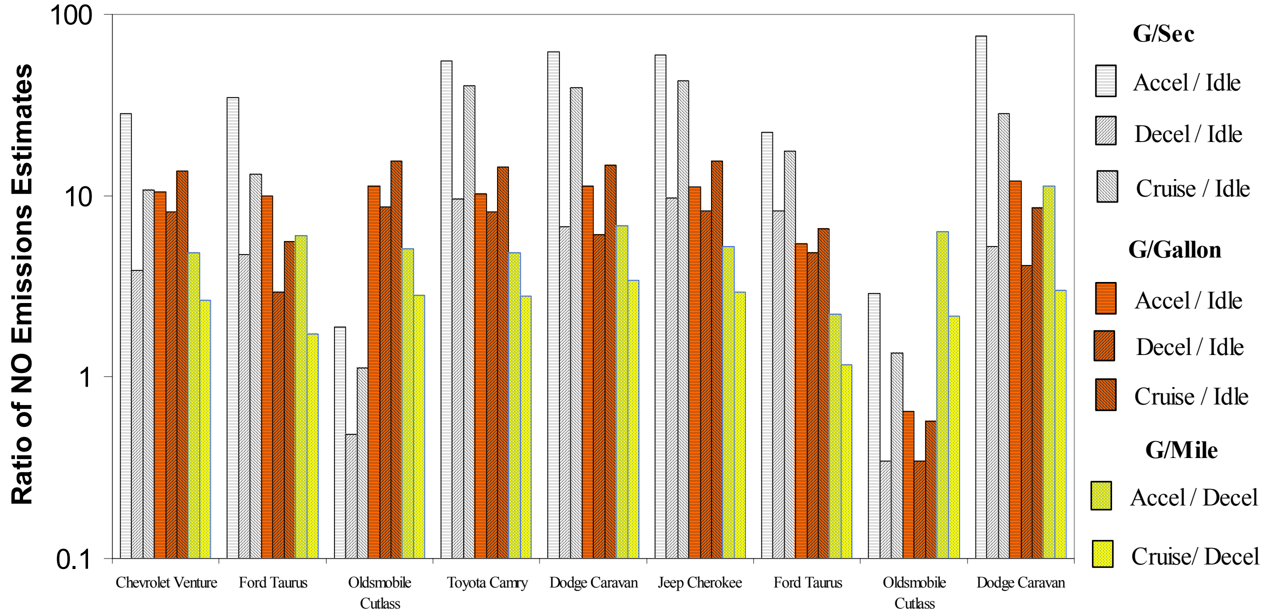


Figure 5. Ratio of Modal Rates for 1999 Ford Taurus Driven on Chapel Hill Road

Table 1. Summary of Modal Rates of Nine Vehicles

Vehicle:			Chevrolet Venture		Ford Taurus		Oldsmobile Cutlass		Toyota Camry		Dodge Caravan		Jeep Cherokee	
Location:			Chapel Hill Road											
Pollutant	**Emission**	**Driving**	μ	CV	μ	CV	μ	CV	μ	CV	μ	CV	μ	CV
NO	Mg/ Sec	Idle	0.067	1.2	0.055	1.1	1.6	0.89	0.069	0.88	0.074	1.0	0.065	0.90
		Accel	1.9	0.66	1.9	0.66	3.0	0.70	3.8	0.73	4.6	0.63	3.9	0.69
		Decel	0.26	0.99	0.26	1.2	0.77	0.96	0.66	0.99	0.50	0.53	0.63	0.99
		Cruise	0.72	0.61	0.72	0.70	1.8	0.64	2.8	0.65	2.9	0.53	2.8	0.62
	G/ Gallon	Idle	0.42	1.1	0.27	0.81	0.44	0.95	0.49	0.92	0.56	1.0	0.46	0.95
		Accel	4.4	0.49	2.7	0.48	5.0	0.57	5.0	0.60	6.3	0.48	5.1	0.56
		Decel	3.4	0.85	0.79	0.76	3.8	0.90	4.0	0.91	3.4	0.49	3.8	0.92
		Cruise	5.7	0.49	1.5	0.44	6.8	0.52	7.0	0.50	8.2	0.41	7.1	0.49
	G/ Mi	Accel	0.42	0.51	0.27	0.61	0.47	0.58	0.47	0.60	0.60	0.49	0.48	0.57
		Decel	0.087	0.65	0.045	1.0	0.092	0.62	0.097	0.62	0.088	0.47	0.092	0.64
		Cruise	0.23	0.44	0.078	0.65	0.26	0.43	0.27	0.41	0.30	0.30	0.27	0.41
HC	Mg/ Sec	Idle	0.19	0.38	0.19	0.64	0.50	0.20	0.48	0.21	0.49	0.22	0.49	0.21
		Accel	0.80	0.48	0.80	0.46	2.0	0.36	2.0	0.31	2.0	0.26	2.0	0.33
		Decel	0.27	0.62	0.27	0.80	0.61	0.51	0.63	0.54	0.81	0.54	0.62	0.52
		Cruise	0.42	0.45	0.42	0.58	1.2	0.36	1.2	0.36	1.3	0.37	1.2	0.36
	G/ Gallon	Idle	2.8	0.37	1.0	0.47	3.4	0.21	3.4	0.23	3.7	0.22	3.4	0.22
		Accel	2.5	0.35	1.2	0.37	2.9	0.19	2.9	0.17	3.0	0.15	2.9	0.19
		Decel	3.2	0.60	0.92	0.47	3.9	0.59	4.0	0.61	5.6	0.53	3.9	0.60
		Cruise	2.7	0.37	1.0	0.43	3.3	0.27	3.3	0.28	3.8	0.27	3.3	0.28
	G/ Mi	Accel	0.24	0.38	0.12	0.48	0.27	0.23	0.27	0.23	0.28	0.15	0.27	0.23
		Decel	0.093	0.55	0.051	0.83	0.11	0.48	0.11	0.49	0.14	0.34	0.11	0.50
		Cruise	0.11	0.35	0.050	0.65	0.13	0.23	0.13	0.23	0.14	0.18	0.13	0.24
CO	Mg/ Sec	Idle	1.3	1.9	1.3	0.99	0.66	1.3	1.5	1.3	0.79	1.3	1.5	1.3
		Accel	44	3.2	44	1.5	34	1.4	31	0.78	10	0.91	13	0.74
		Decel	5.2	0.92	5.2	3.8	4.6	1.2	6.4	1.2	2.2	1.0	4.0	1.2
		Cruise	9.8	0.70	9.8	1.1	14	0.42	12	0.46	4.8	0.49	7.1	0.45
	G/ Gallon	Idle	9.0	1.8	6.1	0.78	8.9	1.4	10	1.4	13	1.3	9.4	1.4
		Accel	15	2.6	57	1.2	7.1	0.62	7.3	0.66	8.8	0.76	7.2	0.64
		Decel	7.2	0.95	15	3.4	8.5	1.3	9.5	1.2	16	0.98	8.9	1.3
		Cruise	6.5	0.63	21	0.93	6.3	0.37	6.3	0.40	8.0	0.38	6.3	0.39
	G/ Mi	Accel	1.4	2.5	6.2	1.4	0.67	0.63	0.69	0.67	0.83	0.75	0.68	0.65
		Decel	0.21	1.0	0.89	2.8	0.24	1.1	0.26	1.1	0.39	0.99	0.24	1.2
		Cruise	0.27	0.57	1.1	0.98	0.26	0.28	0.25	0.27	0.28	0.22	0.25	0.27
CO_2	G/Sec	Idle	1.8	0.13	1.8	0.53	1.3	0.10	1.2	0.10	1.1	0.06	1.3	0.10
		Accel	6.0	0.27	6.0	0.33	6.1	0.28	6.0	0.27	5.8	0.24	6.2	0.27
		Decel	2.7	0.19	2.7	0.70	1.4	0.14	1.4	0.15	1.2	0.08	1.4	0.14
		Cruise	3.9	0.28	3.9	0.46	3.3	0.28	3.2	0.30	2.9	0.16	3.3	0.29
	G/Mi	Accel	840	0.15	880	0.32	820	0.12	820	0.13	820	0.08	820	0.13
		Decel	270	0.40	500	0.68	270	0.49	270	0.48	240	0.37	260	0.47
		Cruise	370	0.18	460	0.54	360	0.21	360	0.21	330	0.23	360	0.21
Fuel	G/Sec	Idle	0.45	0.13	0.58	0.53	0.41	0.10	0.40	0.10	0.37	0.06	0.41	0.10
		Accel	2.0	0.27	1.9	0.33	2.0	0.28	2.0	0.27	1.9	0.24	2.0	0.27
		Decel	0.50	0.19	0.88	0.70	0.46	0.14	0.45	0.15	0.40	0.08	0.46	0.14
		Cruise	1.1	0.28	1.2	0.46	1.1	0.28	1.0	0.30	0.9	0.16	1.05	0.29
	G/ Mi	Accel	270	0.15	280	0.32	260	0.12	260	0.13	260	0.08	260	0.13
		Decel	87	0.40	160	0.68	87	0.49	87	0.48	78	0.37	85	0.47
		Cruise	120	0.18	150	0.54	120	0.21	120	0.21	110	0.23	110	0.22

Notes: μ is the average and CV is the Coefficient of Variation. The same Dodge Caravan was tested on both Walnut Street and Chapel Hill Road. Two different Ford Tauruses and Oldsmobile Cutlasses were tested.

Table 1. Continued.

Vehicle:			Ford Taurus		Oldsmobile Cutlass		Dodge Caravan	
Location:			Walnut Street					
Pollutant	Emission	Driving	μ	CV	μ	CV	μ	CV
NO	Mg/ Sec	Idle	0.063	0.77	1.1	0.68	0.088	0.54
		Accel	1.4	0.59	3.2	0.39	6.7	0.27
		Decel	0.52	0.90	0.38	0.44	0.46	0.33
		Cruise	1.1	0.77	1.5	0.49	2.5	0.23
	G/ Gallon	Idle	0.35	0.78	8.1	0.61	0.75	0.51
		Accel	1.9	0.50	5.2	0.39	9.0	0.21
		Decel	1.7	0.60	2.8	0.41	3.1	0.28
		Cruise	2.3	0.57	4.6	0.44	6.4	0.25
	G/ Mi	Accel	0.19	0.55	0.41	0.42	0.82	0.21
		Decel	0.086	0.89	0.065	0.46	0.073	0.27
		Cruise	0.10	0.75	0.14	0.44	0.22	0.23
HC	Mg/ Sec	Idle	0.25	0.69	0.42	0.26	0.36	0.33
		Accel	1.0	0.41	1.8	0.28	2.03	0.29
		Decel	0.36	0.68	0.44	0.27	0.38	0.29
		Cruise	0.60	0.57	0.96	0.28	1.0	0.26
	G/ Gallon	Idle	1.3	0.37	3.2	0.26	3.1	0.34
		Accel	1.4	0.34	2.9	0.26	2.7	0.27
		Decel	1.2	0.36	3.3	0.27	2.6	0.30
		Cruise	1.3	0.35	3.0	0.25	2.6	0.27
	G/ Mi	Accel	0.13	0.42	0.24	0.28	0.25	0.28
		Decel	0.061	0.70	0.077	0.33	0.061	0.33
		Cruise	0.057	0.58	0.090	0.28	0.091	0.26
CO	Mg/ Sec	Idle	1.5	0.91	0.69	0.50	1.1	0.78
		Accel	23	1.0	19	1.2	11	0.41
		Decel	5.5	1.6	3.8	0.72	1.5	0.40
		Cruise	11	1.3	14	0.52	4.5	0.29
	G/ Gallon	Idle	7.8	0.80	5.3	0.56	9.8	0.79
		Accel	30	0.96	29	0.94	15	0.33
		Decel	19	1.6	28	0.70	10	0.44
		Cruise	24	1.1	43	0.53	11	0.27
	G/ Mi	Accel	3.0	0.98	2.4	1.0	1.3	0.38
		Decel	0.90	1.6	0.64	0.72	0.24	0.46
		Cruise	1.0	1.3	1.3	0.52	0.40	0.31
CO_2	G/Sec	Idle	1.7	0.54	1.1	0.11	1.0	0.04
		Accel	6.4	0.25	5.4	0.12	6.5	0.10
		Decel	2.6	0.58	1.2	0.12	1.3	0.09
		Cruise	4.1	0.48	2.8	0.17	3.4	0.07
	G/Mi	Accel	840	0.24	690	0.09	790	0.10
		Decel	430	0.59	200	0.21	200	0.13
		Cruise	380	0.45	260	0.12	300	0.09
Fuel	G/Sec	Idle	0.54	0.54	0.37	0.11	0.33	0.04
		Accel	2.1	0.26	1.8	0.12	2.1	0.10
		Decel	0.84	0.58	0.38	0.12	0.41	0.09
		Cruise	1.3	0.48	0.89	0.17	1.10	0.07
	G/ Mi	Accel	270	0.24	220	0.09	250	0.10
		Decel	140	0.59	64	0.21	67	0.12
		Cruise	120	0.45	83	0.12	98	0.09

Table 2. Summary of Pair-wise T-Tests Resulted in Statistically Significant Modal Average Rates for 10 Vehicles Tested

Unit	NO	HC	CO	CO2	Fuel
g/sec	56 (93)*	55 (92)	49 (82)	58 (97)	58 (97)
g/gallon	53 (88)	27 (45)	21 (35)	33 (55)	N/A
g/mi	29 (97)	24 (80)	22 (73)	29 (97)	29 (97)

*Values in parenthesis show the percentage of the total data which have statistically significantly different average modal rates.

Table 3. Summary of Variability Analysis for 5 Vehicles Tested

Pollutant	Emission Factor Method	Vehicle:	Ford Taurus	Oldsmobile Cutlass	Ford Taurus	Oldsmobile Cutlass	Chevrolet Venture
		Location:	Walnut Street		Chapel Hill Road		
NO		*TE (mg)*	0.273	0.565	0.270	0.705	0.641
	G/Sec	*Coefficient of Variation*	46.5	32.2	41.7	40.7	40.4
	G/mi		48.6	33.0	49.9	42.9	41.4
	G/Gallon		47.2	32.4	44.4	42.2	40.2
HC		*TE (mg)*	0.189	0.334	0.152	0.403	0.361
	G/Sec	*Coefficient of Variation*	33.0	22.9	34.0	26.2	31.4
	G/mi		37.1	24.0	40.3	28.1	32.9
	G/Gallon		36.0	23.4	36.5	26.4	31.7
CO		*TE (g)*	3.50	3.58	5.40	1.96	1.52
	G/Sec	*Coefficient of Variation*	74.1	50.4	102.8	44.4	170.7
	G/mi		74.4	53.9	103.7	43.7	161.3
	G/Gallon		74.2	51.8	103.1	43.2	171.7
CO_2		*TE (g)*	1260	960	1310	1120	1180
	G/Sec	*Coefficient of Variation*	27.4	17.8	28.4	22.6	22.4
	G/mi		30.8	18.6	34.5	26.8	27.0
	G/Gallon		30.3	17.9	28.4	21.0	22.5

Supplemental Figures

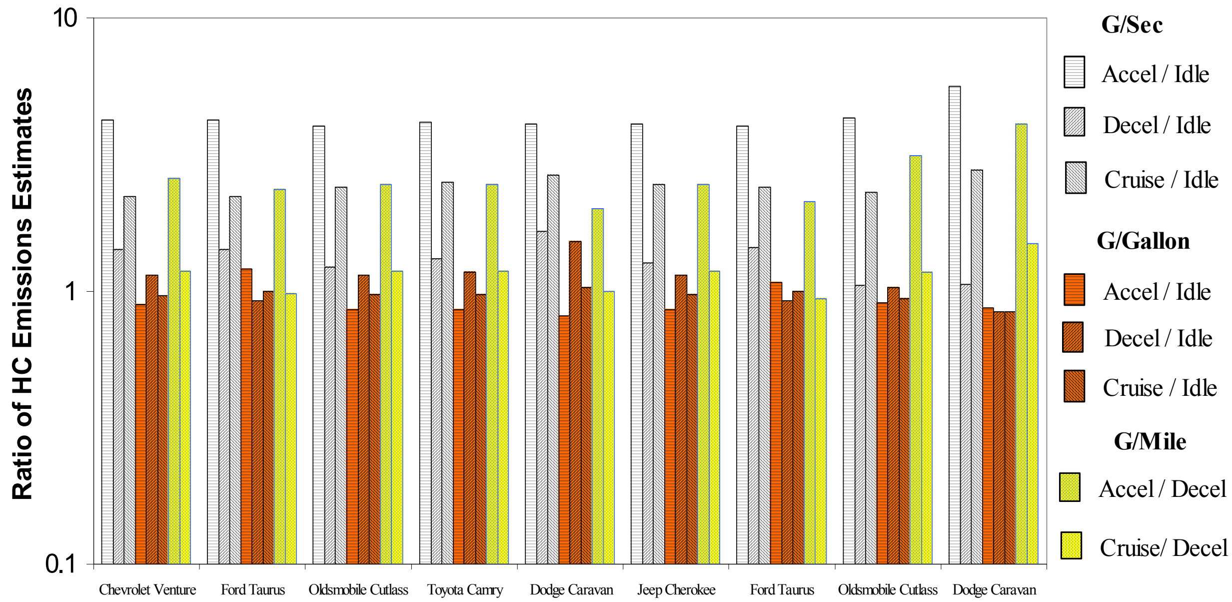


Figure S1. Average HC Modal Emissions for 1999 Ford Taurus

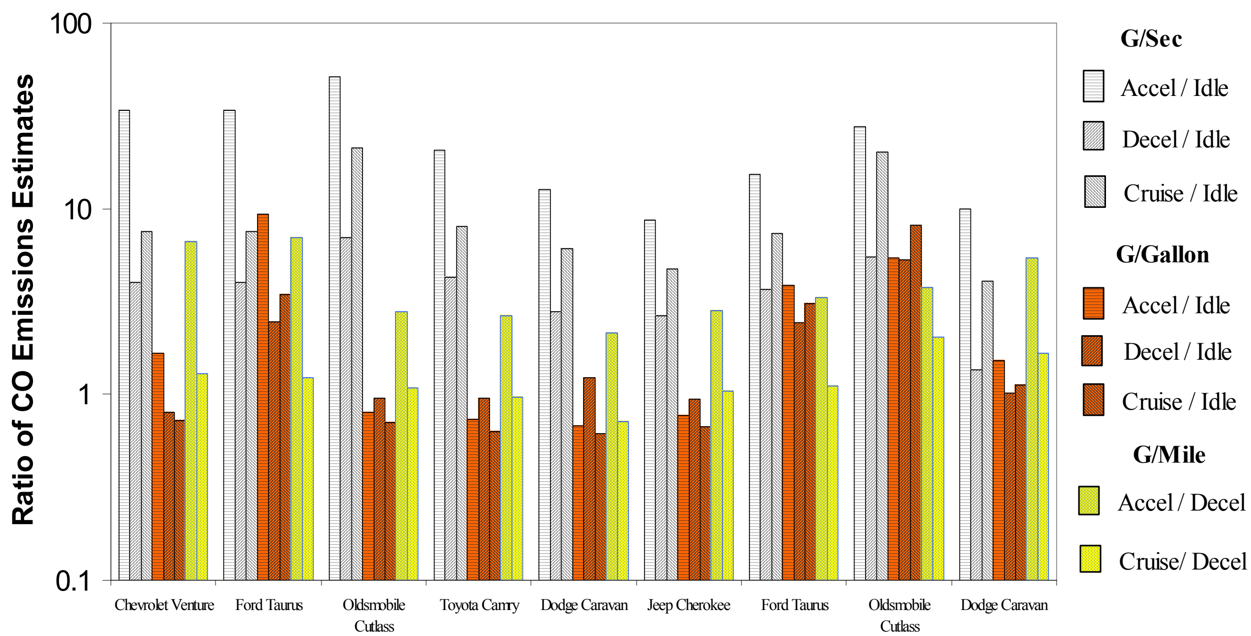


Figure S2. Average CO Modal Emissions for 1999 Ford Taurus

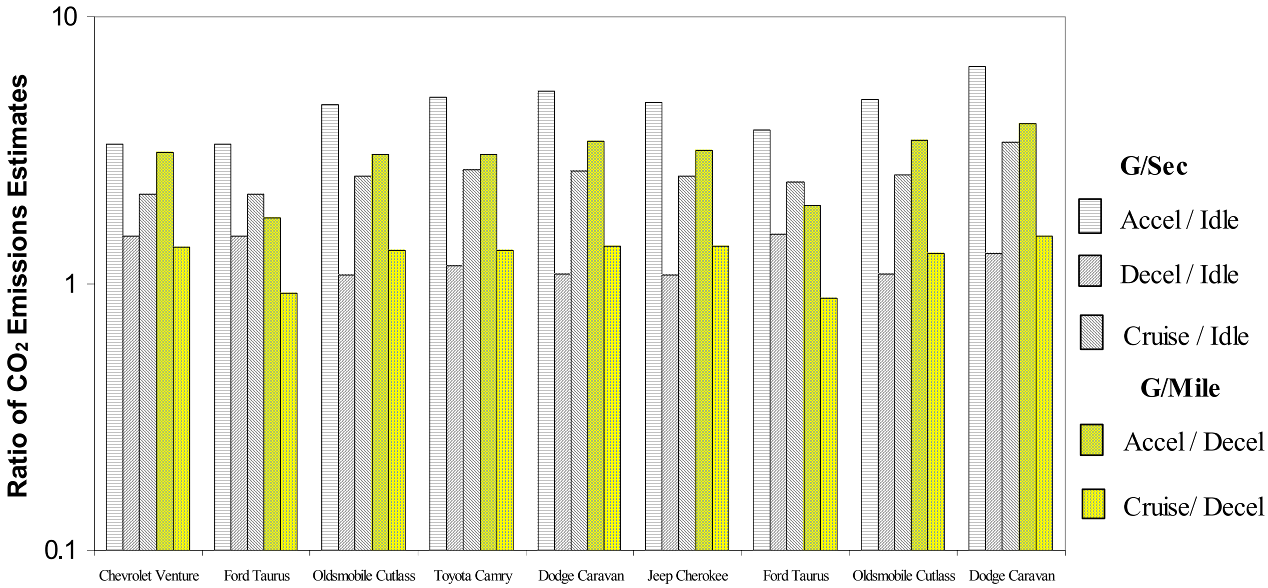


Figure S3. Average CO_2 Modal Emissions for 1999 Ford Taurus

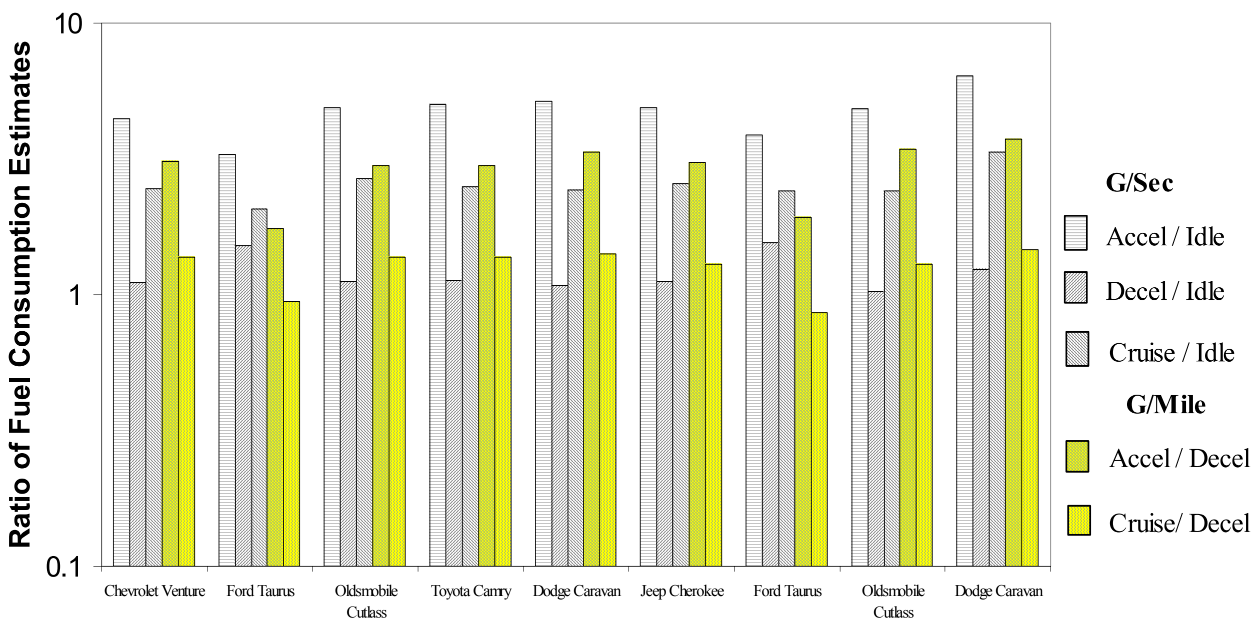


Figure S4. Average Modal Fuel Consumption Rate for 1999 Ford Taurus

PART VI
EFFECT OF ARTERIAL SIGNALIZATION AND LEVEL OF SERVICE ON MEASURED VEHICLE EMISSIONS

Submitted to

Journal of Transportation Research Board

ABSTRACT

The purpose of this research is to study the effect of arterial traffic signal timing and coordination on vehicle emissions. Traffic signal timing improvement is one of the most common congestion management practices in the United States. Although the benefits of improved signal timing for reduced fuel consumption are well documented, its effectiveness as an emission Transportation Control Measure has not been clearly investigated. In this work, an empirical approach based on real-world, on-road vehicle emission measurements was used.

Data for this research were collected using a portable, On-board Emission Measurement unit (OEM-2100^{TM}). The OEM-2100^{TM} allows real-time, field data collection of second-by-second measurement of tailpipe emissions (i.e., CO, HC, and NO) and engine operations (i.e., speed and engine rpm). A total of 824 one-way runs representing 100 hours and 2,020 vehicle miles of travel were conducted involving four drivers and eight gasoline fueled light-duty vehicles on two signalized arterials in Cary, North Carolina: Walnut Street and Chapel Hill Road.

A key result from this study is that signal coordination on Walnut Street yielded improvements in arterial level of service and reduction in emissions. It was observed for Chapel Hill Road that substantial reductions in emissions were observed for uncongested (LOS A/B) versus congested traffic flow (LOS D/E) when comparing travel in the same direction at different times of day. The findings confirm the utility of signal coordination and congestion management as effective tools for emission control.

KEYWORDS: Vehicle Emissions, Signalized Arterials, Level of Service, On-board Vehicle Emissions Measurement, Real-World Vehicle Data, Effect of Traffic Signalization on Emissions, Modal Analysis

1.0 INTRODUCTION AND RESEARCH OBJECTIVES

Highway vehicles contribute substantially to national and local emissions of carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_X), and particulate matter (PM) [1, 2, 3]. Transportation and air quality managers at the state level have the task of developing and evaluating Transportation Control Measurements (TCMs) and other types of Transportation Improvement Plans (TIPs). One of the objectives of TCMs and TIPs is to improve air quality. The benefits of many TCMs and TIPs accrue at the "micro" level, such as individual signalized intersections, traffic control devices, roadway facility improvements (e.g., ramps, roundabouts), improved incident response and management, and others.

Traffic signal timing improvement is the most widespread congestion management practice in the United States [4, 5]. Signal timing improvements can include simple changes in timing plans or can include complex computer-controlled signal coordination along an entire corridor. When effective, signal improvement benefits can include: reduced congestion; increased safety; and improved response times for emergency vehicles. Although the benefits of improved signal timing for reduced fuel consumption are well documented, the effectiveness of signal timing as a TCM has not been empirically investigated. Hallmark *et al.* [4] have conducted a study in Atlanta where MEASURE model was utilized to study the effect of signal timing on CO emissions where on-road activity data were collected using handheld laser range-finding

(LRF) devices. Significant reductions in CO emissions were estimated when traffic signals were coordinated [4], however, model findings were not compared with on-road emissions measurements.

The main objectives of this paper are to: (1) assess the feasibility of current methods for estimating traffic signal impacts on emissions; (2) describe an on-board emission measurement system; (3) discuss key considerations in on-road data collection; (4) present an example of the type of data obtained from one on-road trip with an instrumented vehicle; and (5) evaluate the effect of traffic signal timing and coordination with respect to vehicle emissions on selected corridors based upon field data collection.

2.0 ASSESSMENT OF CURRENT METHODS

The data required to accurately assess the air quality benefits of signal timing improvements must be of sufficient temporal and spatial resolution to enable identification and evaluation of hotspots, and measurement of the change in emissions as a result of traffic signal coordination and timing. Existing regulatory highway vehicle emission factor models, such as EMFAC in California and MOBILE in the rest of the U.S., are based upon assumed standardized driving cycles tested on dynamometers. 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 [2, 3]. 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, 6]. For example, many tests under-represent short-term events that cause high emissions even for a properly functioning vehicle, such as high accelerations.

The development of the new version of the MOBILE emission factor model, MOBILE6, is a substantial improvement over the previous MOBILE5b model [2, 7, 8]. For the first time, it is possible to develop regional emission estimates based upon a weighted averaging of different facility-specific, link-based driving cycles, some of which represent different levels of service. 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 signal improvements. MOBILE6 is designed to evaluate emissions impacts on a regional level not a finer level, and therefore is poorly suited to estimate the emissions-reduction benefits of TCMs [2,4].

In addition to MOBILE6 there are several traffic operations software packages that provide vehicle emissions [9-16]. However, in these models emission estimates are based upon dynamometer testing of vehicles rather than real-world measurements.

3.0 A NEW EMPIRICAL APPROACH

In this work, an empirical approach based on real-world, on-road vehicle emission measurements is utilized. On-board vehicle activity and 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 [17-23]. Variability in vehicle emissions as a result of variation in vehicle operation, signal control and other factors can be represented and analyzed more reliably than with the other methods such as dynamometer tests and Remote Sensing Devices (RSD) measurements. This is because such measurements eliminate the concern about non-representativeness that is often an issue with dynamometer testing. On-board emissions measurement has not been widely used because in the past it has been prohibitively expensive. This is now changing, however, as EPA and others have developed a variety of portable instruments [24-28].

The specific method employed in this research, based upon instrumentation of individual vehicles and measurement of tailpipe emissions, offers the benefit of providing representative on-road second-by-second vehicle activity and emissions data, which enables characterization of emissions at any time or location during a trip. With on-road data of high temporal and spatial resolution, it is then possible to evaluate the local effect of signal control.

3.1 Description of On-Board System

A portable, on-road vehicle data measurement device (OEM-2100™) was deployed to collect vehicle emissions and engine data as the vehicle is driven under real-world conditions [21]. The 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. The engine scanner downloads second-by-second engine and vehicle data from the On-Board Diagnostics (OBD) link of the vehicle.

The OEM-2100™ can be installed in approximately 15 minutes in a light duty vehicle. It has three connections with the vehicle: a power cable typically connected to the cigarette lighter or power port, an engine data link connected to the OBD link, and an emissions sampling probe inserted into the tailpipe. The connections are fully reversible and do not require any modification to the vehicle. Figure 1 illustrates the placement of the OEM-2100^{TM} instrument on

a seat inside a vehicle. Figure 2 illustrates the emission sampling probe and hose, which are routed into the vehicle and to the instrument.

The precision and accuracy of the OEM-2100^{TM} 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 [29]. Three light-duty gasoline vehicles (1997 Oldsmobile sedan, 1998 Plymouth Breeze and 1997 Chevy 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^{TM}. The OEM-2100^{TM} has good precision, as reflected in R^2 values compared to the dynamometer ranging from 0.90 to 0.99, depending on the pollutant. Details regarding the instrumentation can be found elsewhere [21].

3.2 Field Data Collection

Vehicle emissions and activity data collected with the OEM-2100^{TM} were supplemented by additional measurements. Road grade was measured with a digital level on the study corridors at one-tenth mile increments. The data were encoded into a database and synchronized with the engine and emissions data. 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

FIGURE 1. OEM-2100™ installed in a 1998 Toyota Camry

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

was used to record temperature and humidity; vehicle information such as model year, make, model, VIN, engine size, odometer reading, and curb weight; and events, including the time at which the vehicle crossed the centerline of key intersections or entered queues.

4.0 STUDY DESIGN

The primary objective of the experiment was to study the effect of signal coordination on vehicle emissions by comparing vehicle activity and emissions data collected before and after signal coordination plans were implemented. The experiment type chosen was a before-and-after study without control groups with approximately the same number of runs performed before and after the coordination plans were implemented. The focus was on measurement of hot stabilized emissions on arterials. Cold-start emissions, although important [30], were not included in the study but could be addressed in the future.

A variety of potential "threats to validity" of this type of study design were identified and evaluated. Some factors could be controlled in the before and after studies, such as selection of the same vehicle, driver, travel direction, and peak travel period. 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 factors.

Data were collected on two signalized arterials in Cary, North Carolina between September and December 2000. Table 1 depicts the traffic characteristics of the two arterials. A total of 824 one-way runs representing 100 hours and 2,020 vehicle miles of travel were conducted involving four drivers and eight gasoline fueled light-duty vehicles. These vehicles were: two 1999 Ford Taurus sedans; two 1996 Oldsmobile Cutlass sedans; a 1998 Chevrolet Venture Minivan; a 1997 Jeep Cherokee; a 1998

TABLE 1. Traffic Characteristics of Test Signalized Arterials

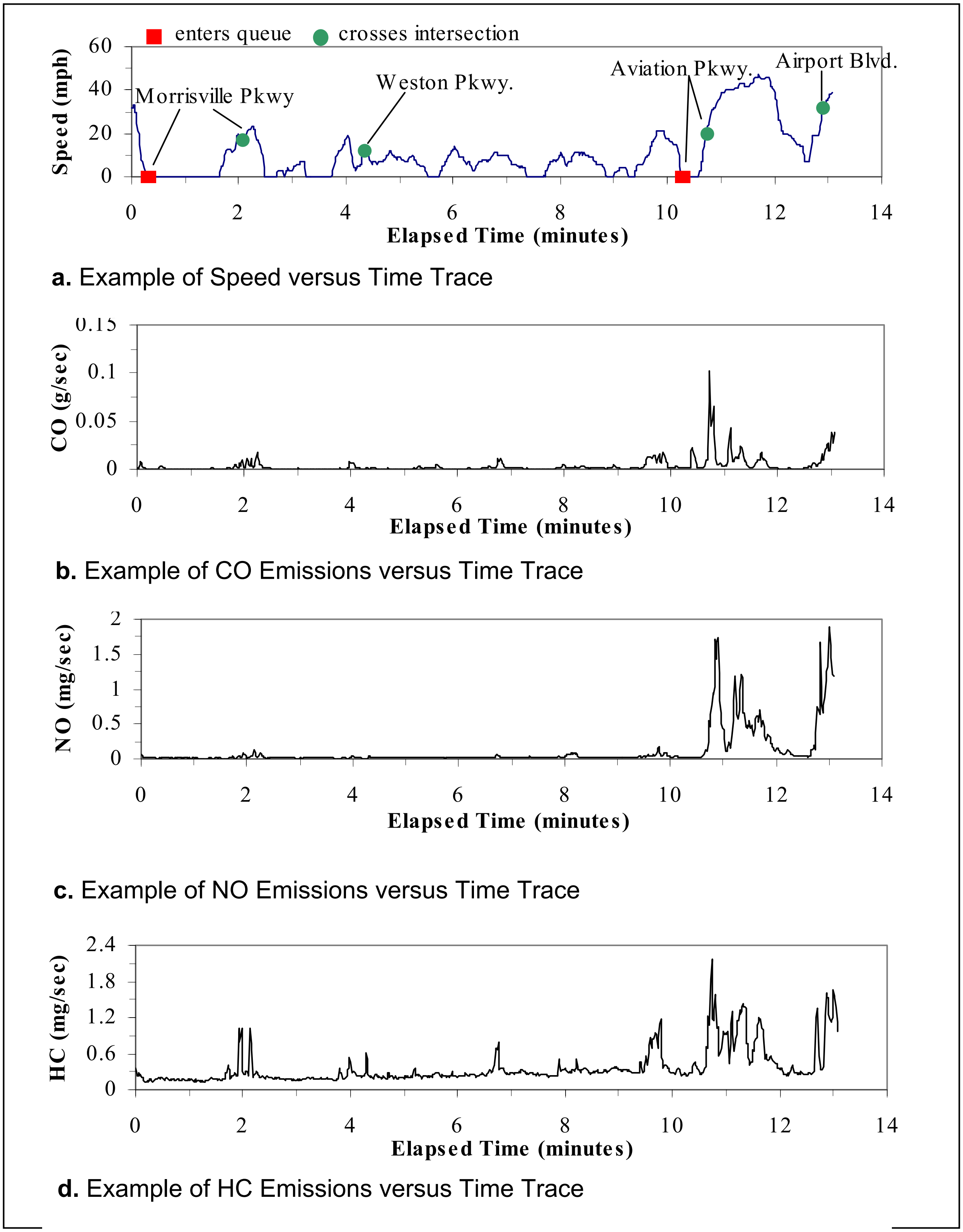
Characteristic	Chapel Hill Rd. (Morrisville Pkwy. to Airport Blvd.)	Walnut Street (Dillard Dr. to Cary Towne Blvd.)
Corridor Length (mi.)	2.6	2.3
Speed Limit (mph)	45	35, 45
Through Lanes	2	4
Center Turn Lane?	No	Yes
Traffic Signals	4	9
Signal Density (signals/mi.)	1.5	3.9
Free Flow Speed (mph)[a]	45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

a. Frey *et al.*, 2001 [21]
b. Based on HCM Exhibit 15-2 [31]

Toyota Camry; and a 1997 Dodge Caravan. Repeated runs were made in order to characterize inter-run variability and to develop stable estimation of mean emissions. Details of the experimental design can be found elsewhere [21].

5.0 SAMPLE RAW DATA AND MODAL EMISSIONS

To illustrate the type of data that were collected, Figure 3 depicts an individual one-way vehicle trip for a 1999 Ford Taurus. Figure 3a shows second-by-second speed versus elapsed trip time. The trip took place on Chapel Hill Road starting south of Morrisville Parkway and ending a short distance north of Airport Boulevard. Instantaneous speed ranged from zero to approximately 50 mph, and the average speed was 11 mph. There is stop-and-go traffic between Weston Parkway and Aviation Parkway, indicating that the signal at Aviation Parkway caused long delays in the corridor.



a. Example of Speed versus Time Trace

b. Example of CO Emissions versus Time Trace

c. Example of NO Emissions versus Time Trace

d. Example of HC Emissions versus Time Trace

FIGURE 3. Example Speed and Vehicle Emissions Profile for a 1999 Ford Taurus Driven on Chapel Hill Road on August 30, 2000.

Emission traces for the measured pollutants are shown in Figures 3b to 3d for CO, NO, and HC respectively. For all three pollutants, it is clear that the highest emission rates, on a mass per time basis, occur during small episodes of the trip. 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. These data suggest that the CO emission rates during idling or crawling are comparatively low compared to the CO emissions during an acceleration such as the one at Aviation Parkway. Similar patterns are observed in Figure 3c and Figure 3d for other two pollutants.

The time traces in Figure 3 also suggest that emission rates differ during different modes of driving [19, 21-23, 32]. In particular, the largest emission rates appear to be associated with acceleration events. Therefore, the data were divided into four modes: (a) acceleration; (b) cruise; (c) deceleration; and (d) idle [21-23].

A modal analysis for the 1999 Ford Taurus (on Walnut Street) is depicted in Figure 4. The average emission rates shown were based upon measurements obtained during 94 runs in the before (no signal coordination) case and 84 runs in the after (with signal coordination) case.

Average emissions during the acceleration mode are significantly higher than for any other driving mode, for all three of the pollutants measured. For each of the three pollutants, the four average modal emission rates are significantly different from each other at the 0.05 significance level, except for cruising and acceleration emissions of NO in the before case. The average acceleration emission rates for CO and NO are more than a factor of 10 higher than the average idling emission rates, and the average acceleration emission rates for HC are approximately a factor of five higher than the average idling emission rates.

Figure 4 also gives insight regarding the differences in modal emission rates between the before and after conditions. The average modal emission rates for a given pollutant were not statistically significantly different in half of the cases. For example, HC idle and deceleration, NO idle and acceleration, and CO idle and acceleration modal emission rates were similar in both the before and after cases. Although the average HC acceleration and cruise emission rates in the before and after cases are statistically significantly different from each other, they are not substantially different and are within 20 percent of each other. When modal emissions were evaluated at a more disaggregated level, such as by time of day and direction of travel, more frequent 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, even though the before and after studies were performed as close together in time as possible.

It is hypothesized that for the same vehicle-corridor-driver-peak-direction combination modal emissions should be similar in the before and after case if data could have been collected under the same ambient conditions, and that differences arise because of factors not under the direct control of the investigators. Thus, it was decided that the comparison of the before and after condition should be based upon similar modal

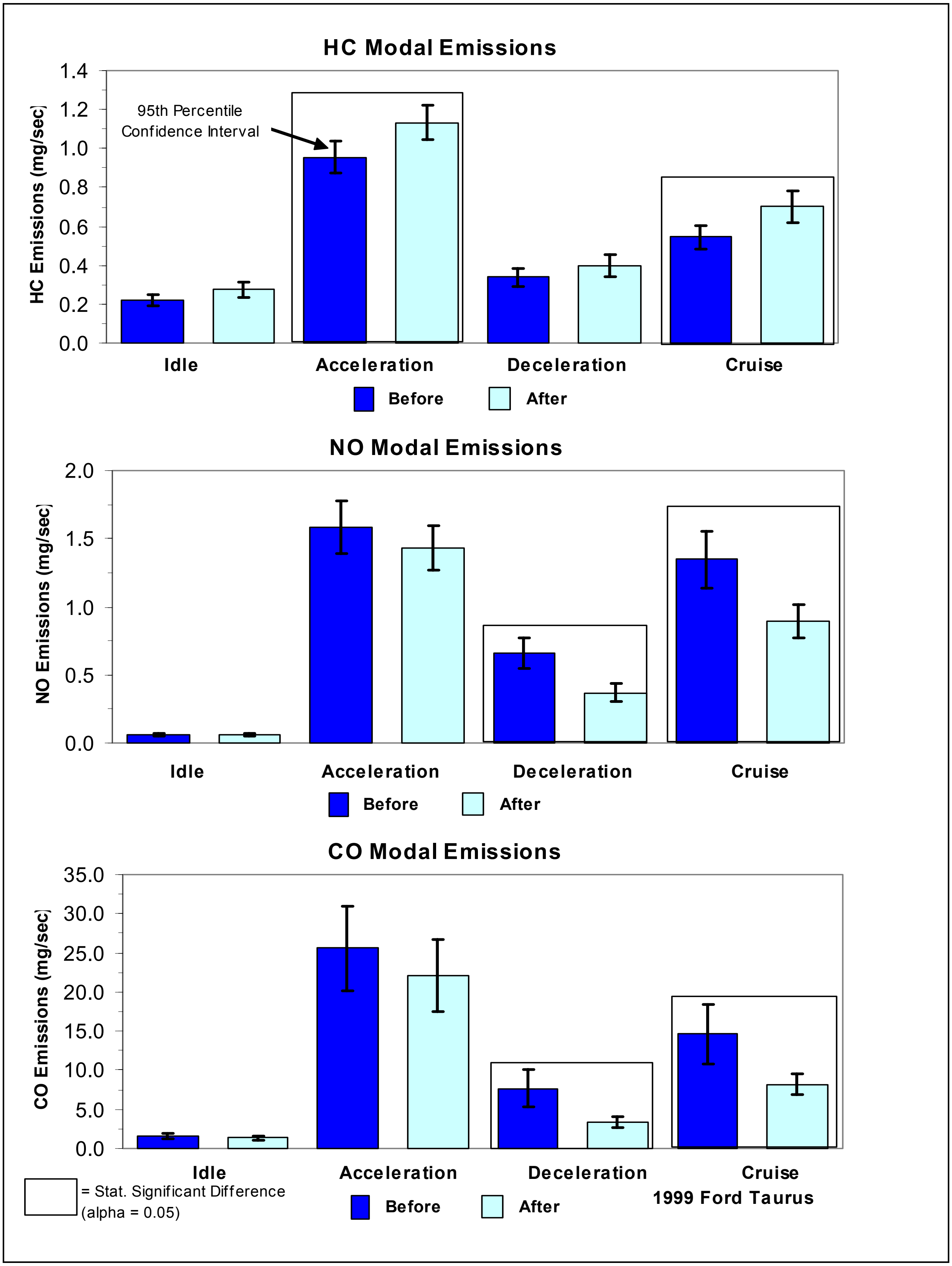


FIGURE 4. Walnut Street Modal Emission Rate for 1999 Ford Taurus Before and After Signal Coordination.

emission rates, using weighted average emission factors. Therefore, before and after total emissions on the corridor were compared by using the empirically observed travel time and distribution of modes and by using the same model emission rates in the before and after cases. Details of that methodology are described elsewhere [21].

6.0 EFFECT OF SIGNAL IMPROVEMENTS ON EMISSIONS

A summary of the measured impact of signal coordination on emissions is presented in this section.

6.1 Walnut Street

For the Walnut Street corridor, between Dillard Drive and Cary Towne Boulevard, the North Carolina Department of Transportation (NCDOT) implemented a new signal timing improvement and coordination plan in mid-November 2000. Therefore, field data collection occurred before the change during the period between October 31st and November 10th and after the change during the period between November 30th and December 13th.

Changes in traffic parameters and vehicle emissions on the corridor-level were examined for two primary vehicles, the Ford Taurus and Oldsmobile Cutlass. Tables 2 and 3 summarize the key findings for Walnut Street in the before and after cases. Total emissions estimated using modal rates that were averaged from the before and after values were utilized in the comparison. Absolute values for traffic variables and emissions are given in Tables 2 and 3, along with percent differences between the before and after cases.

TABLE 2. Traffic and Emission Performance on Walnut Street Arterial Before and After Signal Coordination -- 1999 Ford Taurus

	Before (After)	% Diff.[a]	Before (After)	% Diff.	Before (After)	% Diff.	Before (After)	% Diff.
Time Period	*Morning Peak*				*Afternoon Peak*			
Direction	Northbound		Southbound		Northbound		Southbound	
Runs	24 (24)		24 (25)		22 (16)		24 (19)	
Travel Time (sec)	336 (288)	**-14**	300 (227)	**-24**	433 (332)	**-23**	365 (366)	+0.3
Avg. Speed (mph)	23.9 (27.2)	**+14**	26.6 (35.1)	**+32**	18.4 (23.7)	**+29**	22.0 (21.6)	-1.8
Delay Rate [b] (sec/mi)	55.6 (33.7)	**-40**	43.9 (16.1)	**-63**	87.2 (39.0)	**-55**	65.6 (62.6)	-4.6
Stop Rate (stops/mi)	1.83 (1.29)	**-30**	1.49 (0.591)	**-60**	2.23 (1.58)	**-29**	1.52 (1.49)	-2.3
Level of Service [c]	C (C)		C (A)		D (C)		C (C)	
HC Emissions [d] (mg)	185 (164)	**-12**	167 (137)	**-18**	287 (255)	**-11**	197 (200)	+1
NO Emissions [d] (mg)	233 (215)	**-8**	316 (277)	**-12**	331 (332)	-1	268 (272)	+1
CO Emissions [d] (mg)	3442 (3041)	**-12**	4018 (3272)	**-19**	4562 (4364)	-5	3020 (3063)	+1

a. Percent Difference: (A-B)/B. Bold values indicate that average differences are statistically significant at the 0.05. significance level.
b. Frey *et. al* [21]
c. Based on HCM Exhibit 15-2 [31]
d. Calculated using average modal rates

TABLE 3. Traffic and Emission Performance on Walnut Street Before and After Signal Coordination -- 1996 Oldsmobile Cutlass

	Before (After)	% Diff.[a]	Before (After)	% Diff.	Before (After)	% Diff.	Before (After)	% Diff.
Time Period	*Morning Peak*				*Afternoon Peak*			
Direction	Northbound		Southbound		Northbound		Southbound	
Runs	25 (23)		25 (23)		21 (22)		22 (23)	
Travel Time (sec)	359 (302)	**-16**	292 (243)	**-17**	456 (359)	**-21**	387 (383)	-0.9
Avg. Speed (mph)	23.9 (28.2)	**+18**	29.2 (35.0)	**+20**	18.8 (24.3)	**+29**	22.8 (22.4)	-1.8
Delay Rate [b] (sec/mi)	62.8 (39.1)	**-38**	36.4 (18.2)	**-50**	95.7 (42.6)	**-56**	61.2 (66.4)	+8.5
Stop Rate (stops/mi)	1.90 (1.34)	**-29**	1.11 (0.605)	**-46**	2.34 (1.66)	**-29**	1.68 (1.49)	-11
Level of Service [c]	C (C)		B (B)		D (C)		C (C)	
HC Emissions [d] (mg)	365 (320)	**-12**	285 (251)	**-13**	426 (375)	**-12**	329 (324)	-1
NO Emissions [d] (mg)	595 (519)	**-13**	505 (439)	**-14**	695 (565)	**-19**	590 (581)	-1
CO Emissions [d] (mg)	3702 (3564)	-4	3499 (3180)	**-9**	4619 (4566)	-1	2736 (2709)	-1

a. Percent Difference: (A-B)/B. Bold values indicate that average differences are statistically significant at the 0.05 significance level.
b. Frey *et. al* [21]
c. Based on HCM Exhibit 15-2 [31]
d. Calculated using average modal rates

As shown in Tables 2 and 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 decreased 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. Traffic flow, as quantified by travel time, average speed, delay rate, and stops per mile, improved approximately 15 to 60 percent, while emissions decreased by approximately 10 to 20 percent in most cases. Improvements in level of service were also observed.

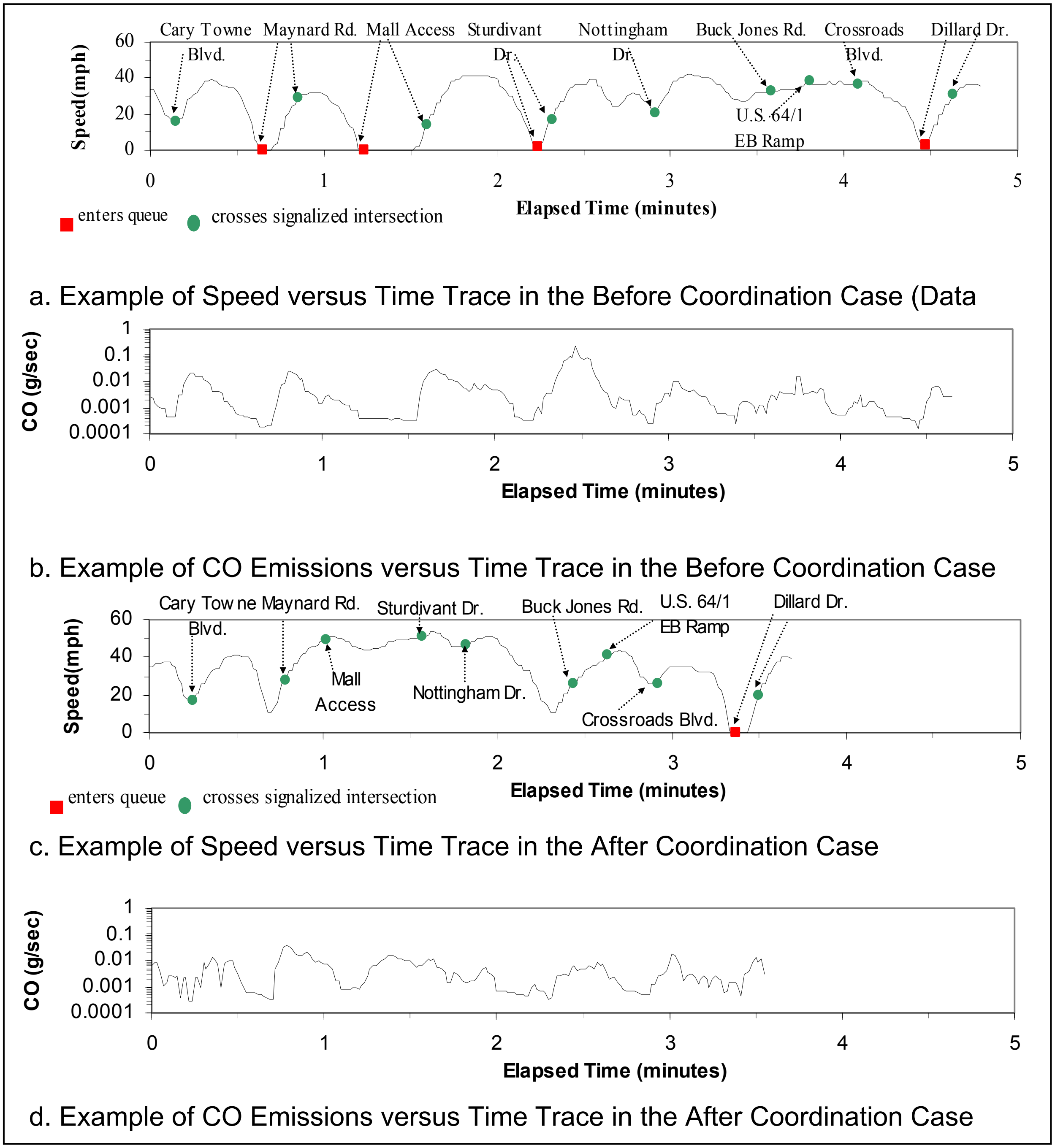
Overall, the Walnut Street corridor illustrates the successful application of a coordinated signal timing plan leading to a reduction in vehicle emissions. Specifically, the changes in signal timing and coordination generally had a beneficial effect in reducing average vehicle emissions on the corridor. The improvement in average 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. To further illustrate the impact, Figure 5a and Figure 5c contrast speed profiles for typical before and after runs. These runs were selected to represent average speed performance in the before and after cases. Figures 5b and 5d contrast CO emissions profiles for the same before and after runs. The example trip for the before case lasted approximately 4.8 minutes and had an average speed of 26 mph, whereas example trip for the after case lasted approximately 3.7 minutes and had an average speed of 35 mph. There were four stops in the example before case, whereas there was only one stop in the example after case. Total CO emissions in the example before case were 2.06 grams compared to 1.05 grams in the example after case.

6.2 Chapel Hill Road

Chapel Hill Road, is a heavily traveled corridor during the morning and evening rush hours and is representative of rush-hour commuting between Cary and the Research Triangle Park, NC. Table 1 summarizes the traffic characteristics. This corridor operated at capacity in the peak direction, both in the AM and PM peak hours. Therefore, changes in signal timing and coordination resulted in relatively little or no improvement in traffic flow.

Because traffic flow on Chapel Hill road is highly directional, it is possible to compare emissions for the same direction of travel under congested and uncongested traffic conditions simply by comparing the morning and afternoon data. Traffic is very congested, with a level of service (LOS) between C and E, in the northbound direction in the morning and in the southbound direction in the afternoon. Both southbound traffic in the morning and northbound traffic in the afternoon are close to free flow conditions, with a LOS of A or B. Table 4 summarizes the key findings for the uncongested and congested cases. Total emissions were estimated using average of the modal rates in the uncongested and congested cases.

The findings from Table 4 are quite clear. There is a substantial decrease of 35 to 60 percent in emissions for all three pollutants for the uncongested cases when compared to congested cases. Thus, there would be a clear emissions benefit to reducing congestion on Chapel Hill Road if that were possible. However, because traffic flow is already at



a. Example of Speed versus Time Trace in the Before Coordination Case (Data

b. Example of CO Emissions versus Time Trace in the Before Coordination Case

c. Example of Speed versus Time Trace in the After Coordination Case

d. Example of CO Emissions versus Time Trace in the After Coordination Case

FIGURE 5 Walnut Street Speed and CO Emissions Traces for 1999 Ford Taurus Before and After Signal Coordination.

TABLE 4. Traffic and Emission Performance on Chapel Hill Road during Uncongested and Congested Cases – 1999 Ford Taurus and 1998 Chevrolet Venture

	Congested (Uncongested)	% Diff. [a]	Congested (Uncongested)	% Diff.	Congested (Uncongested)	% Diff.	Congested (Uncongested)	% Diff.
Vehicle	*1999 Ford Taurus*				*1998 Chevrolet Venture*			
Direction	Northbound		Southbound		Northbound		Southbound	
Runs	37 (31)		32 (44)		38 (30)		32 (37)	
Travel Time (sec)	616 (269)	**-56**	478 (274)	**-60**	676 (273)	**-43**	471 (264)	**-44**
Average Speed (mph)	15.3 (33.3)	**+118**	20.7 (33.3)	**+61**	15.1 (35.7)	**+137**	23.0 (37.7)	**+64**
Delay Rate [b] (sec/mi)	99.9 (23.4)	**-77**	68.4 (22.2)	**-78**	101.2 (19.9)	**-80**	50.9 (19.9)	**-80**
Stop Rate (stops/mi)	3.50 (0.603)	**-83**	2.31 (0.568)	**-75**	3.77 (0.616)	**-84**	2.19 (0.434)	**-80**
Level of Service [c]	E (B)		D (B)		E (A)		C (A)	
HC Emissions [d] (mg)	246 (113)	**-54**	173 (107)	**-38**	692 (290)	**-59**	525 (289)	**-45**
NO Emissions [d] (mg)	291 (139)	**-52**	336 (218)	**-35**	1131 (491)	**-57**	1133 (666)	**-41**
CO Emissions [d] (mg)	4413 (2105)	**-52**	6492 (3891)	**-60**	3256 (1306)	**-60**	1782 (854)	**-52**

a. Percent Difference: (U-C)/C. Bold values indicate that average differences are statistically significant at the 0.05 significance level.
b. Frey *et. al* [21]
c. Based on HCM Exhibit 15-2 [31]
d. Calculated using average modal rates

capacity for this corridor, changes in signal timing and coordination by themselves will not be effective at improving either traffic flow or emissions. Instead, other capacity expansions or demand reduction strategies would have to be employed.

7.0 CONCLUSIONS

The primary purpose of this paper was to evaluate the effects of changes in arterial signal timing and coordination with respect to emissions and LOS. Key findings and conclusions are:

(1) There is substantial episodic variability 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 stop time only may not always be successful in achieving overall reductions in air pollution emissions.

(2) Modal emission rates were found to vary substantially for specific time of day and direction of travel combinations when comparing before and after results, which necessitated development of simplified models to help clarify before and after comparisons of total emissions and to correct for uncontrollable changes in ambient and vehicle conditions.

(3) Coordinated signal timing improved traffic flow on the Walnut Street arterial, which led to reduction in vehicle emissions and moderate improvements in LOS from LOS B/D to LOS A/C.

(4) There is a substantial decrease in estimated emissions for the same direction of travel on Chapel Hill Road when comparing uncongested (LOS A/B) to congested (LOS C/E) conditions. Emissions of NO, CO, and HC were higher in the congested case compared to the uncongested case.

(5) Changes in emissions were associated with changes in traffic performance measures such as travel time, average speed, average control delay, and average number of stops per mile. In particular, the magnitude of the percentage decrease in travel time was typically comparable to the magnitude of the percentage decrease in emissions.

(6) 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.

(7) Since travel occurred over the same distance on both corridors, the comparison of signal timing and coordination on Walnut Street and of uncongested versus congested traffic flow on Chapel Hill Road demonstrate that *how* vehicles are driven is important, not simply how many miles, with respect to emissions.

8.0 RECOMMENDATIONS

Key recommendations of this study are:

(1) On-board emissions measurement studies need a careful experimental design that is specific to a particular study objective. Key factors in study design that should be considered in future studies are vehicle selection, driver selection, routing, deployment of instrumentation, scheduling of on-road data collection by travel direction and time period, and sample size.

(2) Often a signal coordination plan will improve the main through movements of a corridor but not consider the non-priority movements (side street and turning movements). Thus, it is important in the future to evaluate both the priority and non-priority movements to understand the overall impact of signal coordination on vehicle emissions.

(3) Vehicle emissions are higher during cold-start compared to hot-start trips. Studies should take this into account and design experiments that enable characterization of cold-start emissions. Modal analysis should consider cold-start as a separate operation mode.

(4) Substantial variability in vehicle emissions from one run to another was observed 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.

(5) 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 emission 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.

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PART VII

CONCLUSIONS AND RECOMMENDATIONS

Alper Unal

In this part, contributions of this dissertation and the conclusions drawn from the associated research work and the results are presented. Suggestions for future research directions related to this dissertation are provided.

7.1 SUMMARY AND CONCLUSIONS

In this dissertation, contributions in the development of new methodologies for collection and analysis of real-world vehicle activity and emission data are presented. In Part I, the use of on-board instrumentation for collecting and analysis of vehicle emissions is motivated, and then in Part II, the background material fundamental to study of vehicle emissions is given.

7.1.1 Contributions to Methodology for Real-World Vehicle Activity and Emissions Data Collection with On-Board Instrumentation

In Part III, key aspects of the data collection, screening and analysis protocols associated with deployment of a portable on-board tailpipe emissions measurement system is presented. These protocols were utilized successfully to collect data on two signalized corridors in Cary, North Carolina. Eight gasoline fueled light-duty vehicles and four drivers were tested, resulting in a total of 824 one-way runs representing approximately 1000 vehicle-hours and approximately 2,020 vehicle-miles of simultaneous vehicle activity and emissions data.

Experience gained during the field work and data processing lead to the development of rigorous quality procedures, which resulted in a high proportion (over 90 percent) of valid vehicle activity and emissions measurements.

Another contribution of this part is the introduction of *a priori* modal definitions, based upon vehicle operation variables such as speed and acceleration, for vehicle emissions analysis. The modal definitions that were evaluated in this study have proven to yield statistically significantly different emission rates for idle, acceleration, cruise, and deceleration. The average emission rate on a mass per time basis for acceleration was found to be typically a factor of five greater than idle emission rate for HC and CO_2, and a factor of ten or more for NO and CO. A key implication of this finding is that methods for reducing real-world on-road emissions should involve Transportation Control Measures (TCMs) and Transportation Improvement Plans (TIPs) that reduce the frequency and duration of episodic events, such as high accelerations, that lead to short periods of high emissions.

Additional contributions come from the availability of various applications of on-board vehicle emissions data collection. For example, as presented in Part III, the relationship between CO emissions and engine parameters, such as equivalence ratio, can be evaluated utilizing on-board data. Another possible application is the evaluation of the effect of different drivers on vehicle emissions.

7.1.2 Contributions to Methodology for Spatial Analysis of Vehicle Emissions

Part IV of this dissertation investigated hotspots along roadways where high values of emissions were observed based upon real-world on-road vehicle emissions measurements. The contribution of this part is the methodology developed to identify hotspot locations. The methods were successfully applied to an example case study to illustrate the types of insights obtained from measured tailpipe emissions data. For the example case study, it was shown that emissions associated with a single signalized intersection contributed substantially to total emissions for a particular corridor.

This study is unique since analyses were based upon real-world data rather than model results which are based upon average emissions for specified driving cycles as in the case for the current regulatory emission factor model (i.e., MOBILE model). In this study no modeling was involved.

This part of the dissertation also investigated parameters that have significant effects on emissions. For this purpose, multivariate statistical methods were utilized. The result of these analyses indicated that variables related to vehicle operation, such as average speed, average acceleration, standard deviation of speed, percent of time spent in cruise mode, minimum speed, maximum acceleration, and maximum power have significant effects on vehicle emissions. These variables are also indicators of traffic flow conditions. Overall, it was found that stop-and-go traffic conditions which result in sudden changes in speed and high accelerations generate hotspots. Although the data collected were only for CO, NO, and HC, other work suggests that HC emission may be a useful surrogate from which to estimate emissions of some air toxics. Therefore, the type of data collected in this study could be used to support emissions and exposure assessments for a variety of pollutants.

7.1.3 Contributions to Methodology for Evaluation of Sensitivity of Different Emission Factor Estimation Methods for Vehicle Operation Modes

In Part V of this dissertation, the sensitivity of vehicle emission factor estimation methods with respect to vehicle operation conditions was investigated. At present, vehicle emission inventories are estimated using mass per distance emission factors (i.e., distance-based approach). There are studies that criticize this approach and hypothesize that emission factors based upon mass of emissions per fuel consumed (i.e., fuel-based approach) would give more accurate emission estimates, since it is assumed that the fuel-based approach is not sensitive to vehicle operation modes on the g/mi based approach.

The main contribution of this part is that this is the first study that is comparing different emission factor estimation methods by utilizing real-world data that have the necessary temporal and spatial resolution. In this study emission factor estimation based upon mass per unit time (i.e., time-based approach) was also investigated.

Comparison of different emission estimation methods was based upon modal analysis. It was found from these analyses that trip emissions can be dominated by a small number of short term event during the trip whether measured by time elapsed, distance traveled, or normalized with fuel consumption. On average, it has been found for the example case study that, emission rates for the acceleration and cruise modes have the highest values for all different emission factor estimation methods. Deceleration and idle modes have the lowest emissions.

Statistical comparisons indicated that overall, majority of modal emission rates (i.e, more than 80 percent) are statistically significantly different from each other for time-based and distance-based methods. For fuel-based approach approximately 50 percent of the modes are statistically significantly different from each other for HC, CO, and CO_2, whereas 90 percent of the modes are statistically significantly different from each other for NO. These numbers indicated that at macroscale fuel-based approach might be better for some pollutants such as HC, but not for NO emissions. This is not true for meso-scale level modeling. It should be noted that there is additional uncertainty for fuel-based approach, since the activity data, fuel consumption, is also sensitive to different vehicle operation modes. These considerations as well as data availability should be considered in selecting a method for vehicle emission factor estimation.

7.1.4 Contributions to Methodology for Determination of the Effects of Changes in Signal Timing and Coordination on Vehicle Emissions

In Part VI of this dissertation the effects of changes in signal timing and coordination with respect to vehicle emissions was evaluated. Traffic signal timing improvement is the most widespread traffic congestion management practice in the United States. Although the benefits of improved signal timing for reduced fuel consumption are well documented, the effectiveness of signal timing as a Transportation Control Measure (TCM) has not been clearly investigated. This study is unique since it is the first time such a study is conducted utilizing real-world vehicle activity and emissions data.

The main contribution of this part is that methodology was developed to collect, analyze, and interpret real-world on-road tailpipe emissions data regarding before and after comparisons associated with a change in traffic conditions. For the example case study, it was found that coordinated signal timing improved traffic flow on Walnut Street, which lead to a reduction in vehicle emissions. On Chapel Hill Road, changes in signal timing and coordination resulted in relatively little or no improvement in traffic flow. Because traffic flow on Chapel Hill road is highly directional, it was possible to compare emissions for the same direction of travel under congested and uncongested traffic conditions. 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 HC were higher in the congested case compared to the uncongested case. It was found that changes in emissions were highly associated with changes in quantitative measures of traffic flow such as average speed, average control delay, and average number of stops per mile.

7.2 RECOMMENDATIONS FOR FUTURE WORK

Key recommendations of this study are:

(1) On-board emissions measurement is a viable method for measuring representative real-world tailpipe emission 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, driver behavior, and other important factors that may substantially influence real-world emissions.

(2) 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.

(3) On-board emissions measurement can be used to support the development of emission factors and can be used in the development of future emission factor models.

(4) Congestion mitigation measures, such as improved signal timing and coordination, can reduce emissions. Real-world data should be collected to quantify the effect of these congestion mitigation measures as well as others.

(5) Often a signal coordination plan will improve the main through movements of a corridor but do not consider 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. Studies should be designed to investigate the effect of signal coordination of main streets on non-priority movements both from traffic and emissions perspective.

(6) Vehicle emissions are higher during cold-start compared to hot-start trips. Studies should take this into account and design experiments that enable to characterize cold-start emissions. Modal analysis should consider cold-start as a separate operation mode. Modal analysis is a promising method for emission factor development approach. Modal definitions should be improved and methods of incorporating this method to emission factor estimation models should be investigated. Author is currently working in an EPA supported project to investigate the possibilities of improving modal definitions and development of a modal emission factor estimation model (Frey *et al.*, 2002a; Frey *et al.*, 200b).

(7) Substantial variability in vehicle emissions from one run to another were observed 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.

(8) 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.

(9) 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.