

Emission Model Development Using In-vehicle On-Road Emission Measurements

Hesham Rakha
(Corresponding Author)
Civil and Environmental Engineering Department
Virginia Tech
Blacksburg, VA 24060
hrakha@vt.edu
(540) 231-1505
Fax: (540) 231-1555

Kyoungho Ahn
Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg, VA 24060
kahn@vt.edu
(540) 231-1573
Fax: (540) 231-1555

Ihab El-Shawarby
Ain-Shams University, Cairo, Egypt
Virginia Tech Transportation Institute
3500 Transportation Research Plaza
Blacksburg, VA 24060
shawarby@vtti.vt.edu
(540) 231-1577
Fax: (540) 231-1555

Sebong Jang
Urban and Cadastral Engineering Department
YoungDong University
Korea
sbjang@youngdong.ac.kr

Total word count: $5,332 + 3,000 = 8,632$

ABSTRACT

On-road Emission Measurement (OEM) is emerging as a viable alternative for collecting emission data in the field. This paper describes how OEM data can be utilized to develop emission models that are suitable for estimating instantaneous mobile source emissions. Specifically, the research utilizes the OEM-2100TM, manufactured by Clean Air Technologies International, Inc., to collect vehicle-engine and emission data and utilize these data to develop microscopic emission models. The paper demonstrates that, on average, the models that were developed estimate vehicle emissions of Hydrocarbons (HC), Carbon Monoxide (CO), and Oxides of Nitrogen (NO_x) to within 15 percent of field-measured emissions.

INTRODUCTION

Since the 1990 Clean Air Act Amendments (CAAA), the public and private sectors' interests in air quality have increased significantly. Specifically, according to the 1990 CAAA, non-attainment areas should submit emission estimates for all proposed traffic-improvement projects. In response to this need, the Environmental Protection Agency's (EPA) MOBILE model and the California Air Resources Board's (CARB) EMFAC model have been approved by the US government for mobile source emission estimation. However, the MOBILE and EMFAC models were not designed for the evaluation of operational-level transportation projects, such as traffic-signal coordination and/or ramp-metering alternatives. Consequently, a need exists to develop models for such applications.

On-road Emission Measurement (OEM) is a new technology that collects vehicle emissions using a portable instrument. The on-road emission-measurement method is considered a desirable approach for quantifying emissions from test vehicles because of its ability to collect emissions during real driving conditions; in contrast, dynamometer testing is typically utilized to check new vehicles and to inspect in-use vehicles for compliance with emissions standards.

This paper presents a framework for developing emission models using an OEM system (Clean Air Technologies International 2000). These models are suitable for evaluating the environmental impacts of operational-level transportation projects prior to the field implementation of the project.

Research Objectives and Approach

The objectives of this study are three-fold. First, the paper develops a framework for modeling vehicle emissions using on-board emission-measurement data. Second, the paper demonstrates the feasibility of the framework using a single test vehicle. Finally, the model is validated through comparisons against independently collected field data from the on-road emission-measurement system and current state-of-the-practice emission models.

Significance of Research

This paper presents the complete emission-modeling process, including data collection using portable on-road emission data, model development, and model validation. Moreover, the paper demonstrates the applicability of on-road emission-measurement data. The use of on-road emission measurements offers numerous benefits given the large cost savings that are associated with on-road testing in comparison to chassis-dynamometer testing.

Paper Layout

This paper is organized into six sections. The following section illustrates and describes the OEM unit that was utilized in the study. The third section describes the data-collection procedures and data sources that were used to develop the proposed modeling approach. The fourth section describes the model-development procedures and modeling results. The fifth section presents the model-validation results against independently collected field data and against state-of-the-art emission model estimates. Finally, the conclusions of the research and recommendations for future work are presented.

ON-BOARD EMISSION MEASUREMENT UNIT

A portable On-Road Emission Measurement unit, OEM-2100™, manufactured by Clean Air Technologies International, Inc. was utilized for data collection in this study. The OEM unit is designed to collect on-road emission data during actual driving on the road. This section provides a brief overview of the OEM unit.

Overview of the OEM Unit

The OEM unit is designed to measure vehicle mass exhaust emissions using vehicle and engine operational data and concentrations of pollutants in exhaust gas sampled from the tailpipe during actual on-road driving conditions. The unit is comprised of two five-gas analyzers, an engine diagnostic scanner, and an on-board computer that provides second-by-second emissions, fuel consumption, vehicle speed, engine rpm and temperature, throttle position, and other parameters. The unit is designed to connect with the On-Board Diagnostics (OBD) link of the vehicle, from which real-time engine and vehicle operational data may be obtained while the vehicle is in operation. Most of the 1996-year and later models are equipped with an OBD link that is located under the dashboard on the driver's side.

The OEM unit can measure the concentrations of HC, CO, CO₂, NO_x, and O₂ in the vehicle exhaust gas by a functional equivalent of a five-gas analyzer. The vehicle exhaust gas is collected from the tailpipe using a repair-grade probe and sample line. Simultaneously, OBD data, such as vehicle speed, engine rpm, intake air mass flow, coolant temperature, and other engine-operating parameters, are gathered. Using the intake air mass flow (or composition of intake air), measured composition of exhaust gas, and user-specified composition of fuel, a second-by-second exhaust mass flow is calculated from the on-board computer. Multiplying the exhaust mass flow by the concentrations of pollutants generates second-by-second emission data in grams (Frey et al. 2001; Vojtisek-Lom and Allsop 2001).

The use of two gas analyzers allows the unit to provide an average emission estimate based on two independent measurements. Since the analyzers require a zeroing procedure every 10 minutes, the use of two gas analyzers allows the unit to collect data continuously, even when one of the gas analyzers is zeroing (not collecting data), as will be discussed later in more detail.

OEM Unit Installation

The unit typically sits in the passenger seat or on the floor of a vehicle facing the driver. An exhaust sample line from the tailpipe is routed through a window and connected to the unit. In general, the exhaust sample line is attached to the vehicle body using clamps or removable duct tape to prevent separation.

In order to use the OEM, the minimum operating temperature must be 10°C inside the unit. The minimum outside temperature must be at least 3.89°C to prevent condensation inside the sample system, which can restrict or block the air flow. The unit is connected to the vehicle power using a power outlet or a cigarette-lighter outlet.

Once the unit is installed, the system can be powered-up using three switches: the computer, the scanner, and the analyzer. After the analyzer's power is turned on, the analyzer performs an automatic warm-up sequence. The warm-up period primarily depends on the temperature of the instrument. Typically, it takes less time in warm weather or when the unit was only recently turned off. However, if the temperature is very low (less than 0°C), the analyzer cannot be initialized.

ON-ROAD EMISSION MEASUREMENTS

Once the system is installed and powered-up, the OEM unit collects emission data automatically. The OEM unit saves emission data as “second-by-second” and “bag” data. The unit monitors emissions continuously for an unlimited amount of time and is only interrupted by the zeroing procedure every 10 minutes. The zeroing ensures that the analyzer does not drift with time by allowing the gas analyzer to set ambient air readings as “zero” level responses, assuming that the ambient air is free of pollutants. The zeroing procedure takes 40 to 120 seconds, depending on the pollutant levels and the stability of the instrument. The unit includes two gas analyzers so that the system can continue to operate using one of the gas analyzers while the second analyzer is being initialized. The automatic zeroing procedures for the two analyzers are staggered at intervals of 5 minutes, with each analyzer initialized at 10-minute intervals; the first analyzer is initialized 10 minutes after power-up, and the second analyzer is initialized 15 minutes after power-up. However, if the analyzer temperature has changed or an irregular event has occurred, the zeroing procedures take place earlier. Once the unit is powered-up, it takes at least 10 minutes for the system to warm up and stabilize. Therefore, the sample line should be connected to the unit after the 10-minute warm-up procedure.

Data-Collection Procedures

This section describes the data-collection procedures that were employed to develop the microscopic emission models. The vehicle, drivers, and test-route selections were considered for the design of an on-road data-collection procedure. Data were collected between March and April 2002. The minimum test temperature was 5°C and the maximum was 26°C. However, most of the tests were performed at ambient temperatures ranging between 12.8°C (55°F) and 23.9°C (75°F).

A 1999 Ford Crown Victoria was selected for modeling purposes because it was available at the time of the study. It should be noted, however, that the procedures that are described in the paper are general and independent of the type of vehicle. Detailed information about the test vehicle is provided in Table 1.

Driver behavior affects vehicle emissions significantly. Generally, aggressive driving behavior produces more vehicle emissions than normal driving behavior. However, since the proposed emission model utilizes second-by-second vehicle speed and acceleration observations as input variables, driver aggressiveness is accounted for in the modeling procedures and results.

Emission data were collected on a restricted test road and on a local highway section. High-speed data collections with a wide range of speed and acceleration observations were conducted on a restricted test road, while various constant-speed runs were tested on a public highway section. The restricted test road, the Virginia Smart Road, is a 1.5 km experimental test facility located at the Virginia Tech Transportation Institute in Southwest Virginia. The horizontal layout of the test section is fairly straight, with some minor curvature that does not impact vehicle speeds, while the vertical layout demonstrates a substantial upgrade, ranging from 6 percent at the departing point to 2.8 percent at the end. The test road is not accessible to public vehicles.

On the test road, the vehicle was tested for mild, normal, and aggressive acceleration behaviors to investigate a wide range of speed and acceleration impacts for vehicle emissions. It should be noted that the effect of upgrades was normalized by adding the component of gravitational acceleration to acceleration field measurements.

Emission data were also collected along a 5.9-km section of Route 460 in Southwest Virginia, from the Tom's Creek Road exit to the North Main Street exit in Blacksburg, Virginia. This roadway facility is designed with high geometric standards and is fairly flat; thus, no adjustments in vehicle accelerations for grade effects were required. Also, because the traffic volume was low on the roadway, the test vehicle collected emission data with minor traffic interruptions.

Experimental Design of Data Collection

Once the OEM unit is operational, the monitor displays the vehicle operational variables and emission data on a second-by-second basis. Each data-collection run of the OEM unit is also summarized as a tab-delimited formatted text file. The first section of the emission output file displays general test information such as the test date, time, vehicle characteristics, driver information, weather conditions, and test-site data. The second section displays a summary of each bag data. The bag data fields include bag number, distance traveled, bag duration, total exhaust flow, fuel consumption, and HC, CO, NO_x, CO₂ emissions (g/mi and grams). Following the bag data, second-by-second emission data is displayed in the output file. Each record displays a time stamp, bag number, vehicle speed, acceleration, engine speed, throttle percent, fuel consumption, and HC, CO, NO_x, and CO₂ emissions.

As mentioned earlier, data were collected at the restricted Virginia Tech Smart Road test facility and on US Route 460. Aggressive, normal, and mild acceleration tests were performed on the Smart Road to gather extreme-acceleration data. Specifically, the test vehicle accelerated from a complete stop and continued to accelerate for the duration of the test drive. All acceleration (aggressive, normal, mild) tests were repeated ten times in order to obtain multiple repetitions for various engine loads. The data were recorded as bag data and as second-by-second data. As was mentioned earlier, the vehicle acceleration levels were normalized to account for grade effects.

In addition to the acceleration test drives, data were gathered for different cruise test runs that included cruising at speeds of 72, 88, and 104 km/h (45, 55, and 65 mi/h). As was the case with the acceleration test runs, each constant-speed test run was repeated ten times in order to capture any potential variability within the data.

Figure 1 summarizes the speed/acceleration frequency distribution for the field data that were gathered. The figure demonstrates that the majority of data cover the constant speed and mild acceleration range (0 to 1.4 m/s²); however, the data also cover a wide range of speed and acceleration levels: with a maximum speed of 129 km/h and a maximum acceleration of 3.6 m/s². The figure clearly demonstrates coverage of the speed/acceleration envelope of the test vehicle with some occasional holes in the data. The use of a controlled test facility enables the collection of data at the boundary of the speed/acceleration envelope of the vehicle, which is critical in developing models that are reflective of the entire operation envelope of a vehicle.

In summary, the framework proposes the following runs in gathering in-field emission data:

- a. Gathering data for 10 repetitions of three levels of acceleration (mild, normal, aggressive).
- b. Gathering data for 10 repetitions at three cruising speeds (72, 88, and 104 km/h).

DEVELOPMENT OF MICROSCOPIC VEHICLE EMISSION MODEL

This section describes the framework for developing instantaneous vehicle-emission models using on-road second-by-second OEM measurements. The proposed approach utilizes instantaneous vehicle speed and acceleration levels as vehicle-specific input variables.

Data Normalization

The OEM data included approximately 18,683 records. Each record included the time stamp of the record, the bag number, the instantaneous speed and acceleration levels, the engine speed (revolutions per minute), amount of in-take air, total exhaust flow, second-by-second fuel consumption and emissions (HC, CO, CO₂, and NO_x), and other engine-related data.

The first step was to temporally offset the emission data in order to reflect the time lag between vehicle emissions and speed observations. This time lag typically ranges between 5 and 15 seconds, depending on the data-collection procedure. The accurate estimation of the time lag is important because it ensures that the independent-variable values are associated with their corresponding instantaneous vehicle-emission rates.

Secondly, the OEM data were aggregated and averaged within a speed and acceleration bin in order to reduce the noise in the data. The speed bins ranged from 0 to 129 km/h at increments of 1 km/h, while the acceleration bins ranged from -13 to +13 km/h/s at increments of 1 km/h/s.

Development of Vehicle Emission Model

The proposed emission model is a nonlinear regression model that utilizes a multi-dimensional polynomial model structure that is described in great detail in the literature (Ahn et al. 2002; Rakha et al. 2000). This multiple regression model (VT-Micro model) relates the dependent variables (instantaneous emission estimates) to a set of quantitative independent variables, namely, instantaneous speed and acceleration levels. The regression model includes a combination of linear, quadratic, and cubic speed and acceleration terms. While a more detailed description of the derivation of the model is provided in the literature (Ahn et al. 2002), it is sufficient to note at this point that the structure of the model involves a logarithmic transformation of a dual-regime third-order polynomial, as summarized in Equation 1:

$$MOE_e = \begin{cases} \exp\left(\sum_{i=0}^3 \sum_{j=0}^3 (L_{i,j}^e \times u^i \times a^j)\right) & \text{for } a \geq 0 \\ \exp\left(\sum_{i=0}^3 \sum_{j=0}^3 (M_{i,j}^e \times u^i \times a^j)\right) & \text{for } a < 0 \end{cases} \quad [1]$$

Where:

- MOE_e = instantaneous fuel consumption or emission rate (l/s or mg/s),
- $L_{i,j}^e$ = Model regression coefficient for MOE “e” at speed power “i” and acceleration power “j” for positive accelerations,
- $M_{i,j}^e$ = Model regression coefficient for MOE “e” at speed power “i” and acceleration power “j” for negative accelerations,
- u = Instantaneous speed (km/h), and
- a = Instantaneous acceleration (km/h/s).

The logarithmic transformation of the emission measurements ensures non-negative model predictions and accurate model predictions in the low-speed and low-acceleration range, with their associated low-emission rates. Furthermore, the use of a dual-regime model ensures a better fit to the data over the full range of the vehicle-operation envelope. Specifically, the use of a separate regime for the deceleration mode of operation allows the model to capture the higher vehicle-emission rates at higher vehicle speeds during a vehicle-deceleration maneuver. A common problem with multi-regime models is the function’s discontinuity at the regime boundaries. In an attempt to overcome this potential problem, the emission data for the deceleration regime was shifted by the value of the y-intercept for the acceleration regime in order to ensure that both intercepts were equal. It should be noted that the models were confined to speed and acceleration levels within the envelope of the OEM data. This limitation resulted from the inherent limitation of any model to extrapolate response values beyond the boundaries used in developing the model. While vehicles may travel faster than 129 km/h (80 mi/h), it is highly unlikely to observe speeds outside this range within typical in-field driving. Consequently, the envelope of data coverage appears to cover the full range of typical vehicle operation. However, in cases in which speed/acceleration data fall outside the model envelope (illustrated in Figure 2), the authors recommend

using boundary speed and acceleration levels in order to ensure realistic vehicle measure of effectiveness (MOE) estimates.

Figure 3 demonstrates field measurements super-imposed on the model prediction lines. The figure demonstrates a reasonable fit between the model and the field data. Specifically, the prediction lines accurately follow the solid lines for the -3 , 3 , and 6 km/h/s (-0.83 , 0.83 , and 1.67 m/s²) data; however, the model appears to underestimate the emissions at an acceleration of 0 m/s², particularly for NO_x and CO₂ emissions. However, even though the predicted line cannot follow the raw data points exactly, the model generally estimates the trend in the emissions successfully. It should be noted that each raw data point in Figure 3 represents an average value of all emission measurements within a speed/acceleration bin. Sample coefficients for the HC model is provided in Table 2.

MODEL VALIDATION

This section presents some validation efforts of the vehicle-specific model against instantaneous second-by-second independent field measurements. The model predictions are also compared against state-of-the-art models such as EPA's MOBILE5a and MOBILE6 models, the CMEM model, the EMIT model, and the VT-Micro model. The comparison against the VT-Micro model category LDV5 serves a number of purposes. First, it compares the use of a vehicle-specific model against the use of a composite vehicle model. Second, it validates the VT-Micro framework for a specific vehicle and composite vehicle. Third, it provides an equitable comparison against the different models.

MOBILE6 Model Description

MOBILE5a and MOBILE6 models were developed by the EPA Office of Transportation and Air Quality (OTAQ). MOBILE6 is the latest of the MOBILE models, and thus is described in further detail. The MOBILE6 is significantly different from MOBILE5a. Specifically, MOBILE6 was developed using recent vehicle-emission testing data collected by the EPA, CARB, automobile manufacturers, as well as inspection and maintenance tests conducted in various states. A major characteristic of the MOBILE6 model is the addition of so-called off-cycle emissions, which involve aggressive driving with various facility-type modeling. MOBILE6 estimates emission factors based on different roadway types (e.g., highways, arterials, locals). Emission factors can be adjusted for different facility types and different average speeds based on vehicle testing over a series of facility cycles. Also, MOBILE6 estimates emission factors for the start portion and the running portion of the trip separately.

In order to utilize the MOBILE models in this study, input files were carefully coded to reflect the field conditions that were analyzed. Since the OEM measurements did not include cold-start effects and evaporative emissions, only exhaust running emissions of Light-Duty Gasoline Vehicles (LDGV) were utilized for the comparison. Vehicle model year, mileage rate, vehicle age, facility-type percentage (only for MOBILE6), altitude information, and average speeds were also taken into account in running the models. It should be noted that the calendar year was set for 2002 in order to be consistent with the field conditions.

CMEM Model Description

The Comprehensive Modal Emissions Model (CMEM 2.0), which is one of the newest power demand-based emission models, was developed by researchers at the University of California, Riverside. CMEM estimates LDV and LDT emissions as a function of the vehicle's operating mode. The term "comprehensive" is utilized to reflect the ability of the model to predict emissions for a wide variety of LDVs and LDTs in various operating states (e.g., properly functioning, deteriorated, malfunctioning). For the test data, both engine-out and tailpipe emissions of over 300 vehicles, including more than 30 high

emitters, were measured second-by-second over three driving cycles, including the Federal Test Procedure (FTP), US06, and the Modal Emission Cycle (MEC). CMEM predicts second-by-second tailpipe emissions and fuel-consumption rates for a wide range of vehicle/technology categories. The model is based on a parameterized, physical approach that decomposes the entire emission process into components corresponding to the physical phenomena associated with vehicle operation and emission production. Vehicle and operation variables (such as speed, acceleration, and road grade) and model-calibrated parameters (such as cold-start coefficients and engine-friction factor) are utilized as input data for the model (Barth et al. 2000). In order to compare the results of the CMEM model with measured emissions and the other models, the CMEM vehicle category 11 was utilized since the test vehicle, a 1999 Crown Victoria, falls within this category. The speed profiles of the test runs were utilized as input data for the purposes of comparison.

EMIT Model Description

The EMIT model is a new dynamic model that estimates second-by-second fuel consumption and emissions from light-duty vehicles. The model, which is based on the similar approach and format as the Vehicle Specific Power (VSP) model, was developed by researchers at Massachusetts Institute of Technology and Ford Motor Company. The EMIT model also utilizes the same independent variables as the Post's model, which is a fuel-consumption model based upon the instantaneous power demand undergone by a vehicle (Post et al. 1984). The model was derived from the load-based emission modeling approaches and calibrated using a linear regression method. The EMIT model was developed using the emission data that were gathered for the development of the CMEM model (vehicle category 11).

In order to estimate fuel consumption and emissions, the EMIT model first approximates estimated instantaneous vehicle-power demand using vehicle speed and acceleration. Depending on the value of the power demand, the EMIT model calculates engine-out emissions and fuel consumption using instantaneous speed and acceleration profiles. In particular, if the instantaneous power is greater than zero, the model estimates the engine-out emissions and energy consumption using an engine-out function based on the vehicle speed, squared speed, speed raised to the third power, and the product of speed and acceleration. However, if the instantaneous power is equal to or less than zero, the EMIT model utilizes a constant rate for fuel consumption and emission estimates. After estimating the engine-out emissions, the EMIT model calculates the catalyst pass fraction (CPF) for each emission. In order to estimate the CPFs, the model utilizes different multi-regime linear functions for each emission. In particular, CO and HC emissions utilize three-regime linear equations, while NO_x emission utilizes a single-regime linear equation to estimate the CPF for NO_x emission. However, for CO₂ emissions, the EMIT model estimates tailpipe emissions directly without using the CPF function. Each CPF function utilizes the engine-out emission as an input. In order to partition the regime, the CPF function also utilizes the value of the engine-out emission. Multiplying the CPF by the engine-out emission, the EMIT model estimates the tailpipe-out emissions (Cappiello et al. 2002).

Since the EMIT model was developed for the CMEM model vehicle category 11, the coefficients provided in the literature were utilized (Cappiello et al. 2002) without any input file modifications. It should be noted that the EMIT model may estimate negative emissions, especially in the case of fuel consumption and NO_x emissions.

Microscopic Model Validation

Figure 4 illustrates the speed profile of a sample trip, which involves several full and partial stops in addition to high-speed travel (speeds in the range of 100 km/h). The figure clearly demonstrates that the drive cycle involves some aggressive driver behavior. The data were collected on the local highway and arterials in the Blacksburg, Virginia area in November 2001 using the OEM unit. The data collection continued for 899 seconds over 10.97 km, including a 3.35 km highway section and a 7.63 km local

arterial section. The average speed for the trip was 43.93 km/h, while the average speeds of the highway and arterial sections were 81.01 km/h and 36.54 km/h, respectively. It should be noted that the vehicles were tested under hot-stabilized engine conditions in order to eliminate a possible cold-start effects.

Figure 5 illustrates the variations in the instantaneous vehicle emissions of HC, CO, NO_x as measured by the OEM unit as the vehicle traveled along the local highway and arterial sections. Superimposed on the figure are the proposed model estimates of vehicle emissions based on instantaneous vehicle speed and acceleration levels. As illustrated in the figure, the predicted emissions generally follow the peaks and valleys of the measured vehicle emissions. However, it should be noted that the proposed model slightly underestimates some peaks of HC and CO emissions. Also, the CO model overestimates emissions for the section between 180 and 240 seconds, which is the freeway section. The figure illustrates that, in general, the model predictions follow the field-collected, on-road emission measurements, demonstrating the uniqueness of the model for assessing the effects of traffic-improvement projects, including ITS technology, on the environment.

Table 3 summarizes the emission results for the various state-of-the-art models applied to the drive cycle of Figure 4. The total vehicle emissions of HC as measured using the OEM unit was 2.49 grams, while the estimated HC emissions based on the proposed hybrid model was 2.34 grams, which corresponds to a 6-percent error over the entire drive cycle. The table also demonstrates a 10 and 28 percent error for CO and NO_x emissions, respectively.

Table 3 demonstrates that MOBILE5a produced errors that ranged between 29 and 80 percent, while MOBILE6 produced errors in the range of 17 and 131 percent, with an average error of 61 percent. Besides the MOBILE models, Table 3 shows the results for the CMEM, EMIT, and VT-Micro models. The CMEM model significantly underestimated all three emissions when compared to the OEM data. Table 3 shows that the HC-emission estimate, 0.1 grams, of the CMEM model was significantly less than the measured HC emissions of 2.49 grams. The EMIT model, another power-based model, also underestimated all emissions, with an average error of 81 percent. The table also demonstrates that the VT-micro model produced an average error of 43 percent.

Bag Model Validation

This section describes the macroscopic validation efforts of the proposed model using bag-emission measurements. The measured emissions and the vehicle-specific model predictions are also compared with state-of-the-art models, such as EPA's MOBILE5a and MOBILE6 models, and the CMEM (Category 11), EMIT, and VT-Micro (Category LDV5) models. Given that the vehicle-specific model was developed using the VT-Micro framework, the inclusion of the VT-Micro LDV5 category provided an opportunity to evaluate the VT-Micron framework and to demonstrate the additional benefits of modeling a specific vehicle. It should be noted that bag emissions were compiled by driving along a local highway and an arterial section in March of 2003 using the OEM unit.

Figure 6 illustrates the speed profiles of the 10 freeway test runs. Each speed profile includes full stops at the entrances and exits to the freeway as well as high-speed travel along the freeway. The data were collected on the local highway (Route 460-bypass) in the Blacksburg and Christiansburg areas. The test vehicle was driven ten times for a round trip that started at the South Main exit, ended at the Christiansburg exit on Route 460, and returned again to the South Main exit. All trips started at the same point and involved traveling at the highway speed limit of 96 km/h (60 mi/h) for a total length of 8.8 km. The average speed for the ten tests was 72.43 km/h, with a maximum speed of 100.8 km/h. The test vehicle collected emission data under hot-stabilized engine conditions. It should be noted that although each test run was repeated on the same section of road at a similar average speed, the speed profile of each run was slightly different depending on the traffic conditions and traffic control scenarios that the driver experienced. These differences in the speed and acceleration profiles resulted in considerable differences in vehicle emissions.

Figure 7 illustrates the variation in vehicle emissions over the entire trip as measured in the field together with the predicted emissions from the proposed model and the state-of-the-art models. The figure illustrates that the trend of the predicted HC emissions from the proposed model are consistent with the field measurements. On the other hand, because the CMEM, EMIT, VT-Micro, and MOBILE models were developed based on different emission sources, they may not be comparable to the absolute values of the OEM measurements. However, it should be noted that the general trend of the estimates should follow the trend of the measured emissions. Figure 7 shows that the HC estimates from the VT-Micro model generally follow the trend of the measured HC emissions. However, the MOBILE5a and MOBILE6 models were found to be less sensitive to differences across the drive cycles, given that the average speed did not vary significantly, thus demonstrating that the MOBILE models cannot capture the intricate differences in speed profiles. The figure also shows that the HC estimates from the CMEM and EMIT models are also significantly different from the measured emissions and the other model estimates. Both the CMEM and EMIT models show unreasonable increases (in runs 7 and 9) that are not found in the measured emissions.

Figure 7 also shows the comparison between measured and predicted CO emissions. It should be noted that the trend for all model estimates for CO emissions are very similar to the OEM CO measurements, except for the CMEM and EMIT model estimates. These models' results show sudden drops and increases in CO estimates that are absent from the field measurements. In contrast, the NO_x emission estimates are consistent with the field measurements for all the models.

Figure 8 illustrates the speed profiles of eight test runs along a local arterial (Route 460-business) in the Blacksburg/Christiansburg area. The test vehicle was driven from the South Main intersection to the New River Valley Mall intersection and back for a total trip length of 6.1 km (3.05 km in each direction). The trip duration ranged from a minimum of 382 seconds to a maximum of 507 seconds. Figure 8 clearly demonstrates differences in the eight speed profiles caused by differences in the signal indications when the vehicle passed the four signalized intersections along the study section.

Figure 9 demonstrates the variations in the field measured vehicle emissions together with the various model estimates for the entire trip. As was the case for the highway section, generally, the emission results of the vehicle-specific model and the VT-Micro model (average composite vehicle) follow the trends of the measured HC, CO, and NO_x emissions. Alternatively, the MOBILE5 and MOBILE6 model estimates are less sensitive to emission variability across the various trips. In particular, the NO_x estimates from both MOBILE models are almost constant and do not reflect for trip differences. Similar to the emission results for the highway, the CMEM and EMIT models demonstrate a level of variability that exceeds the measured variability significantly. Specifically, the CMEM and EMIT model demonstrate significant variability in CO emissions that exceed the field measurements significantly.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The paper demonstrates that on-board emission measurements provide a cost-effective means to collect field data for the development of vehicle-specific emission models using the VT-Micro framework. Furthermore, the paper provides a data collection framework for the collection of field data that covers the entire envelope of operation of a vehicle. The validity of the vehicle-specific model was demonstrated using an independent field data set. Furthermore, the study demonstrated that the VT-Micro framework was able to capture differences in vehicle emissions across the various drive cycles. Alternatively, the MOBILE5a and MOBILE6 models were unable to capture differences in emissions across different drive cycles when the average speed remained fairly stable, while the CMEM and EMIT models were too sensitive to minor differences in the drive cycles.

Several areas of research are recommended to expand the applicability of the emission models. First, further data collection and procedures need to be developed to account for the wide range of vehicle emissions. Second, more vehicle data need to be collected to expand the VT-Micro model in order to represent a more general on-road fleet. Third, data are required to develop emission models for heavy-

duty trucks. Finally, it is recommended that the effects of ambient temperature, relative humidity, vehicle type, and driving behavior on vehicle emissions be characterized.

REFERENCES

- Ahn, K., Rakha, H., Trani, A., and Van Aerde, M. (2002). "Estimating vehicle fuel consumption and emissions based on instantaneous speed and acceleration levels." *Journal of Transportation Engineering*, 128(2), 182-190.
- Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M., and Wenzel, T. (2000). *Comprehensive modal emission model (CMEM), version 2.0 user's guide*, Riverside, CA.
- Cappiello, A., Chabini, I., Nam, E., Abou-Zeid, M., and Lue, A. (2002). "A Statistical Model of Vehicle Emissions and Fuel Consumption." *IEEE ITSC 2002 Paper*, (Number 107).
- Clean Air Technologies International. (2000). *Real-world emissions monitoring on-board testing equipment light duty vehicle system, operation and maintenance manual version 4*, Buffalo, NY.
- Frey, H. C., Roupail, N. M., Unal, A., and Colyar, J. (2001). "Measurement of On-Road Tailpipe CO, NO, and Hydrocarbon Emissions Using a Portable Instrument." *Annual Meeting of the Air & Waste Management Association*, Orlando, Florida.
- Post, K., Kent, J. H., Tomlin, J., and Carruthers, N. (1984). "Fuel consumption and emission modeling by power demand and a comparison with other model." *Transportation Research*, 18A, 191-213.
- Rakha, H., Van Aerde, M., Ahn, K., and Trani, A. A. (2000). "Requirements for evaluating traffic signal control impacts on energy and emissions based on instantaneous speed and acceleration measurements." *Transportation Research Record. n 1738 2000*, 56-67 00-1133.
- Vojtisek-Lom, M., and Allsop, J. E. (2001). "Development of Heavy-Duty Diesel Portable, On-Board Mass Exhaust Emissions Monitoring System With Nox, Co2 and Qualitative Pm Capabilities." *SAE International Fall Fuels & Lubricants Meeting & Exhibition, Session: Real-World Emissions Measurement Technology for Internal Combustion Systems*, San Antonio, TX, USA,.

List of Tables

Table 1. Test Vehicle Characteristics

Table 2. Sample Coefficients of the Proposed HC Model

Table 3. Model Validations with Field Data

List of Figures

Figure 1. Speed and Acceleration Frequency Distribution

Figure 2. Speed and Acceleration Feasible Range of Application

Figure 3. Model Predictions

Figure 4. Speed Profiles of Model Validation Test

Figure 5. Instantaneous Model Validations

Figure 6. Sample Test Runs (Highway)

Figure 7. Validation Results (Highway)

Figure 8. Sample Test Runs (Arterial)

Figure 9. Validation Results (Arterial)

Table 1. Test Vehicle Characteristics

Make	Ford
Model Year	1999
Model	Crown Victoria
VIN	2FAFP73W6XX191763
Mileage	13,000
Transmission	Automatic
Gross Wight	3741 lb.
No. Cylinders	8
Engine Size	4.6
Engine Type	V8
Horse Power	200 hp @ 4250 rpm
Fuel Capacity	19 gal

Table 2. Sample Coefficients of the Proposed HC Model

Positive Acceleration Coefficients	Constant	Speed	Speed ²	Speed ³
Constant	-6.56522	0.03884	-0.00085	5.62E-06
Acceleration	-0.06485	0.03481	-0.00076	4.57E-06
Acceleration ²	0.03736	-0.00787	0.000193	-1.2E-06
Acceleration ³	-0.0023	0.000424	-1E-05	6.23E-08
Negative Acceleration Coefficients	Constant	Speed	Speed ²	Speed ³
Constant	-6.56522	0.03739	-0.00082	5.47E-06
Acceleration	0.38993	0.01175	-0.00038	2.21E-06
Acceleration ²	0.08748	0.00055	-5.8E-05	4.21E-07
Acceleration ³	0.00514	-3E-05	-2.9E-06	2.51E-08

(Speed: km/h, Acceleration: km/h/s, HC Emission Rate: g/s)

Table 3. Model Validations with Field Data

	Predicted (grams)			Relative Difference			Average
	HC	CO	NO _x	HC	CO	NO _x	
Measured	2.49	18.20	6.02	0%	0%	0%	0%
Proposed model	2.34	16.30	4.33	-6.01%	-10.46%	-28.00%	14.82%
Mobile6	2.07	41.96	3.83	-16.75%	130.52%	-36.46%	61.24%
Mobile5a	0.55	12.89	1.71	-77.93%	-29.17%	-71.52%	59.54%
CMEM (LDV11)	0.10	4.00	1.00	-95.96%	-78.04%	-83.32%	85.77%
EMIT (VSP based)	0.23	5.10	1.17	-90.93%	-71.98%	-80.13%	81.01%
VT-Micro (LDV5)	1.25	30.51	6.73	-49.82%	67.61%	11.75%	43.06%

		Acceleration (m/s ²)																				Sum							
		-3.6	-3.3	-3.1	-2.8	-2.5	-2.2	-1.9	-1.7	-1.4	-1.1	-0.8	-0.6	-0.3	0.0	0.3	0.6	0.8	1.1	1.4	1.7		1.9	2.2	2.5	2.8	3.1	3.3	3.6
Speed (km/h)	5			1			4	1	8	18	8	30	23	36	160	48	33	34	26	32	4	19	1	2	3		2	3	1940
	10		1		5	2	7	7	13	9	7	13	9	5	8	3	23	19	17	28	8	15	2	5		1	2	209	
	15		2	1	2	3	9	9	8	8	6	6	8	10	30	25	24	25	18	19	7	13	6	2	1		1	1	244
	20		2	3	9	8	12	11	8	9	8	4	8	6	9	26	28	41	20	25	7	7		5	3		3	2	264
	25	2	1	1	2	3	8	3	8	8	8	7	3	3	12	17	23	40	30	28	5	4	1	3	1		1	1	223
	30	3	4	2	6	6	14	11	10	13	2		3	2	16	20	26	53	35	23	7	7			1	2	4	2	272
	35	3	3	3	5	5	12	10	10	7	2	2	1	4	33	39	40	69	47	30	11	8	1	2	3	1	3	2	356
	40	1	5	2	7	5	4	8	8	4	3	6		4	38	32	43	49	41	20	4	4		1	1	1	2	1	294
	45	7	7	3	7	3	9	12	10	2	3	1	2	8	47	36	60	53	43	14	8	2	1	1	2	2	2	2	345
	50	3	2	2	3		8	2	8	8	5	4	4	16	65	26	55	65	33	22	2		2	2	6	3			346
	55	4	3	2	5	5	5	7	3	10	4	6	3	20	103	39	60	54	58	9	2		1	1	5	1	1		411
	60	4	4	2	2	1	8	4	7	5	4	3	26	11	29	10	47	62	53	47	10	4	2		7	1	2	2	3228
	65		1	1	1	1	3	6	6	10	5	7		15	51	32	32	57	51	11	2	2	2	3					299
	70	3	4	1	1	4	5	2	10	7	5	15	4	6	57	38	48	48	59	1	2	4	5	2	1				332
	75	2	5		1	2		3	3	9	4	5	11	13	25	32	29	144	60	49	8	1	7	2	1				2990
	80	4	2		1	1		5	5	7	5	5	14	58	30	43	69	50	10	6	9			2					326
	85	3	7	2			1	2	2	10	4	4	11	15	38	37	28	36	52	11	1	8							272
	90	2	1		4	2		1	3	4	5		2	174	1735	184	21	40	47	14	2	5							2246
	95		3		1			1		2	3	4	5	16	53	28	27	45	24	19	1	3							235
	100	7	1	4	6	1	5			2	2	7	9	22	46	35	31	33	24	13	10	1							259
105	4	1	1	2	4	2		2	1	5	4	2	73	1665	90	26	30	30	16	5	1							1964	
110		5	3	4	3	2	3	2	1	4	2	2	15	181	16	15	18	11	10	5	2							304	
115	1	1		1	3	5	1		2	1	2	1	6	26	6	16	22	17	15									126	
120	1			5	6	1	3		4	3	2	8	17	61	9	16	28	8	11	4								187	
125	1		1	3	1		5	4	5	8	29	3	36	622	11	6	14	5	2									756	
130										8	4			27	1														40
Sum	55	65	35	83	69	124	112	138	163	124	172	252	547	12027	904	930	1055	842	401	108	123	24	39	28	13	23	12	18468	

Figure 1. Speed and Acceleration Frequency Distribution

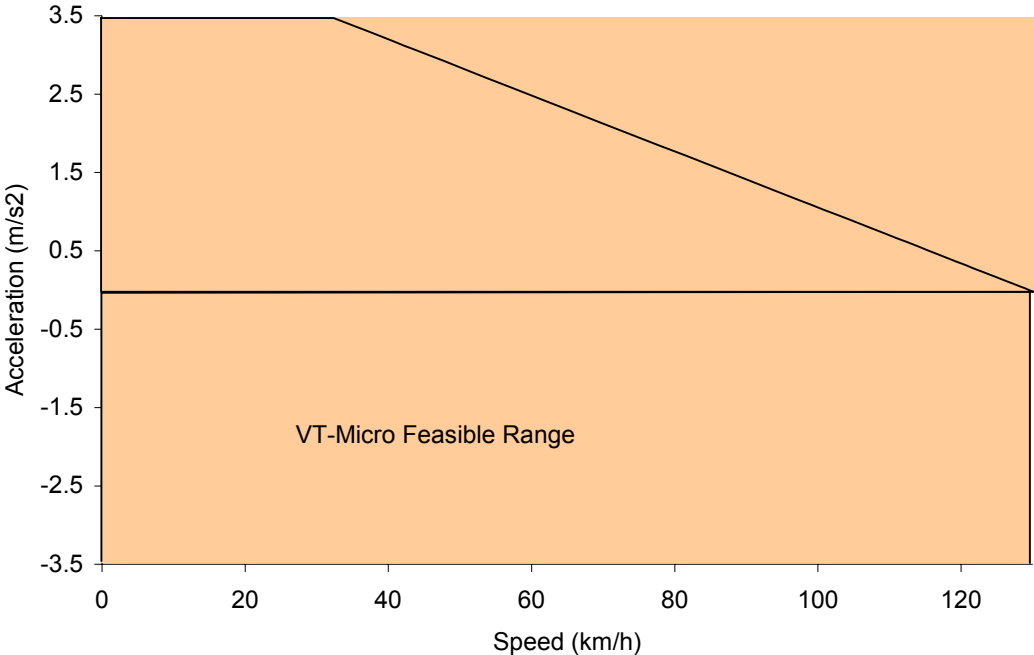


Figure 2. Speed and Acceleration Feasible Range of Application

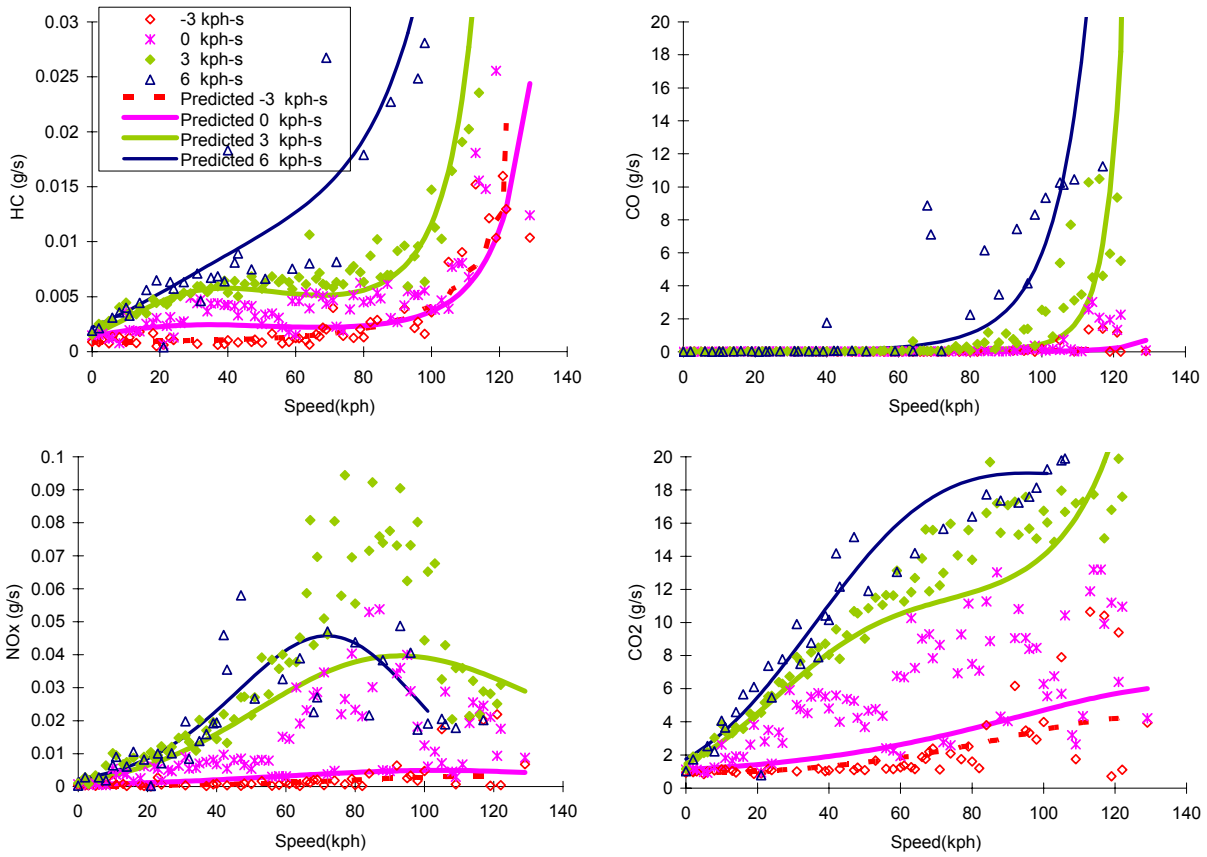


Figure 3. Model Predictions

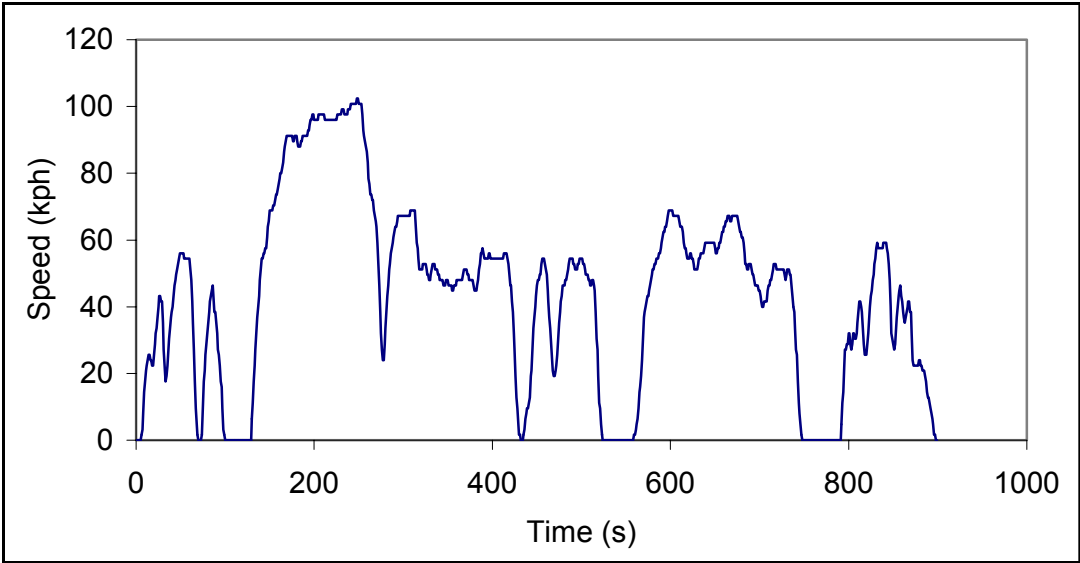


Figure 4. Speed Profiles of Model Validation Test

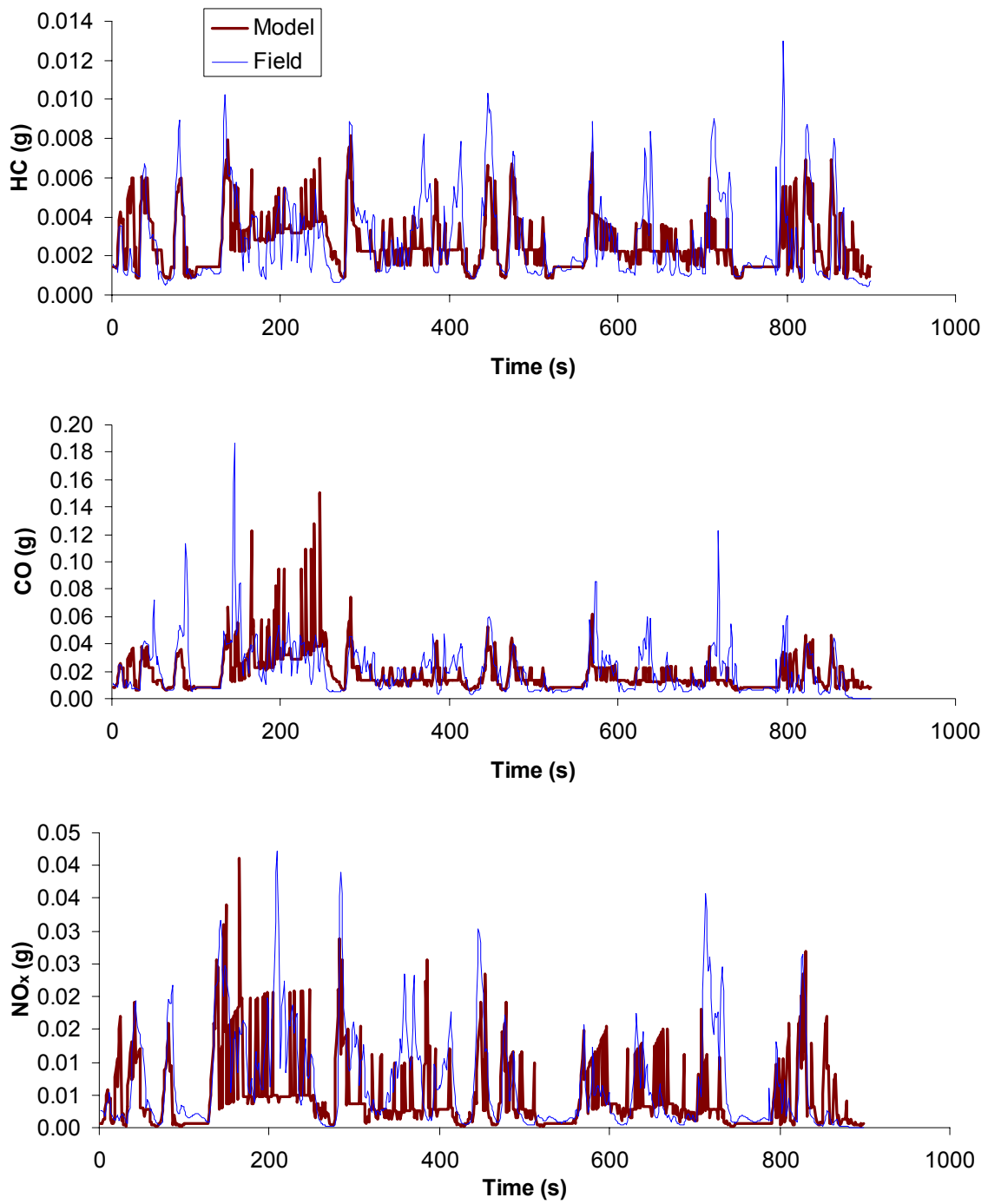


Figure 5. Instantaneous Model Validations

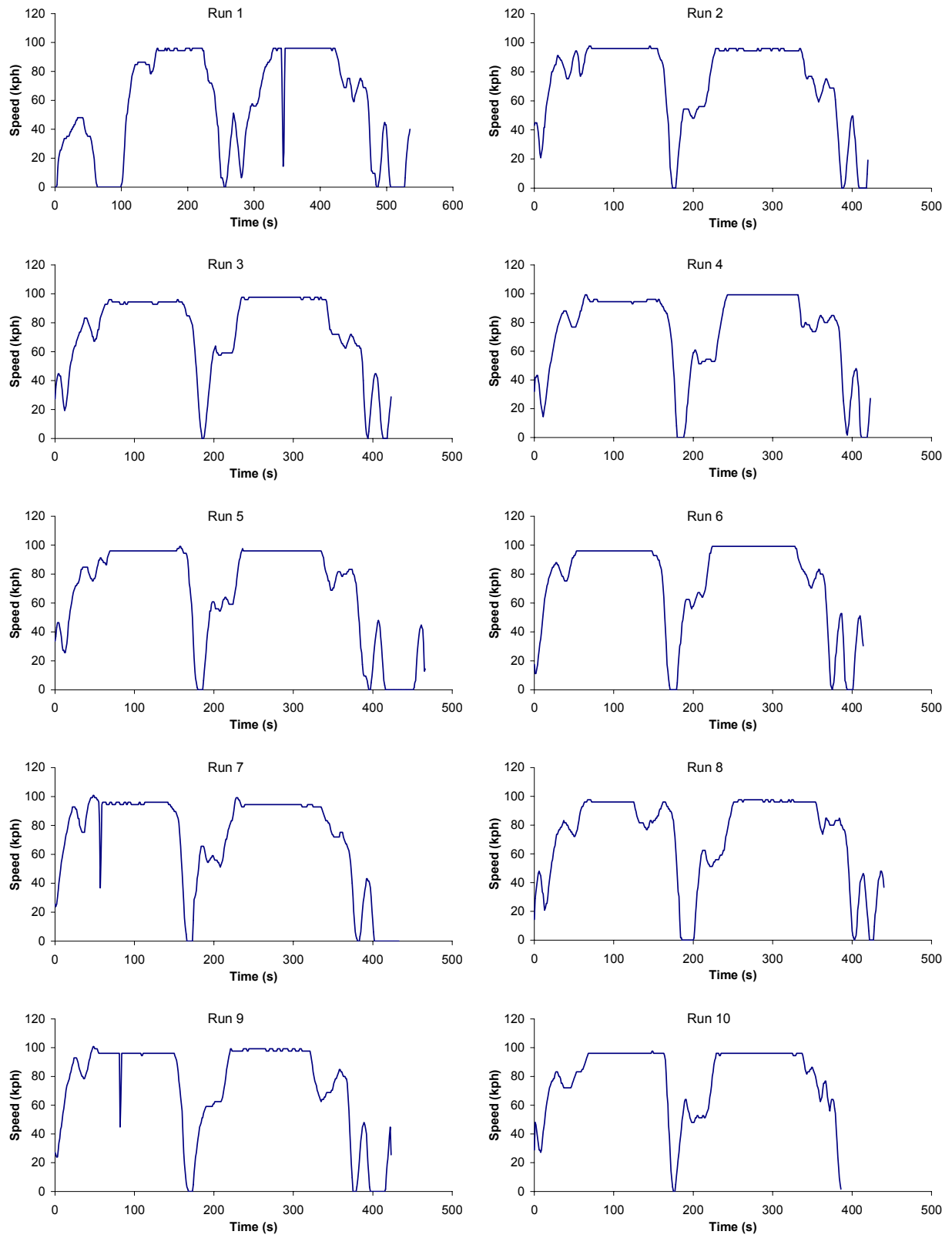


Figure 6. Sample Test Runs (Highway)

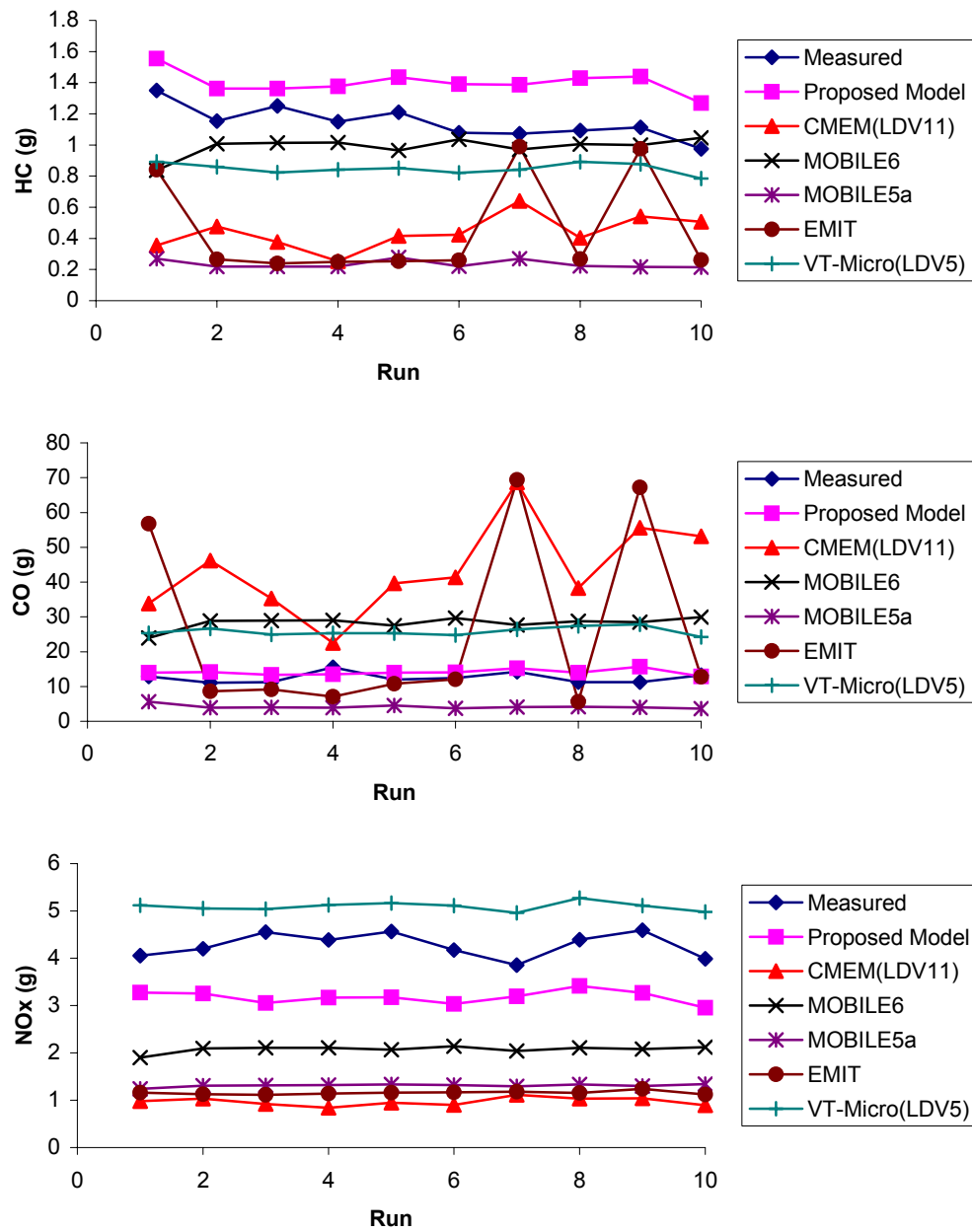


Figure 7. Validation Results (Highway)

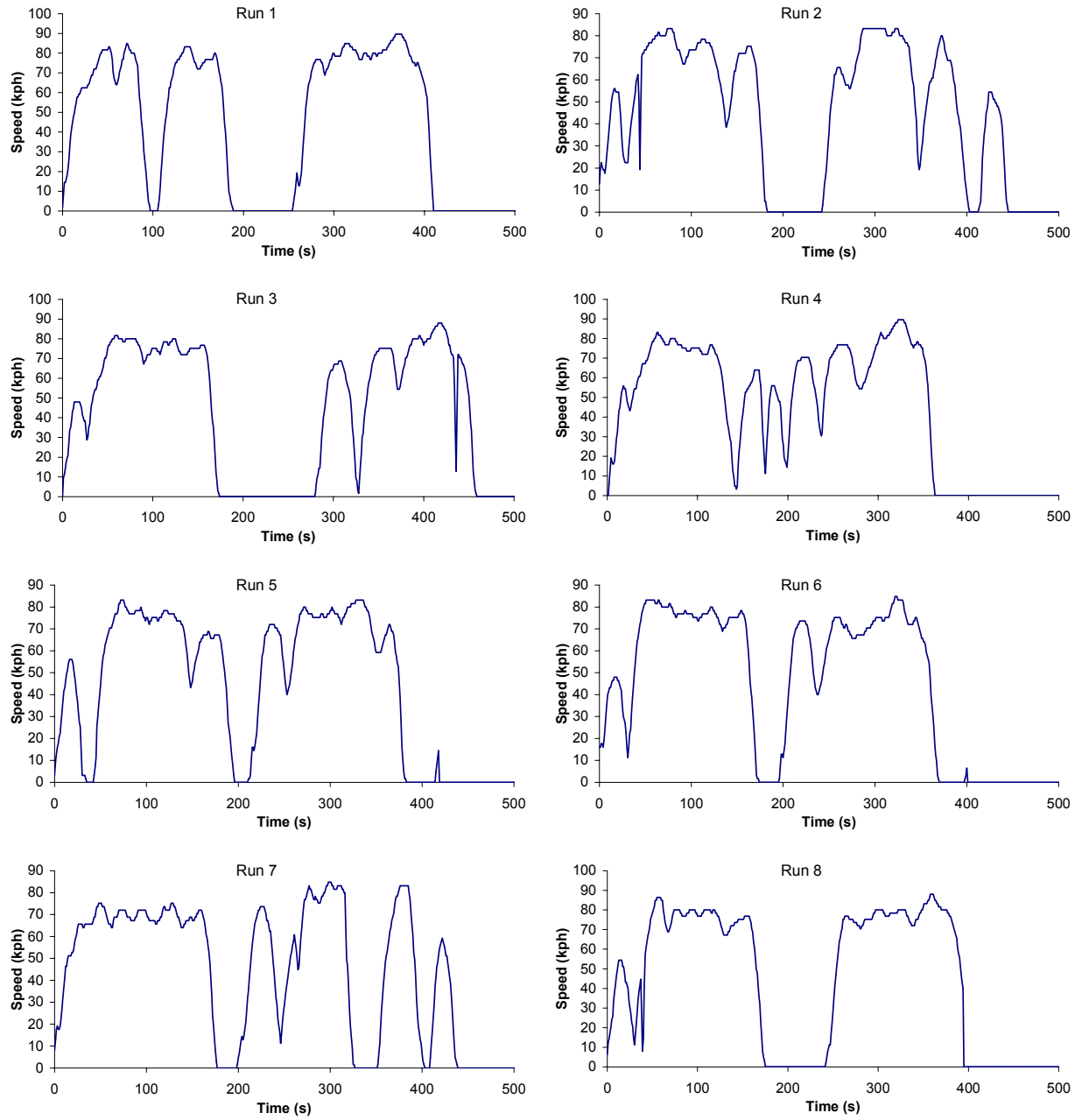


Figure 8. Sample Test Runs (Arterial)

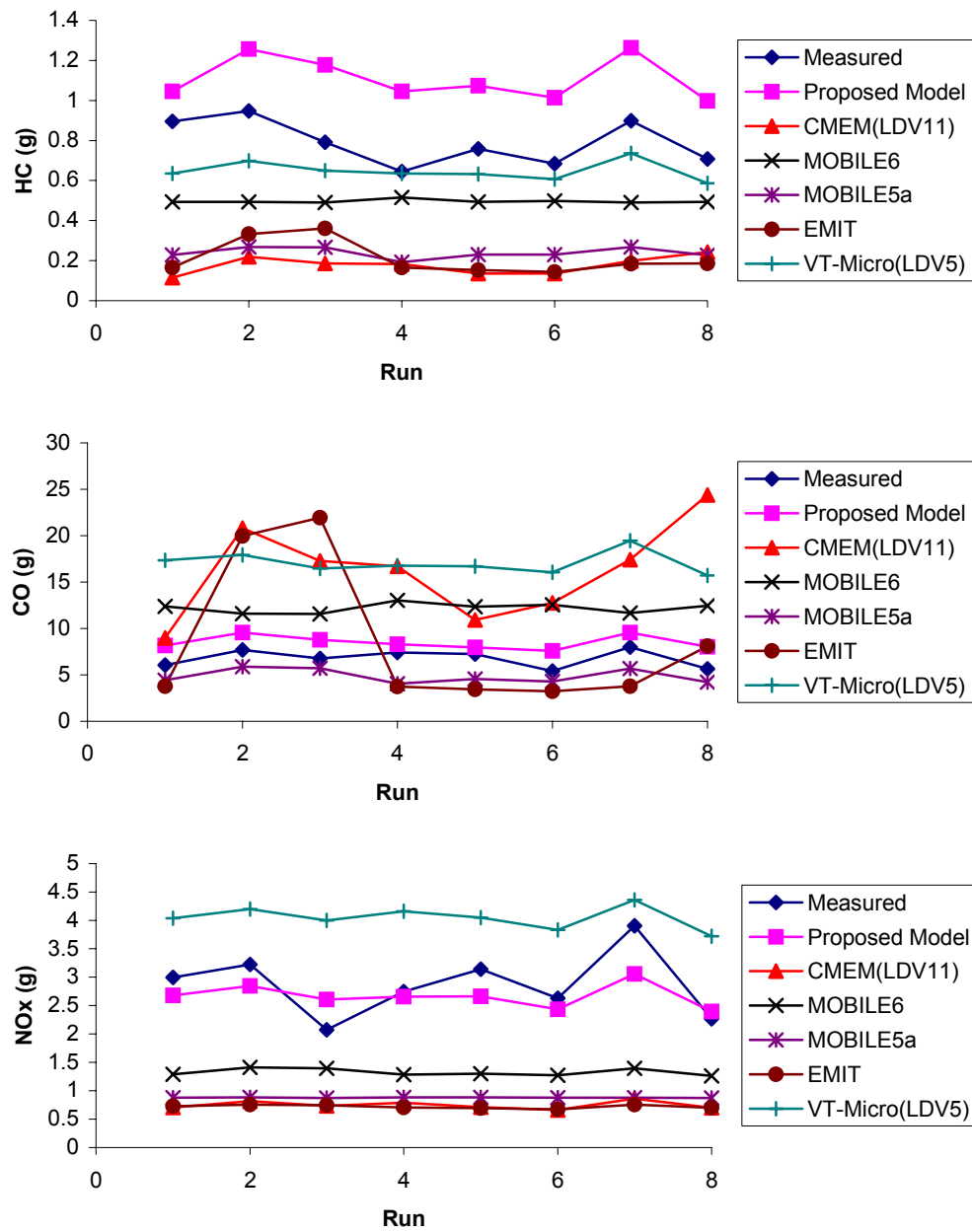


Figure 9. Validation Results (Arterial)