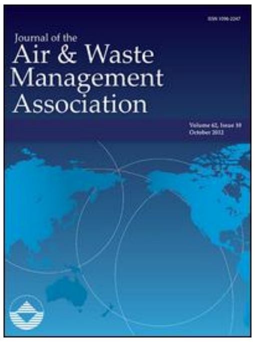

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On-Road Measurement of Vehicle Tailpipe Emissions Using a Portable Instrument

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ABSTRACT

A study design procedure was developed and demonstrated for the deployment of portable onboard tailpipe emissions measurement systems for selected highway vehicles fueled by gasoline and E85 (a blend of 85% ethanol and 15% gasoline). Data collection, screening, processing, and analysis protocols were developed to assure data quality and to provide insights regarding quantification of real-world intravehicle variability in hot-stabilized emissions. Onboard systems provide representative real-world emissions measurements; however, onboard field studies are challenged by the observable but uncontrollable nature of traffic flow and ambient conditions. By characterizing intravehicle variability based on 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 5 times greater than during idle for hydrocarbons and carbon dioxide and 10 times greater for nitric oxide and carbon monoxide. A statistical method for comparing on-road emissions of different drivers is presented. Onboard data demonstrate the importance of accounting for the episodic nature of real-world emissions to help develop appropriate traffic and air quality management strategies.

IMPLICATIONS

Real-world vehicle emissions are episodic in nature. Onboard data enable quantification of high emissions episodes with respect to location as well as with respect to microscale trip characteristics, based on representative on-road data. Idle emission rates were found to be low compared with 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 and transportation improvement plans that effectively reduce emissions.

INTRODUCTION

Motor vehicle emissions contribute substantially to national and local emission inventories for hydrocarbons (HCs), nitrogen oxides (NO_x), and carbon monoxide (CO).[1–3] 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 on 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 on driving cycles with low average speeds to a g/sec basis but are not estimated based on measurement of actual idling. A key hypothesis of this work is that the emission rate during idling is substantially lower than for other driving modes. Second-by-second data collected in the laboratory and on the road demonstrate that vehicle emissions are episodic in nature, indicating that 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 to identify and develop effective 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.[4–8]

In this work, an empirical approach to measurement of real-world, on-road vehicle emissions is emphasized.[4] The focus is on real-world hot-stabilized operation on signalized primary arterials. 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. Although the focus here is on hot-stabilized emissions, in other work, the contribution of cold starts to trip emissions based on onboard data has been assessed.[5,6]

The main objectives of this paper are to document (1) the onboard emission measurement system; (2) key considerations in experimental design for on-road data collection; (3) data collection procedures; (4) the approach for preparation of a joint emissions and traffic parameter database; (5) data screening, processing, and analysis; and (6) exemplary case studies of data and insights. The case studies highlight (1) the episodic nature of vehicle activity and hot-stabilized emissions data; (2) variability and uncertainty in modal nitric oxide (NO), HC, CO, and carbon dioxide (CO_2) emissions; and (3) a comparison of emissions based on two different drivers. The use of onboard measurements for transportation and air quality management applications is discussed.

THE ROLE OF ONBOARD INSTRUMENTATION

There are three typical vehicle tailpipe emission measurement methods: (1) dynamometer tests, (2) remote sensing, and (3) onboard 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.[2,3,9,10] The data obtained from driving cycles are also used to develop emission estimation models, such as EMFAC7F, MOBILE6, the Mobile Emission Assessment System for Urban and Regional Evaluation, and the Comprehensive Modal Emissions Model.[2,3,9–12] A key concern with such tests is that they may not represent real-world on-road driving in a given geographic area.[2,9,13–15]

Remote sensing devices (RSDs) use IR and, in some cases, UV spectroscopy to measure the mixing ratios of pollutants in exhaust emissions.[16–19] 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 mixing ratio or fuel basis. There are constraints on the siting of 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.[19,20] Furthermore, although evaluated for use in some tunnel studies,[21] remote sensing is primarily a fair-weather technology.[19,20]

Onboard 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.[4,22–29] In the past, onboard instrumentation was not widely used because it was prohibitively expensive. Therefore, onboard emissions measurement studies have typically focused on a very small number of vehicles.[13,22–26] In some studies, researchers have measured engine parameters only.[14,30,31] However, in recent years, portable instruments have become available. One study showed that a low-cost portable nondispersive infrared (NDIR) instrument provided CO and HC measurements with excellent correlation to dynamometer measurements.[32] Another demonstrated the use of a portable system for measuring transit bus emissions.[33] The U.S. Environmental Protection Agency (EPA) is developing an onboard measurement system, Real-Time On-Road Vehicle Emissions Reporter (ROVER), for both light- and heavy-duty vehicles.[34] Clean Air Technologies International, Inc. (CATI), Sensors, Inc., Ford Motor Co., and Horiba are among those who have developed portable onboard instruments.[35–38]

INSTRUMENTATION

The instrument used for onboard 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 onboard computer. The five-gas analyzer measures the volume percentage of CO, CO_2, HC, NO, and oxygen (O_2) in the vehicle exhaust. Simultaneously, the engine scanner is connected to the Onboard 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 airflow (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.[33]

The precision and accuracy of the OEM-2100 was tested by the New York Department of Environmental Conservation (NYDEC) and at EPA's National Fuels and Vehicle Emissions Laboratory in Ann Arbor, MI.[39] 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 New York City Cycle (NYCC) driving cycles. Two light-duty vehicles, a

Mercury Grand Marquis and a Dodge full-size pickup truck, were tested by EPA using the federal test procedure (FTP), US06, NYCC, and freeway high-speed driving cycles at Ann Arbor. The emissions were measured simultaneously by the dynamometer equipment and by the OEM-2100. OEM-2100 has good precision, as reflected in R^2 values compared with the dynamometer of 0.90–0.99. The standard error was less than 10% of mean emissions for all of the pollutants, including HCs, when compared with NDIR measurements in the laboratory. The measurements of NO_x and CO have good accuracy as reflected by a slope of close to 1 when comparing OEM-2100 versus laboratory data.

The measurements of HC are biased low because the onboard instrument uses NDIR, the same technology typically used in RSDs. NDIR is well-known to respond only partially to a typical HC speciation profile of vehicle exhaust.[40–42] NDIR responds accurately to low-molecular-weight straight-chain alkanes. The response is biased low for branched alkanes and aromatic compounds. The reported comparisons of NDIR with flame ionization detection (FID) measurements imply that HC emissions measurements obtained using NDIR should be multiplied by approximately a factor of 1.5–2 to obtain a more accurate indication of total HC emissions.

During data collection, the OEM-2100 was calibrated on a routine basis using a calibration gas composed of 4.03% CO, 12% CO_2, 1190 ppm HC (as C_3H_8), and 2026 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 before calibration, the instrument was used to measure the calibration gas, and the errors were typically on the order of ±5% or less, compared with a typical error of approximately ±2% immediately after calibration.

During on-road data collection, the instrument automatically "zeros" on a periodic basis 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 vol % and 0.03 vol %, respectively.

Supplemental data were collected using other instruments. Road grades were measured at 0.1-mi increments with a digital level. The road grade information was encoded into a database and was synchronized with the 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, using a laptop computer, for each significant traffic event including stopping at a signalized intersection, passing through the center of a signalized intersection, and stopping or slowing significantly at a midblock location because of a turning vehicle or incident. Vehicle specifications, driver identity, and weather conditions were also recorded using the laptop computer.

EXPERIMENTAL DESIGN

An onboard 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 is important to have a baseline characterization of the intravehicle variability in measurements for similar ambient and traffic conditions to determine whether it is possible to estimate meaningful emission rates based on onboard 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 who both operated two primary vehicles on each of two corridors. The largest number of driver/vehicle/route data collection runs was made with primary drivers and vehicles to characterize intravehicle 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% ethanol and 15% gasoline. These data were collected to evaluate the robustness of the data analysis method applied to different fuels.

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 (RTP), NC. Data were also collected on Walnut Street in Cary 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 ±5%.

INSTRUMENT DEPLOYMENT

The OEM-2100 can be installed in ~15 min in a light-duty vehicle. The equipment has a width of 53 cm, a height of 41 cm, and a depth of 31 cm. It weighs ~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, vehicle identification number) 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 3 sec. 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 ~45 min. 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.

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 personal computer 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 (°C); throttle position (%); intake airflow (g/sec); dry exhaust flow (g/sec); fuel flow (g/sec); fuel economy (g/mi); NO mixing ratio (ppm); HC mixing ratio (ppm); CO mixing ratio (vol %); CO_2 mixing ratio (vol %); O_2 mixing ratio (vol %); NO mass emissions (g/sec); HC mass emissions (g/sec); CO mass emissions (g/sec); CO_2 mass emissions (g/sec); and road grade (%). 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:

(1) Laptop computer errors. Possible problems include not synchronizing the laptop and OEM-2100

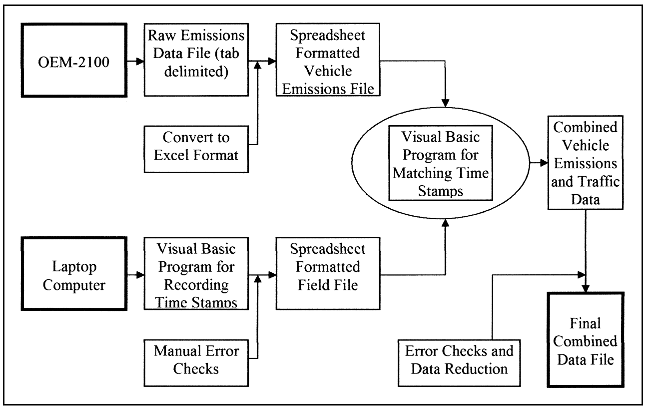

Figure 1. Data collection, data processing, and data screening.

clocks, the laptop battery running out before data collection is complete, or not pressing the timestamp keys at the proper place.

(2) Engine analyzer errors.On occasion, communication between the vehicle's onboard computer and the engine scanner may be lost, such as because of a loose cable, leading to loss of data.

(3) 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 these files were analyzed in detail, they were removed from the database. On average, 90% 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 before each run, and that zeroing has taken place before a data collection run help reduce the frequency of data quality problems.

RESULTS FROM DATA COLLECTION AND ANALYSIS

Data collection and analysis focused on three 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) comparing emissions based on two different drivers.

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 ~14 min. The instantaneous speed ranged from 0 to ~45 mph, and the average speed was 10 mph. The longest waiting times occurred in the queue before the 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 0 to ~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 less than 0.02 g/sec for the first 10 min of the trip, corresponding to a period of stop-and-go travel with speeds ranging from 0 to less than 20 mph. These data suggest that the CO emission rate during idling or crawling is low compared with the CO emission rate during acceleration.

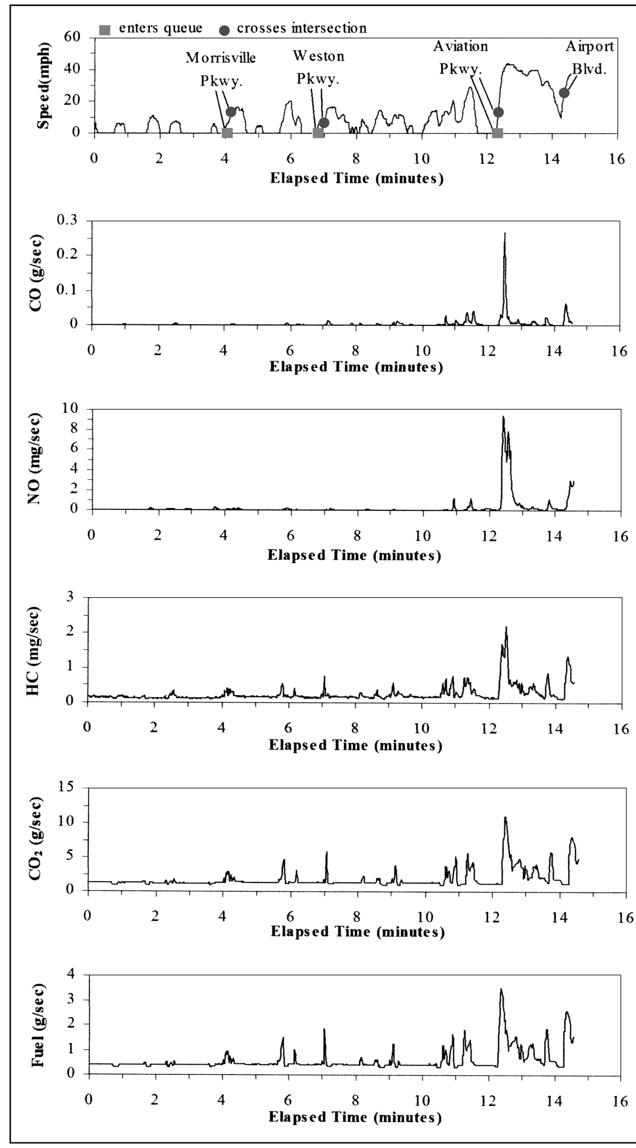

Figure 2. Time traces of vehicle speed, emission rates, and fuel consumption for a 1999 Ford Taurus driven on Chapel Hill Road on August 29, 2000.

The emission rate for NO remains below 0.2 mg/sec for ~85% 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 2 min of the trip, as in the case for CO, HC, and CO_2 emissions.

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 10 min of the trip. Similar to both CO and NO, the HC emission rates are highest during the higher speed portion of the trip, during which there is also 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 with the CO_2 emissions, it is estimated that more than 99.8% of the carbon in the fuel is 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.

Modal Emissions Analysis Results

Analysis of on-road emissions with respect to driving modes, also referred to as modal emissions, has been done in several recent studies.[4,5,7,43] 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 used.[4] 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 be at least 2 mph/sec. However, in some cases, a vehicle may accelerate slowly. Therefore, an acceleration rate averaging at least 1 mph/sec for 3 sec or more is also classified as acceleration. Deceleration is defined in a similar manner as acceleration, except that the criteria for deceleration are based on 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 to calculate the driving mode for each second of data, determine the average value of emissions for each of the driving modes, and calculate total emissions for the trip. To illustrate the types of results obtained from modal analysis of the emissions data, example results are developed based on 141 one-way trips obtained using a 1999 Ford Taurus on Chapel Hill Road between August and October 2000. The vehicle has a 3-L 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 ~2 mg/sec to ~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 intertrip variability. The 95% confidence interval of the mean is 33–55 mg/sec.

As detailed elsewhere, analysis of variance (ANOVA), nonparametric regression, statistical multicomparisons of means, and comparisons of ECDFs were used to help identify possible explanations for the inter-run variability in emission rates.[4] 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 or not 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% confidence intervals of the mean emission rates. For each pollutant, based on 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 the study. Table 1 presents the average modal NO, HC, CO, and CO_2 emission rates and 95% confidence intervals of the averages for 10 vehicles tested on three

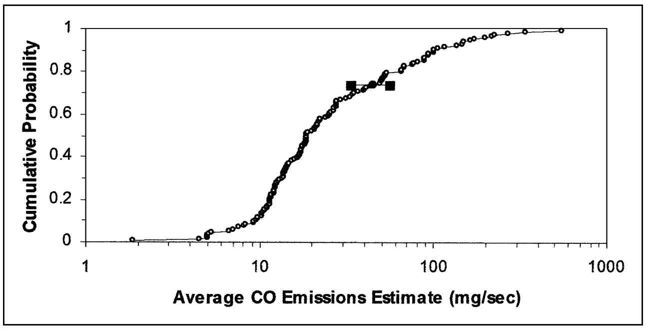

Figure 3. ECDF of CO emission rates in acceleration mode for a 1999 Ford Taurus operated on Chapel Hill Road based on 141 trips.

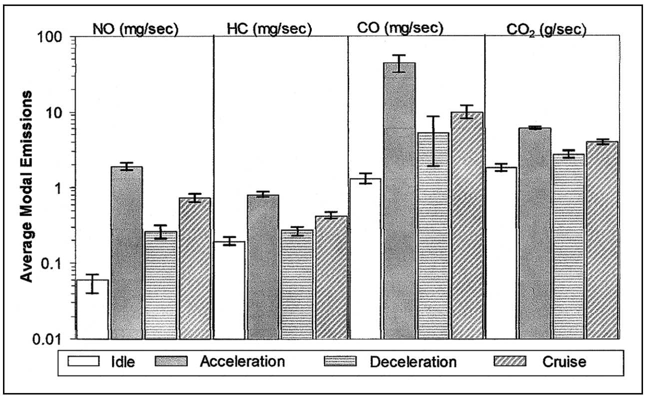

Figure 4. Average modal emission rates for a 1999 Ford Taurus operated on Chapel Hill Road based on 141 trips.

different sites: Chapel Hill Road, Walnut Street, and NC-54. These vehicles are four different 1999 Ford Tauruses, two different 1996 Oldsmobile Cutlasses, a 1998 Chevrolet Venture minivan, a 1998 Toyota Camry, a 1997 Dodge Caravan, and a 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 the 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.

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, four pollutants, and six pairwise comparisons per pollutant), 247 of them, or 94%, are statistically significantly different from each other. It should be noted that of 17 insignificant cases, 15 were for data sets with $\leq$32 data points and 11 of them involved comparisons of deceleration and idle. Because 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 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 5 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 ~30%. These differences could be a combination of intervehicle 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 with 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 sport utility vehicle (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 with the sedans. The latter may be because the SUV did not have as high a frequency of command enrichment as the sedans. Overall, it is clear that there is intervehicle variability in emissions. However, the same or similar vehicle tested on different corridors typically had similar emission rates. Because of the intravehicle variability in emission rates from one run to another, it is important to use a statistical method for making the comparisons.

To evaluate the relative importance of each of the four driving modes, the distribution of average trip time, distance, and emissions is given in Figure 5 based on averages for all eight gasoline vehicles. Approximately similar amounts of time were spent, on average, in each of the idle, acceleration, and decleration modes, with more than 40% of the time spent in cruising. Idling contributes typically 5% or less to fuel consumption and emissions of each of the pollutants. In contrast, acceleration contributes ~35–40% of total average fuel use and emissions, even though it comprises less than 20% of average time and distance traveled. Average emissions during deceleration

Table 1. Summary of modal NO, HC, CO, and CO_2 emission rates based on onboard tailpipe emission measurements of 10 vehicles.

		Ford Taurus 1		Oldsmobile Cutlass 1		Dodge Caravan		Ford Taurus 2		Chevrolet Venture		Oldsmobile Cutlass 2		Toyota Camry		Dodge Caravan		Jeep Cherokee		Ford Taurus 3 (E85 fuel)		Ford Taurus 4 (E85 fuel)	
		Walnut Street		Walnut Street		Walnut Street		Chapel Hill Road		Chapel Hill Road		Chapel Hill Road		Chapel Hill Road		Chapel Hill Road		Chapel Hill Road		NC 54		NC 54	
		Primary driver		Primary driver		Secondary driver		Primary driver		Primary driver		Primary driver		Secondary driver		Secondary driver		Primary driver		Primary driver		Primary driver	
	Driving Mode	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI	μ	95% CI
NO (mg/sec)	Idle	0.06	0.06–0.07	1.1	1–1.2	0.09	0.06–0.11	0.06	0.04–0.07	0.06	0.04–0.07	1.6	1.2–2.1	0.07	0.04–0.1	0.07	0.03–0.12	0.07	0.04–0.09	0.18	0.12–0.24	0.05	0.03–0.07
	Accel.	1.4	1.3–1.6	3.2	3–3.4	6.7	5.9–7.6	1.9	1.7–2.1	1.9	1.7–2.1	3	2.5–3.5	3.8	2.7–4.9	4.6	3–6.3	3.9	2.9–4.9	2.7	2.4–3.2	2.2	1.9–2.6
	Decel.	0.52	0.45–0.58	0.38	0.35–0.4	0.46	0.39–0.53	0.26	0.21–0.31	0.26	0.21–0.31	0.77	0.61–0.92	0.66	0.41–0.91	0.5	0.35–0.65	0.63	0.4–0.86	0.68	0.52–0.86	0.25	0.19–0.32
	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	0.72	0.64–0.81	1.8	1.5–2	2.8	2.1–3.4	2.9	2–3.7	2.8	2.2–3.5	1.4	1.1–1.7	1.1	0.91–1.2
HC (mg/sec)	Idle	0.25	0.22–0.27	0.42	0.4–0.43	0.36	0.3–0.42	0.19	0.17–0.22	0.19	0.17–0.22	0.5	0.46–0.54	0.48	0.44–0.53	0.49	0.42–0.55	0.49	0.45–0.53	0.16	0.12–0.2	0.11	0.08–0.14
	Accel.	1	0.94–1.1	1.8	1.8–1.9	2	1.8–2.3	0.8	0.74–0.86	0.8	0.74–0.86	2	1.8–2.3	2	1.7–2.2	2	1.7–2.3	2	1.8–2.3	0.75	0.63–0.9	0.77	0.61–0.95
	Decel.	0.36	0.33–0.4	0.44	0.42–0.46	0.38	0.33–0.43	0.27	0.23–0.3	0.27	0.23–0.3	0.61	0.5–0.72	0.63	0.5–0.76	0.81	0.56–1.1	0.62	0.5–0.73	0.21	0.16–0.26	0.15	0.11–0.19
	Cruise	0.6	0.55–0.65	0.96	0.92–1	1	0.9–1.1	0.42	0.38–0.46	0.42	0.38–0.46	1.2	1.1–1.4	1.2	1–1.4	1.3	1–1.6	1.2	1–1.4	0.37	0.31–0.45	0.34	0.28–0.41
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	1.3	1.1–1.5	0.66	0.43–0.9	1.5	0.98–2.1	0.79	0.36–1.2	1.5	1–2	0.87	0.69–1.1	0.45	0.23–0.68
	Accel.	23	19–26	19	16–22	11	8.9–13	44	33–55	44	33–55	34	16–51	31	14–48	10	6.1–15	13	9.3–16	33	13–55	40	25–55
	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	5.2	1.9–8.5	4.6	2.9–6.2	6.4	4.9–7.8	2.2	1.3–3.1	4	2.7–5.3	2	1.3–2.8	2.3	1.7–3
	Cruise	11	9–13	14	13–15	4.5	3.9–5.1	9.8	8–12	9.8	8–12	14	8.3–19	12	9.4–14	4.8	3.7–6	7.1	4–10	7.4	5.1–10	12	9.8–15
CO_2 (g/sec)	Idle	1.7	1.6–1.8	1.1	1.1–1.2	1	0.99–1	1.8	1.6–2	1.8	1.6–2	1.3	1.2–1.3	1.2	1.2–1.3	1.2	1.1–1.2	1.3	1.2–1.3	1.6	1.3–1.9	1.5	1.3–1.7
	Accel.	6.4	6.2–6.6	5.4	5.3–5.5	6.5	6.2–6.7	6	5.7–6.3	6	5.7–6.3	6.1	5.5–6.7	6	5.4–6.7	5.8	5–6.6	6.2	5.6–6.8	6.5	6.1–7.1	6.4	6.3–6.8
	Decel.	2.6	2.4–2.8	1.2	1.1–1.2	1.3	1.2–1.3	2.7	2.4–3	2.7	2.4–3	1.4	1.4–1.5	1.4	1.3–1.5	1.3	1.2–1.3	1.4	1.3–1.5	2.6	2.1–3.2	1.9	1.7–2.2
	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	3.9	3.6–4.2	3.3	3–3.6	3.2	2.8–3.6	2.9	2.6–3.2	3.3	2.9–3.6	4.1	3.6–4.8	3.6	3.4–3.9

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

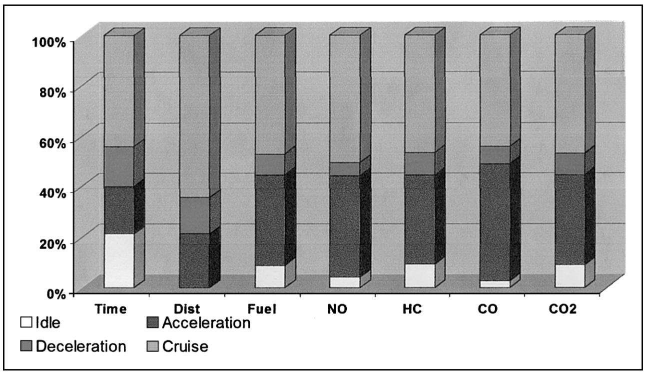

Figure 5. Average distribution of idle, acceleration, deceleration, and cruise modes with respect to travel time, distance traveled, fuel use, and emissions for eight vehicles operated on selected signalized primary arterials.

are typically less than 10% of the total even though deceleration contributes ~15% to the average time and distance traveled. The implication is that for operation of newer vehicles on signalized primary arterials, cruise and acceleration modes contribute substantially to total emissions and the idle and deceleration modes are minor components.

Comparison of Two Drivers

Differences in driving behavior are often hypothesized to produce differences in emissions.[14,43–47] To illustrate a method for comparing two different drivers, a data set based on 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% confidence interval for the mean value of the distribution is also shown.

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. Therefore, although it is widely assumed that each individual will produce different emissions for the same vehicle and roadways because of differences in behavior, it is also possible to find drivers who have similar driving behavior and emissions. Furthermore, these results indicate that it is reasonable to combine data collected from Drivers 1 and 2 into a single database, thereby increasing sample size.

CONCLUSIONS

This paper documents key aspects of the data collection, screening, and analysis protocols associated with deployment of a portable onboard tailpipe emissions measurement system. Experience gained during fieldwork and data processing leads 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 (>90%) of measurement attempts resulted in valid vehicle activity and emissions files.

Onboard emissions measurement can be used to support a variety of study objectives. A key objective of this work was to gain insight into the intravehicle variability in emissions obtained from repeated runs with the same combinations of drivers and routes. Knowledge of intravehicle 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 onboard 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 5 greater than the idle emission rate for HC and CO_2 and a factor of 10 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 intravehicle variability in emissions.

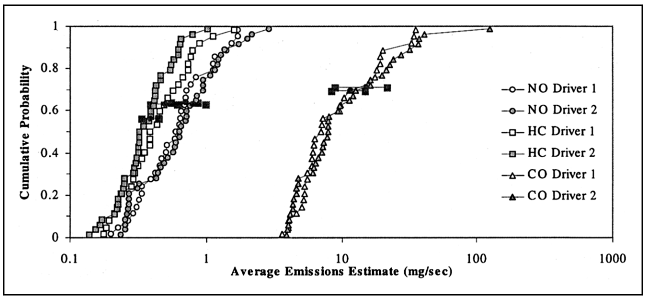

Figure 6. ECDF for average pollutant emissions rates for two different drivers operating 1999 Ford Taurus on Chapel Hill Road during August and September 2000 (n = 31 for Driver 1 and n = 41 for Driver 2).

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

Other study objectives will motivate different combinations and numbers of vehicles, drivers, routes, and schedules than used in this study. For example, the focus here was not on development of area-wide emission factors, which would require measurements with a larger set of vehicles, a larger range of roadway functional classes, and a smaller number of repetitions. Cold starts can be measured as needed. In addition to the challenges already discussed regarding the observational nature of onboard measurements, onboard emissions measurements have some limitations, such as (1) only tailpipe emissions are addressed; (2) NDIR does not measure total HC; 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, including a capability to assess the accuracy of second-by-second and not just total trip emissions or the use of other methods, such as FID. Many vendors already have developed capabilities to measure particulate matter (PM) emissions, with particular focus on diesel vehicles. Sensor arrays for measuring or estimating exhaust flow for non-OBD vehicles are available, including for nonroad vehicles.

This study has been successful in establishing data collection, screening, processing, and analysis protocols, and in providing key insights regarding how to quantify intravehicle variability in emissions. This work demonstrates the feasibility of using onboard emissions measurements to develop useful insights regarding the episodic nature of vehicle emissions, on-road emissions hotspots, intravehicle variability in emissions, and intervehicle variability in emissions. A statistical analysis of factors contributing to the observed variability in emissions is underway and will be reported separately. Onboard emissions measurement is recommended as an important method for collecting real-world, representative activity and emissions data to improve the accuracy and applicability of emissions estimation methods at the microscale as well as for higher levels of temporal and spatial aggregation.

DISCLAIMER

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REFERENCES

1. *National Air Quality and Emissions Trends Report*; EPA 454/K-01–004; U.S. Environmental Protection Agency: Research Triangle Park, NC, 2001.
2. National Research Council. *Modeling Mobile-Source Emissions;* National Academy Press: Washington, DC, 2000.
3. Kini, M.D.; Frey, H.C. *Probabilistic Modeling of Exhaust Emissions from Light Duty Gasoline Vehicles*; Prepared by North Carolina State University for the Center for Transportation and the Environment, North Carolina State University: Raleigh, NC, December 1997.
4. Frey, H.C.; Rouphail, N.M.; Unal, A; Colyar, J.D. *Emission Reductions through Better Traffic Management: An Empirical Evaluation Based on On-Road Measurements*; FHWY/NC/2002–001; Prepared by Department of Civil Engineering, North Carolina State University for North Carolina Department of Transportation: Raleigh, NC, December 2001
5. Frey, H.C.; Unal, A.; Chen, J. *Recommended Strategy for On-Board Emission Data Analysis and Collection for the New-Generation Model*; Prepared by Department of Civil Engineering, North Carolina State University for Office of Transportation and Air Quality, U.S. Environmental Protection Agency: Raleigh, NC, January 2002.
6. *EPA's Onboard Analysis Shootout: Overview and Results*; EPA420-R-02–026; Office of Transportation and Air Quality, U.S. Environmental Protection Agency: Ann Arbor, MI, 2002.
7. Frey, H.C.; Unal, A.; Chen, J.; Li, S.; Xuan, C. *Methodology for Developing Modal Emission Rates for EPA's Multi-Scale Motor Vehicle and Equipment Emission System*; EPA420-R-02–033; Prepared by North Carolina State University for Office of Transportation and Air Quality, U.S. Environmental Protection Agency: Ann Arbor, MI, 2002.
8. *Draft Design and Implementation Plan for EPA's Multi-Scale Motor Vehicle and Equipment Emission System (MOVES)*; EPA420-P-02–006; Office of Transportation and Air Quality, U.S. Environmental Protection Agency: Ann Arbor, MI, 2002.
9. Transportation Research Board. *Expanding Metropolitan Highways: Implications for Air Quality and Energy Use*; Special Report 245; National Research Council: Washington, DC, 1995.
10. *Federal Test Procedure Review Project: Preliminary Technical Report,*; Report No. EPA/420/R-93–007; U.S. Environmental Protection Agency: Washington, DC, 1993; pp 16-20.
11. Barth, M.; Norbeck, J.; Ross, M.; Wenzel, T.; Younglove, T.; Scora, G. *Phase 2 Interim Report for NCHRP 25–11 Development of a Modal Emissions Model*; Prepared by University of California, Riverside, University of Michigan, and Ford Motor Co. for Transportation Research Board: Riverside, CA, 1997.
12. Bachman, W.H. *A GIS-Based Modal Model of Automobile Exhaust Emissions Final Report*; Prepared by Georgia Institute of Technology for U.S. Environmental Protection Agency: Atlanta, GA, 1999.
13. Kelly, N.A.; Groblicki, P.J. Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles; *J. Air & Waste Manage. Assoc.* **1993**, *43*, 1351-1357.
14. St. Denis, M.J.; Cicero-Fernandez, P.; Winer, A.M.; Butler, J.W.; Jesion, G. Effects of In-Use Driving Conditions and Vehicle/Engine Operating

Parameters on "Off-Cycle" Events: Comparison with Federal Test Procedure Conditions; *J. Air & Waste Manage. Assoc.* **1994**, *44*, 31-38.
15. Barth, M.; An, F.; Norbeck, J.; Ross, M. Modal Emissions Modeling: A Physical Approach; *Transportation Res. Record* **1996,** *1520*, 81-88.
16. Bishop, G.A.; Starkey, J.R.; Ihlenfeldt, A. IR Long-Path Photometry: A Remote Sensing Tool for Automobile Emissions; *Analyt. Chem.* **1998,** *61A* (10), 671-677.
17. Stedman, D.H. Automobile Carbon Monoxide Emissions; *Environ. Sci. Technol.* **1989**, *23*, 147-149.
18. Stephens, R.D.; Cadle, S.H. Remote Sensing Measurements of Carbon Monoxide Emissions from On-Road Vehicles; *J. Air & Waste Manage. Assoc.* **1991,** *41*, 39-46.
19. Rouphail, N.M.; Frey, H.C.; Unal, A.; Dalton, R. *ITS Integration of Real-Time Emissions and Traffic Management Systems*; IDEA Project No. ITS-44; Prepared by North Carolina State University for the IDEA Program, Transportation Research Board, National Research Council: Washington, DC, May 2000.
20. Frey, H.C.; Eichenberger, D.A. *Remote Sensing of Mobile Source Air Pollutant Emissions: Variability and Uncertainty in On-Road Emissions Estimates of Carbon Monoxide and Hydrocarbons for School and Transit Buses*; Report No. FHWY/NC/97–005; Prepared by North Carolina State University for the North Carolina Department of Transportation: Raleigh, NC, 1997.
21. Bishop, G.A.; McLaren, S.E.; Stedman, D.H. Method Comparisons of Vehicle Emissions Measurements in the Fort McHenry and Tuscarora Mountain Tunnels; *Atmos. Environ.* **1996**, *30* (12), 2307-2316.
22. Staab, J.; Schuermann, D. Measurement of Automobile Exhaust Emissions under Realistic Road Conditions; *J. Soc. Auto. Eng.* **1988**, *SAE 871986*, 5.636-5.642.
23. De Vlieger, I. On-Board Emission and Fuel Consumption Measurement Campaign on Petrol-Driven Passenger Cars; *Atmos. Environ.* **1997**, *31* (22), 3753-3761.
24. Cicero-Fernandez, P.; Long, J.R. Effects of Grades and Other Loads on On-Road Emissions of Hydrocarbons and Carbon Monoxide; *J. Air & Waste Manage. Assoc.* **1997**, *47*, 898-904.
25. Gierczak, C.A.; Jesion, G.; Piatak, J.W.; Butler, J.W. On-Board Vehicle Emissions Measurement Program. In *Proceedings of the 11th CRC Conference*, San Diego, CA; Coordinating Research Council: Atlanta, GA, 2001.
26. Tong, H.Y.; Hung, W.T.; Cheung, C.S. On-Road Motor Vehicle Emissions and Fuel Consumption in Urban Driving Conditions; *J. Air & Waste Manage. Assoc.* **2000**, *50*, 543-554.
27. Rouphail, N.M.; Frey, H.C.; Colyar, J.D.; Unal, A. Vehicle Emissions and Traffic Measures: Exploratory Analysis of Field Observations at Signalized Arterials. In *Proceedings of the Annual Meeting of the Transportation Research Board*, Washington, DC, January 2001.
28. Unal, A.; Rouphail, N.M.; Frey, H.C. Effect of Arterial Signalization and Level of Service on Measured Vehicle Emissions. In *Proceedings, 82nd Annual Meeting of the Transportation Research Board*, Washington, DC, January 12–16, 2003; Paper No. 03–2884.
29. Frey, H.C.; Rouphail, N.M.; Unal, A.; Colyar, J.D. Measurement of On-Road Tailpipe CO, NO, and Hydrocarbon Emissions Using a Portable Instrument. In *Proceedings of the 94th Annual Conference & Exhibition of A&WMA, Orlando, FL, June 2001*; A&WMA: Pittsburgh, PA, 2001.
30. LeBlanc, D.C.; Meyer, M.D.; Saunders, F.M.; Mulholland, J.A. Carbon Monoxide Emissions from Road Driving: Evidence of Emissions Due to Power Enrichment; *Trans. Res. Rec.* **1994**, *1444*, 126-134.
31. West, B.H.; McGill, R.N.; Hodgson, J.W.; Sluder, C.S.; Smith, D.E. Development of Data-Based Light-Duty Modal Emissions and Fuel Consumption Models; *J. Soc. Auto. Eng.* **1997**, *2910*, 1274-1280.
32. Guenther, P.L.; Stedman, D.H.; Lesko, J.M. Prediction of IM240 Mass Emissions Using Portable Exhaust Analyzers; *J. Air & Waste Manage. Assoc.* **1996**, *46*, 343-348.
33. Vojtisek-Lom, M.; Cobb, J.T. Vehicle Mass Emissions Measurement Using a Portable 5-Gas Exhaust Analyzer and Engine Computer Data. In *Proceedings of Emission Inventory: Planning for the Future Conference*; A&WMA: Pittsburgh, PA, 1997; pp 656-669.
34. Scarbro, C. An Investigation of Rover's Capabilities to Accurately Measure the In-Use Activity and Emissions of Late-Model Diesel and Gasoline Trucks. In *Proceedings of the 10th CRC On-Road Vehicle Emissions Workshop*, San Diego, CA; Coordinating Research Council: Atlanta, GA, 2000.
35. Wilson, R. On-Road, In-Use Emissions Test Systems. Presented at Mobile Sources Technical Review Subcommittee, Alexandria, VA, February 2002.
36. Butler, J.W. Dynamometer Quality Data On-Board Vehicles for Real-World Emissions Measurements. In *Proceedings of the 9th CRC On-Road Vehicle Emissions Workshop*, San Diego, CA; Coordinating Research Council: Atlanta, GA, 1999.
37. Oestergaard, K. The Horiba Approach to On-Board Measurement. Presented at Mobile Sources Technical Review Subcommittee, Alexandria, VA, February 2002.
38. Nam, E. In *Proceedings of the 12th CRC On-Road Vehicle Emissions Workshop*, San Diego, CA; Coordinating Research Council: Atlanta, GA, 2002.
39. Vojtisek-Lom, M. Clean Air Technologies International, Inc., Buffalo, NY. Personal communication, January 2001.
40. Singer, B.C.; Harley, D.A.; Littlejohn, D.; Ho, J.; Vo, T. Scaling of Infrared Remote Sensor Hydrocarbon Measurements for Motor Vehicle Emission Inventory Calculations; *Environ. Sci. Technol.* **1998**, *32* (21), 3241-3248.
41. Stephens, R.D.; Mulawa, P.A.; Giles, M.T.; Kennedy, K.G.; Groblicki, P.J.; Cadle, S.H. An Experimental Evaluation of Remote Sensing-Based HC Measurement: A Comparison to FID Measurements; *J. Air & Waste Manage. Assoc.* **1996**, *46*, 148-158.
42. Stephens, R.D.; Cadle, S.H.; Qian, T.Z. Analysis of Remote Sensing Errors of Commission and Omission under FTP Conditions; *J. Air & Waste Manage. Assoc.* **1996**, *46*, 510-516.
43. Cernuschi, S.; Giugliano, M.; Cemin, A.; Giovannini, I. Modal Analysis of Vehicle Emission Factors; *Sci. Total Environ.* **1995**, *169*, 175-183.
44. Shih, R.; Fable, S.; Sawyer, R.S. Effects of Driving Behavior on Automotive Emissions. In *Proceedings of the 7th CRC On-Road Vehicle Emissions Workshop*, San Diego, CA; Coordinating Research Council: Atlanta, GA, 1997.
45. LeBlanc, D.C.; Saunders, F.M.; Meyer, M.D.; Guensler, R. Driving Pattern Variability and Impacts on Vehicle Carbon Monoxide Emissions; *Trans. Res. Rec.* **1995**, *1472*, 45-52.
46. Holmen, B.A.; Niemeier, D.A. Characterizing the Effect of Driver Variability on Real-World Vehicle Emissions; *Trans. Res. Rec. Part D* **1998**, *3* (2), 117-128.
47. Ericsson, E. Independent Driving Pattern Factors and their Influence on Fuel-Use and Exhaust Emission Factors; *Trans. Res. Rec. Part D* **2001**, *6*, 325-345.

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