# Comparison of MOBILE5a, MOBILE6, VT-MICRO, and CMEM models for estimating hot-stabilized light-duty gasoline vehicle emissions

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Hesham Rakha
Virginia Polytechnic Institute and State University


Kyoungho Ahn
Virginia Polytechnic Institute and State University

# COMPARISON OF MOBILE5A, MOBILE6, VT-MICRO, AND CMEM MODELS FOR ESTIMATING HOT-STABILIZED LIGHT-DUTY GASOLINE VEHICLE EMISSIONS

by:

Hesham Rakha,[1] Kyoungho Ahn,[2] and Antonio Trani,[3]

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[1] Assistant Professor, Charles Via Jr. Department of Civil and Environmental Engineering, Virginia Tech. Virginia Tech Transportation Institute, 3500 Transportation Research Plaza (0536), Blacksburg, VA 24061, E-mail: hrakha@vt.edu, Tel: (540) 231-1505, Fax: (540) 231-1555.

[2] Senior Research Associate, Virginia Tech Transportation Institute, Blacksburg, VA 24061. E-mail: kahn@vt.edu.

[3] Associate Professor, Charles Via Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061.

# ABSTRACT

The paper compares the MOBILE5a, MOBILE6, VT-Micro, and CMEM models for estimating hot-stabilized, light-duty vehicle emissions. Specifically, Oak Ridge National Laboratory (ORNL) and Environmental Protection Agency (EPA) laboratory fuel consumption and emission databases are utilized for model comparisons. The comparisons demonstrate that the CMEM model exhibits some abnormal behaviors when compared to the ORNL data, EPA data, and the VT-Micro model estimates. Specifically, Carbon Monoxide (CO) emissions exhibit abrupt changes at low speeds and high acceleration levels and constant emissions at negative acceleration levels. Furthermore, Oxides of Nitrogen ($NO_x$) emissions exhibit abrupt drops at high engine loads. In addition, the study demonstrates that MOBILE5a emission estimates compare poorly to EPA field data, while MOBILE6 model estimates show consistency with EPA field data and VT-Micro model estimates over various driving cycles. The VT-Micro model appears to be accurate in estimating hot-stabilized, light-duty, normal vehicle tailpipe emissions. Specifically, the emission estimates of the VT-Micro and MOBILE6 models are consistent in trends with laboratory measurements. Furthermore, the VT-Micro and MOBILE6 models accurately capture emission increases for aggressive acceleration drive cycles in comparison with other drive cycles.



**Key words**: Transportation energy, transportation environmental impacts, VT-Micro Model, CMEM, MOBILE5, MOBILE6, Fuel Consumption Models, Emission Models.

## INTRODUCTION

Numerous energy and emission models have been developed over the past decade. Typically, these models differ in their modeling approach, modeling structure, and in the data used to develop the models. Consequently, there is a need to validate and compare these models in a systematic fashion.

### Objectives of Research

The objective of this paper is to compare a number of state-of-the-art and state-of-the-practice energy and emission models described in the literature in an attempt to identify any similarities and/or differences in model predictions. The study attempts to identify the conditions that result in similar and/or different model estimates and the potential reasons for these differences.

### Significance of Research

The research provides two significant contributions. First, the research evaluates the accuracy of the various state-of-the-art energy and emission models for both aggregate trip estimates and instantaneous estimates. Second, the research identifies under what conditions (speed and acceleration levels) the models provide accurate energy and emission estimates.

### Paper Layout

The paper first describes the state-of-the-art energy and emission models in terms of model approach, structure, and development. This study does not attempt to cover all existing energy and emission models; rather, it covers the most significant contributions to energy and emission modeling. The next section describes the data sources used to compare the proposed models, as well as the data collection procedures, driving cycles, and test vehicle characterization. Subsequently, the VT-Micro, CMEM, MOBILE5a, and MOBILE6 models are compared to the ORNL data and EPA field data both microscopically and macroscopically. The last section summarizes the findings of the study and presents the main conclusions of this analysis.

## STATE-OF-THE-ART ENERGY AND EMISSION MODELS

State-of-the-art energy and emission models are categorized as either macroscopic or microscopic. Macroscopic models use average aggregate network parameters to estimate network-wide emission rates. Alternatively, microscopic models estimate instantaneous vehicle fuel consumption and emission rates, which are aggregated to estimate network-wide measures of effectiveness.

### Macroscopic Emission Models

This section focuses on macroscopic emission models used in the North America for evaluating transportation related environmental impacts.

#### *Traditional Macroscopic Emission Models (MOBILE and EMFAC)*

Two emission models commonly used in the North America are the Environmental Protection Agency's (EPA) MOBILE5 model and the California Air Resources Board's (CARB) EMFAC model. There are different versions of the MOBILE5 model such as

MOBILE5a and MOBILE5b. These models have been authorized by EPA to perform conformity analysis. The EMFAC model is currently used in the state of California while the MOBILE5 model is used throughout North America. Both models produce activity-specific emission rates that are functions of vehicle type and age, average speed, temperature, altitude, vehicle load, air conditioning usage, and vehicle operating mode. These emission rates are multiplied by vehicle activities such as vehicle miles-traveled, number of trips, and vehicle-hours traveled in order to estimate total emission levels. The MOBILE5 model estimates three pollutants: hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen ($NO_x$). Similarly, the EMFAC model produces composite emission factors for these three pollutants and particulate matter.

Vehicle emission estimates produced by the MOBILE5 and EMFAC models use average trip speeds as input to select trip-specific emission factors that are computed by testing vehicles through a limited number of driving cycles. The MOBILE5 model uses baseline emission rates that are derived from the Federal Test Procedure (FTP) cycle. This cycle is commonly used for Light-Duty Vehicle (LDV) testing and is composed of three different phases: a cold start phase, a stabilized phase, and a hot start phase. The emissions from vehicles operating in all three phases are used to estimate baseline emissions. The baseline emission rate for a vehicle class is estimated from the average result of the FTP cycle at an speed of 31.6 km/h (19.6 mph), the average test speed of the entire FTP cycle. Alternatively, in the latest EMFAC model (EMFAC2000), the baseline emission rate is derived from the Unified Drive Cycle (LA92) with an average operating speed of 39.4 km/h (24.6 mph).

For both the MOBILE5a and EMFAC models, emission rates at other average speeds are computed by multiplying the base emission rate by the appropriate vehicle-specific Speed Correction Factor (SCF) for average speeds ranging 4 to 105 km/h, in the case of the MOBILE5a model. These SCFs are derived from laboratory emission measurements gathered over a limited number of drive cycles of different average speeds using the average cycle speed as an independent variable and the emission rate as a dependent variable. Consequently, the speed-corrected emission rates that are used within macroscopic emission models are highly dependent on the average cycle speed (Guensler *et al.* 1993 and EPA 1993).

The use of SCFs for estimating vehicle emissions has its shortcomings. First, these factors are derived from a limited set of drive cycles, which may not represent all traffic flow conditions. Specifically, many of the drive cycles are out of date (e.g. the FTP drive cycle is more than 20 years old); thus, they may not represent current real world driving conditions. Second, these emission models predict emission rates based on a single traffic-related variable, namely the average speed and thus ignore differences in speed and acceleration distributions over a trip, which can vary significantly depending on the level of congestion and facility type. For example, such models would not be able to reflect differences in vehicle emissions that result from travel on a high-speed facility with several stops (e.g. travel along a signalized arterial with frequent stops) and travel along a medium-speed facility with no stops (e.g. travel along an unsignalized arterial with a lower speed limit) if both trips have identical average speeds. Clearly, such scenarios would result in significantly different vehicle emissions as has been demonstrated by Rakha and Ding (2003).

### *MOBILE6 Model*

EPA's Office of Transportation and Air Quality (OTAQ) recently developed a new version of the MOBILE model, which is referred to as MOBILE6. This version is significantly different from MOBLE5 in many model components. MOBILE6 is based on recent vehicle emission testing data collected by EPA, CARB, automobile manufacturers, and Inspection and Maintenance (I/M) tests from several states. MOBILE6 also models the impact of different petroleum refiners on vehicle emissions.

A major characteristic of MOBILE6 is the addition of "off-cycle emissions," which involve aggressive driving with the air conditioning operating. This aggressive driving behavior is not included in the FTP drive cycle, but is included in the Supplemental FTP cycle (which applies to model year 2000 and newer vehicles). As drive cycles used in MOBILE6 include operations at high speeds and high accelerations, the model produces significantly higher pollutants in comparison with MOBILE5. MOBILE6 estimates emission factors based on different roadway types (e.g., highways, arterials, and locals). Emission factors can be adjusted, based on vehicle testing over a series of facility cycles, for different facility types and different average speeds. MOBILE6 estimates emission factors from the start portion and the running portion of the trip separately. The cold start emissions are calculated using the FTP bag1 (e.g., cold start emissions) and the FTP bag3 (e.g., hot start emissions).

Other significant enhancements to MOBILE6 include: (i) dramatic reductions in vehicle emissions as vehicles age and accumulate mileage, (ii) control of off-cycle emissions with the Supplemental FTP (SFTP) drive cycle, (iii) the inclusion of evaporative diurnal emission factors estimated from real-time diurnal test data previously unavailable, (iv) the revision of oxygenated fuel effects, (v) the revision of I/M program effects on vehicle emissions, (vi) the addition of off-cycle $NO_x$ emissions for heavy-duty diesel vehicles, (vii) the effects of in-use fuel sulfur content on all emissions, and (viii) the effects of national low-emission vehicles (NLEV) and Tier 3 standards (EPA 2001 and NRC 2000). It should be noted, however, that in spite of these model improvements, the MOBILE6 model generates identical emission estimates for trips with identical average speeds if the roadway facility is the same.

**Microscopic Energy and Emission Models**

Instantaneous fuel consumption and emission models are derived from a relationship between dependent variables (instantaneous fuel consumption and emission rates) and instantaneous measurements of explanatory variables (vehicle power, tractive effort, acceleration, and/or speed). Second-by-second vehicle characteristics, traffic conditions, environmental conditions, and roadway conditions are required to estimate vehicle fuel consumption and emission rates. These models are sensitive to changes in vehicle acceleration behavior and thus can be utilized for the evaluation of operational-level transportation projects such as re-timing signals, modeling toll plazas, and modeling highway sections.

The Comprehensive Modal Emissions Model (CMEM) is a state-of-the-art model widely used and referenced in the literature. Alternatively, the Virginia Tech Microscopic energy and emissions model (VT-Micro) is an emerging model that was developed using instantaneous speed and acceleration levels as independent variables. The CMEM and VT-Micro models are evaluated in an effort to compare field fuel consumption and emission data and to demonstrate any similarities/differences in the model estimates.

### ***The Comprehensive Modal Emissions Model***

CMEM is one of the newest power demand-based emission models that was developed by researchers at the University of California, Riverside. The CMEM model estimates LDV emissions as a function of the vehicle's operating mode. The term "comprehensive" reflects the model’s ability to predict emissions for a wide variety of LDVs in various operating states (e.g., properly functioning, deteriorated, malfunctioning). CMEM predicts second-by-second tailpipe emissions and fuel consumption rates for a wide range of vehicle/technology categories (Barth *et al*. 2000). In developing these models, both engine-out and tailpipe emissions of over 300 vehicles (including more than 30 high emitters) were measured in a laboratory at a second-by-second level of resolution along three drive cycles: FTP, US06, and Modal Emission Cycle (MEC).

The CMEM model is based on a parameterized physical approach that breaks down the entire emission process into components that correspond to the physical events associated with vehicle operation and emission production. The model consists of six modules that predict engine power, engine speed, air-to-fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction. Vehicle and operation variables (e.g., speed, acceleration, and road grade) and model calibrated parameters (e.g., cold start coefficients and an engine friction factor) are input to the model (Barth *et al*. 2000 and Barth *et al*. 1996).

***The Virginia Tech Microscopic Energy and Emission Model***

While the CMEM model was developed as a power-demand model, the VT-Micro model was developed as a regression model from experimentation with numerous polynomial combinations of speed and acceleration levels. Linear, quadratic, cubic, and quartic terms of speed and acceleration were tested using chassis dynamometer data collected at the Oak Ridge National Laboratory (ORNL). The final regression model includes a combination of linear, quadratic, and cubic speed and acceleration terms because it provides the least number of terms with a relatively good fit to the original data ($R^2$ in excess of 0.92 for all Measures of Effectiveness [MOE]).

While a more detailed description of the model derivation is provided in the literature (Ahn *et al*. 2002), a number of regression models have been tested. The first regression model tested improved upon the Post and Akcelik models (Post *et al.*1984 and Akcelik 1989) by introducing more variables (Equation 1). The model produced reasonable fits to the original data except when negative dependent values were produced. To solve this problem, a data transformation technique using the natural logarithm was adopted. This resulted in a new log-transformed model presented in Equation 2.

Using Equation 2, the coefficient of determination of the MOE estimates ranges from 0.69 to 0.99. The statistical results indicate a good fit for fuel consumption ($R^2$ = 0.995) and $NO_x$ estimates ($R^2$ = 0.960) and a relatively poor fit for HC and CO emission estimates ($R^2$ = 0.689 and 0.717, respectively). The errors in the HC and CO model estimates are significant at high acceleration levels (overestimates HC emissions by up to 25% and CO emissions by 100%). The errors in the regression model estimates are caused by significant sensitivity of the dependent variable to the independent variables at high accelerations (compared with the marginal sensitivity of the dependent variable in the negative acceleration range). Differences in positive versus negative accelerations can be attributed to the power vehicles exert in positive accelerations, compared to the lack of power exerted when in the negative acceleration range.

Consequently, separate regression models were developed for positive and negative accelerations (Equation 3). The intercept at zero speed and zero acceleration was estimated using the positive acceleration model and fixed in order to ensure a continuous function between the two regression regimes. Figure 1 illustrates the quality of fit between the regression models and the ORNL data. The final models that were developed resulted in good fits to the ORNL data as demonstrated in Figure 1 ($R^2$ in excess of 0.92 for all MOEs). Figure 1 also shows the effectiveness of the hybrid log-transformed model in predicting vehicle fuel consumption and emission rates as a function of a vehicle's instantaneous speed and acceleration levels. Table 1 shows sample coefficients for HC emissions for the VT-Micro model.

It should be noted that the VT-Micro models were developed for application within a microscopic simulation model or using field instantaneous speed measurements using Global Positioning Systems (GPS) (Rakha et al. 2001; Rakha and Ahn 2003). Such applications require models that are sensitive to engine loads without having to explicitly model the engine, catalytic converter, and tailpipe behavior.

[1] $$MOE_m = \sum_{i=0}^{3}\sum_{j=0}^{3}(K_{i,j}^{m} \times u^i \times a^j)$$

[2] $$MOE_m = e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(K_{i,j}^{m} \times u^i \times a^j)}$$

[3] $$MOE_m = \begin{cases} e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(L_{i,j}^{m} \times u^i \times a^j)} & \text{for } a \geq 0 \\ e^{\sum_{i=0}^{3}\sum_{j=0}^{3}(M_{i,j}^{m} \times u^i \times a^j)} & \text{for } a < 0 \end{cases}$$

Where:

$MOE_m$ = instantaneous fuel consumption or emission rate for MOE "m" (l/s or mg/s),

$K^m{}_{i,j}$ = Model regression coefficient for MOE "m" at speed power "i" and acceleration power "j",

$L^m{}_{i,j}$ = Model regression coefficient for MOE "m" at speed power "i" and acceleration power "j",

$M^m{}_{i,j}$ = Model regression coefficient for MOE "m" at speed power "i" and acceleration power "j",

$u$ = Instantaneous vehicle speed (km/h), and

$a$ = Instantaneous vehicle acceleration (km/h/s).

## DATA DESCRIPTION

This section describes the ORNL and EPA fuel consumption and emission databases that were utilized to compare the various energy and emission models prior to analyzing the model outputs in the next section. It should be noted at this point that the ORNL data were also utilized to develop the VT-Micro model while the EPA data were utilized to develop the MOBILE6 model, and thus it would be expected that these models would closely match the database that was utilized for model development.

### ORNL Energy and Emission Database

The ORNL data were gathered using vehicles that were tested both on-road and on a chassis dynamometer to characterize the entire operating range of each vehicle. Specifically, test vehicles were driven in the field in order to verify their engine parameters as functions of vehicle speed and acceleration; this was done while the vehicles drove through their entire operating envelope. Following road testing, vehicle fuel consumption and emission rates were measured in a laboratory on a chassis dynamometer within each vehicle's feasible vehicle speed and acceleration envelope based on the on-road engine parameters. Data sets were generated that included vehicle energy consumption and emission rates as a function of the vehicle's instantaneous speed and acceleration levels. Several measurements were made in order to obtain an average fuel consumption and emission rate (West *et al*. 1997). The emission data that were gathered included HC, $NO_x$, and CO emission rates.

Nine normal emitting vehicles were tested: six LDVs and three Light-Duty Trucks (LDTs). These vehicles were selected in order to produce a composite vehicle consistent with average vehicle sales in terms of engine displacement, vehicle curb weight, and vehicle type (West *et al*. 1997). The average engine size was 3.3 liters, the average number of cylinders was 5.8, and the average curb weight was 1497 kg (3300 lbs) (West *et al*.).

The data collected at ORNL contained between 1,300 to 1,600 individual measurements for each vehicle and MOE combination depending on the envelope of vehicle operation. Typically, vehicle acceleration values ranged from –1.5 to 3.7 $m/s^2$ at increments of 0.3 $m/s^2$ (-5 to 12 $ft/s^2$ at 1 $ft/s^2$ increments). Vehicle speeds varied from 0 to 33.5 m/s (0 to 121 km/h or 0 to 110 ft/s) at increments of 0.3 m/s.

The ORNL data represent a unique vehicle performance envelope. Specifically, high power-to-weight ratio vehicles have better acceleration characteristics at high speeds than their low power-to-weight ratio counterparts. This inherent performance boundary is extremely important when these models are used in conjunction with microscopic traffic flow models, as they represent a physical vehicle dynamic constraint in the car-following equations of motion. In order to represent the on-road vehicle fleet, the composite vehicle was created.

**EPA Second-by-Second Field Data**

As was mentioned earlier, the MOBILE5 model is not sensitive to the facility type and thus would estimate identical emission patterns for both a highly congested freeway and a normal density arterial with the same average speed, although each may involve a significantly different distribution for speeds and accelerations causing distinct emission levels. In order to address this limitation, EPA developed new facility-specific and area-wide drive cycles based on real-world driving studies.  These cycles have been incorporated within EPA's new MOBILE6 model (Brzezinski *et al*. 1999a). Table 2 provides a brief description of the new cycles and additional emission test cycles used for emission testing. EPA made available data from a total of 101 vehicles for 17 cycles for use in this comparison effort.

These new drive cycles include a number of high-speed freeway cycles, four moderate and congested freeway cycles, a freeway ramp cycle, three arterial/collector cycles, a local roadway cycle, and several standard cycles. The maximum speed in the cycles approaches 120 km/h (High Speed Freeway cycle) with a maximum acceleration of 11.04

km/h/s in the LA92 cycle. Apart from two observations from the 17 drive cycles, all speed/acceleration combinations were within the feasible range of the ORNL composite vehicle. Consequently, it appears that the ORNL range of coverage is consistent with field driving behavior.

Field data from these comparisons were collected in the spring of 1997 by EPA at the Automotive Testing Laboratories, Inc. (ATL) in Ohio and EPA's National Vehicle and Fuels Emission Laboratory (NVREL) in Michigan. All the vehicles at ATL were drafted at Inspection and Maintenance lanes used by the State of Ohio and tested under as-received condition (without repairs). A total of 62 vehicles in East Liberty, Ohio, and 39 vehicles in Ann Arbor, Michigan were recruited and tested. The sample of 101 vehicles included 3 heavy-duty trucks, 34 light-duty trucks, and 64 light-duty vehicles The model years ranged from 1986 through 1996 (Brzezinski *et al*. 1999b). All vehicles were tested using the standard vehicle certification test fuel. Vehicle emission tests were performed in random in order to offset any possible order bias that could result in different ambient conditions for the tested cycles. The emission results were measured as composite "bags" and in grams on a second-by-second basis for HC, CO, $NO_x$, and $CO_2$ emissions. Figure 2 illustrates a sample speed/acceleration frequency distribution for one of the test vehicles over all drive cycles. As illustrated in the figure, the majority of the speed and acceleration data occur at steady-state conditions (acceleration ranging between -1 and 1 km/h/s).

## COMPARISON OF VT-MICRO AND CMEM MODELS USING ORNL DATA

The CMEM (version 2.0) and VT-Micro model (version 1.0) predictions are compared microscopically and macroscopically. Initially, the ORNL data are utilized for comparison purposes and subsequently the EPA data are utilized. It should be noted that since the VT-Micro model was developed using the ORNL data, it is expected that the VT-Micro model closely match these data. However, the use of these data for the first round of comparisons is intended to identify any similarities and/or differences in model predictions and to identify when such differences occur. Specifically, the ORNL data are unique because they are well-calibrated second-by-second steady-state data measurements that cover the full range of the vehicle performance envelope, and thus are ideal for comparison purposes. It should be noted however, because the CMEM model is proprietary, it is difficult to actually identify the cause of any observed differences between CMEM model predictions and field data.

Two CMEM composite vehicles were created: CMEM-1, a low power-to-weight ratio vehicle that is a weighted average of categories 6 (22%), 10 (45%), and 17 (33%), and CMEM-2, a high power-to-weight ratio vehicle that is a weighted average of categories 7 (22%), 11 (45%), and 17 (33%). These composite vehicles were constructed in a similar fashion to the ORNL vehicles (no high emitters and mileage less than 50K). The following sections describe the results for the CMEM-1 composite vehicle. These results were found to be very similar to the CMEM-2 results and thus the CMEM-2 results are not presented.

In an attempt to isolate and explain the differences between the VT-Micro and CMEM models, various MOE estimates were predicted for the full envelope of operation of a typical vehicle (1,305 speed-acceleration combinations). Each speed-acceleration observation was estimated for a duration of 5 consecutive seconds to ensure steady-state behavior was attained when applying the CMEM model. It should be noted that analysis of the CMEM model predictions over time demonstrated that vehicle emissions did not change over the 5-second analysis period and thus transient and steady-state conditions were found to be identical within the CMEM model. In other words, vehicle emission estimates were found to remain constant over the 5-second analysis period regardless of how the vehicle reached steady-state conditions.

A comparison of the VT-Micro and CMEM models using the low power-to-weight ratio composite vehicle (CMEM-1) revealed a similar behavior in fuel consumption estimates as a function of the cruising mode of operation, though the CMEM model shows a discontinuous increase as speeds increase (Figure 3). These discontinuous drops in the function are most probably attributed to gear shifts within the engine modeling module of CMEM. It should be noted that the VT-Micro and CMEM model predictions differ when the vehicle engages in deceleration or acceleration maneuvers. While the CMEM model predicts a constant emission rate as a function of vehicle speed while decelerating, the ORNL data and the VT-Micro model predict rates that increase with the vehicle speed. Unlike the ORNL data, the CMEM model displays a sudden change in the fuel consumption slope around a speed of 50 km/h for a 1.5 $m/s^2$ acceleration operation. At this point it is not clear why such a behavior is exhibited within the CMEM model.

Figure 4 illustrates a similar behavior for HC emissions. There appears to be consistency between the models for the cruise mode of operation with ORNL data; however; there are inconsistencies in the deceleration and acceleration modes of operation. In addition, the CMEM model tends to underestimate vehicle HC emissions in comparison to the ORNL data and the VT-Micro model. The CMEM model estimates tend to respond marginally to increases in speeds in the range of 0 to 40 km/h, and then increase rapidly for higher speeds in the acceleration mode of operation.

The CO emissions exhibit a similar trend of behavior as compared to the HC emissions, as illustrated in Figure 5. However, the CMEM model appears to predict higher CO emissions in the 0-to 20-km/h ranges than in the 20-to 40-km/h ranges for the same acceleration (2.4 m/s$^2$). It is not clear why this trend is observed given that the engine load increases with higher speeds for the same acceleration level. This should result in higher CO emissions with higher speeds, as predicted by the ORNL data and the VT-Micro model. For example, the literature indicates that sharp accelerations, which cause vehicles to operate in a fuel-rich mode, contribute significantly to high emission levels for CO and Volatile Organic Compounds (VOCs) or HCs (NRC 1995).

In Figure 6, the ORNL data and VT-Micro model demonstrate a reduction or a slow rise in $NO_x$ emissions at high engine loads, which is not the case for the CMEM model. This decrease in $NO_x$ emissions at extremely high engine loads is consistent with what is described in the literature. For example, a National Research Council (1995) report indicates sharp accelerations commanding fuel enrichment have little effect on $NO_x$ emissions. However, mild accelerations, which do not cause fuel enrichment, increase $NO_x$ emissions (NRC 1995). Furthermore, the CMEM model estimates tend to respond marginally to speed increases in the range of 0 to 110 km/h and then respond rapidly to higher speeds for the cruise mode of operation. The CMEM model estimates also show sudden drops and rises during acceleration operation modes.

Figure 7 illustrates the microscopic comparison of ORNL data, VT-Micro model, and CMEM model for a -0.3 $m/s^2$ acceleration rate. Figure 7 demonstrates a high degree of consistency between the ORNL data and the VT-Micro model estimates for all four MOEs. Alternatively, CMEM model estimates introduce an interesting result: fuel consumption and emissions are steady in the range of 0 to 80 km/h and then increase after 80 km/h. While this behavior is not necessarily consistent with the ORNL data and the VT-Micro model estimates, more interesting is the strange $NO_x$ behavior with a sudden increase at a speed of 1 km/h and a sudden drop at a speed of 80 km/h. The fuel consumption and emission increments of the CMEM model during a deceleration mode are inconsistent with previous results (Figures 3 to 6). Also, most power-based models produce a constant emission value for the entire deceleration maneuver, because vehicles do not generate any tractive force during the deceleration operation mode.

The abnormal behaviors of the CMEM model might be attributed to the complexity of the model structure. Specifically, the CMEM model models power demands, engine speeds, and engine air/fuel ratios to estimate vehicle fuel consumption and emission rates using the instantaneous vehicle speed as a single input variable. The model attempts to capture the condition of vehicle operation among stoichiometric, enrichment, and enleanment conditions. However, the engine operation mode of a vehicle is complicated and varies by engine type, environmental conditions, driver aggressiveness, and engine temperature. Consequently, it is extremely difficult to model the engine operation condition using a single input variable, namely the instantaneous speed, especially at boundary regions.

Unfortunately, detailed descriptions of the CMEM model calibration are not discussed in the manual and thus it is difficult to explain the strange behavior that is observed with the CMEM model.

Alternatively, the VT-Micro model is derived from empirical studies and utilizes generalized and simplified procedures to capture vehicle fuel consumption and emission behavior using instantaneous vehicle speed and acceleration levels without having to model the engine operation. The study demonstrates that a more generalized empirical model can estimate vehicle fuel consumption and emission levels more accurately thatn power-based models without having to explicitly model the engine operation.

## MODEL VALIDATION AGAINST EPA FIELD DATA, MOBILE5A, AND MOBILE6

The next step in the analysis was to compare the VT-Micro and CMEM models against third-party field data collected on a chassis dynamometer and against the state-of-practice MOBILE5a and MOBILE6 model estimates. EPA second-by-second data were used for this study. For comparison purposes only, normal vehicles (50 vehicles from the dataset) were considered by using standard emission cut-points of 0.82 g/mile for HC, 10.2 g/mile for CO, and 2.0 g/mile for $NO_x$ (for the FTP bag emission results) to screen the high emitting vehicles from the vehicle fleet. Using EPA data, the mean values were estimated for the normal vehicles for each of the three emissions (HC, CO, and $NO_x$) and used for comparison purposes. It should also be noted that any trips that included vehicle start effects were excluded from the study in order to conduct a direct comparison for hot-stabilized engine operation.

In addition to the field data, the MOBILE5a and MOBILE6 models were used to estimate vehicle emissions for each cycle. This was accomplished by using the average speed and vehicle mileage of each cycle in the range of 2 to 20k per year to be consistent with the ORNL vehicle sample. A vehicle composition of 67% LDVs and 33% LDTs was used to maintain the same vehicle distribution as the ORNL data. Both MOBILE5a and MOBILE6 models were analyzed using a low altitude region. The mean values of tail-pipe emission estimates for the different vehicle mileage configurations were estimated (Figure 8).

Figure 8 illustrates an excellent correspondence between the VT-Micro model and the field data. The VT-Micro model estimates show similar tendency with the field data, except for slight overestimations on HC emissions. Specifically, the VT-Micro model estimates respond to the increase in HC emissions for the "ART E-F" and Ramp cycles in a fashion that is consistent with the field data. Figure 8 illustrates excellent fit the VT-Micro model has between the CO and $NO_x$ estimates and the EPA mean values.

Shortcomings of the MOBILE5a model are also shown in Figure 8. While the field data and the VT-Micro model indicate an increase in vehicle emissions for the Ramp cycle with its aggressive accelerations, the MOBILE5a model indicates a reduction in vehicle emissions. This limitation is attributed to the fact that the MOBILE5a model uses the average speed as a single traffic-related explanatory variable, which ignores the acceleration levels involved in the drive cycle.

The MOBILE6 estimates over various driving cycles are shown in Figure 8. The major improvements of the MOBILE6 model are clearly evident when compared to the MOBILE5a model estimates. Specifically, the MOBILE6 model estimates are consistent with cycle-to-cycle variations in the EPA data except for slight overestimations for all MOEs. Specifically, all three emission estimates are higher for the RAMP cycle with its more aggressive acceleration behavior. It is not surprising that the MOBILE6 model follows the cycle-to-cycle variations in vehicle emissions given that the model was developed using these data and cycles.

Figure 8 also illustrates the CMEM model estimates for various cycles. In order to compare the models, the 50 EPA normal vehicles were categorized into the CMEM categories (class 4 for 7 vehicles, class 5 for 19, class 6 for 1, class 7 for 3, class 8 for 1, class 11 for 8, class 16 for 8, class 17 for 2, and class 18 for 1). All 14 drive cycles were simulated using each of the CMEM vehicle classes to compute a weighted average CMEM model emission estimate. The CMEM model estimates appear to generally follow the EPA mean values. However, the CMEM model generally underestimates $NO_x$ emissions and does not capture cycle-to-cycle variations accurately. For example, CMEM CO emissions increase for the Freeway G drive cycle and the Arterial C-D drive cycle, whereas the field data, MOBILE6, and VT-Micro models indicate no increase for the Freeway G cycle and the Arterial C-D cycle.

## SUMMARY FINDINGS AND CONCLUSIONS

The performance of various fuel consumption and emission models was compared using two sources of data: ORNL and EPA. The general conclusions of the study can be summarized as follows:

a) The CMEM model exhibits some abnormal behaviors. The model approximates constant MOE estimates during deceleration maneuvers. The $NO_x$ emissions do not exhibit the typical decay in emission rates at high engine loads, and the CO emission estimates exhibit strange behavior at low speeds and high acceleration levels (sudden drops of emissions). In addition, the model generally underestimates MOEs for acceleration maneuvers when compared to EPA field data and ORNL data.

b) MOBILE5a model estimates show poor prediction when compared to EPA field data. MOBILE6 prediction show consistency with EPA field data and the VT-Micro model over various driving cycles.

c) The VT-Micro model is valid in terms of absolute hot-stabilized, light-duty normal vehicle tailpipe emissions. Specifically, the emission estimates were found to follow cycle-to-cycle variations in vehicle emissions in a fashion that is consistent with field data and within the same level of magnitude as the MOBILE6 model estimates.

d) The VT-Micro model was found to reflect differences in drive cycles in a fashion that is consistent with field observations. Specifically, the model accurately captures the increase in emissions for the Ramp cycle, with its associated aggressive acceleration maneuvers, in comparison with other drive cycles.

In conclusion, the VT-Micro model is consistent with field data and can be incorporated within microscopic traffic simulation models to estimate on-road energy and emission impacts of operational-level transportation projects, including ramp metering, traffic signal coordination, and alternative Intelligent Transportation System (ITS) strategies. The development of the VT-Micro model attempts to bridge the gap between traffic simulation models, traditional transportation planning models, and environmental impact models.

Given the current power of desktop computers, the implementation of any of the models presented in this paper adds an acceptable computational overhead to a microscopic simulation model. The benefit of this integration would be substantial when considering that current environmental models are quite insensitive to traffic and driver-related factors on vehicle emissions. The models developed in this study have been incorporated within the microscopic traffic simulation tool INTEGRATION to further demonstrate their application and relevance to traffic engineering studies (Rakha *et al*. 2000; Rakha and Ahn, 2003).

Further research is required to expand the domain of applicability of the VT-Micro model for the modeling of different light duty vehicle and truck categories, for the modeling of heavy duty trucks, for the modeling of high emitters, and the modeling of vehicle start effects on vehicle emissions.

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**Table 1: Sample Coefficients of Hybrid Regression Model (HC Emissions for Composite Vehicle)**

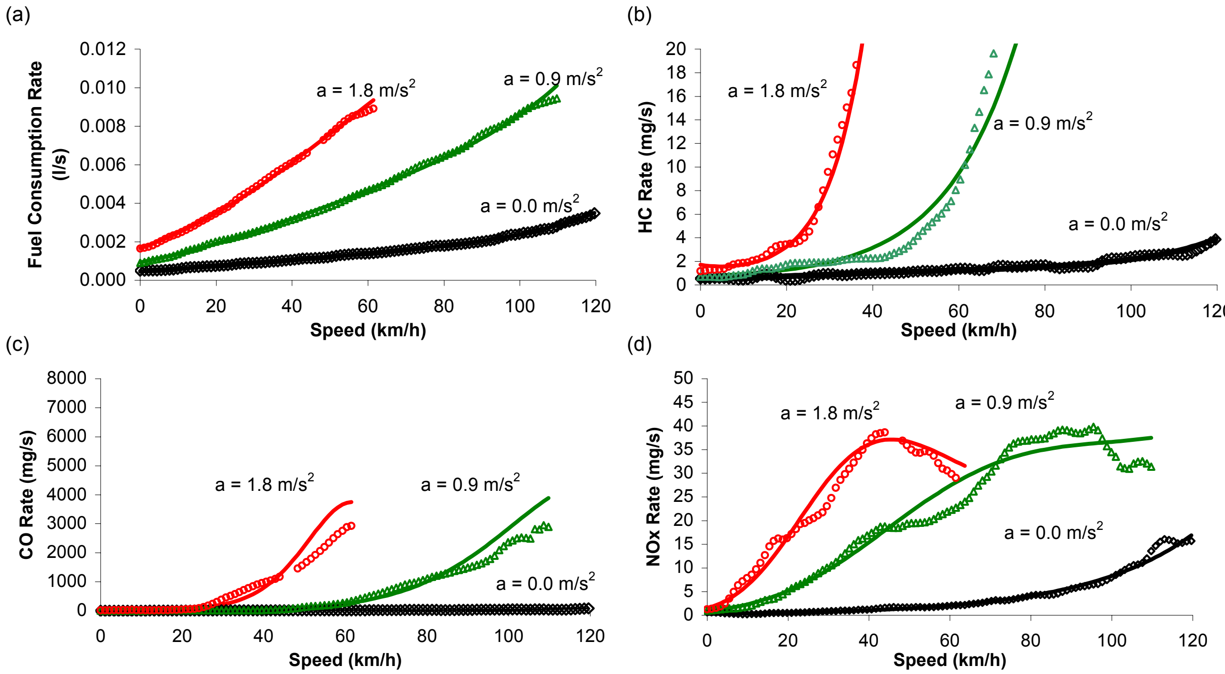
| Positive Acceleration Coefficients | Constant | Speed | $Speed^2$ | $Speed^3$ |
|---|---|---|---|---|
| Constant | -0.89611 | 0.036991 | -0.00048 | 2.78E-06 |
| Acceleration | 0.067323 | 0.008482 | -0.00038 | 3.36E-06 |
| $Acceleration^2$ | 0.034822 | -0.00527 | 0.000261 | -1.6E-06 |
| $Acceleration^3$ | -0.00225 | 0.000381 | -1.5E-05 | 9.74E-09 |
| **Negative Acceleration Coefficients** | **Constant** | **Speed** | **$Speed^2$** | **$Speed^3$** |
| Constant | -0.89611 | 0.030522 | -0.00031 | 1.71E-06 |
| Acceleration | -0.12923 | 0.020706 | -0.00037 | 1.74E-06 |
| $Acceleration^2$ | -0.00798 | 0.002835 | -3.9E-05 | 1.55E-07 |
| $Acceleration^3$ | -0.00053 | 0.000143 | -6.9E-07 | -2E-09 |

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

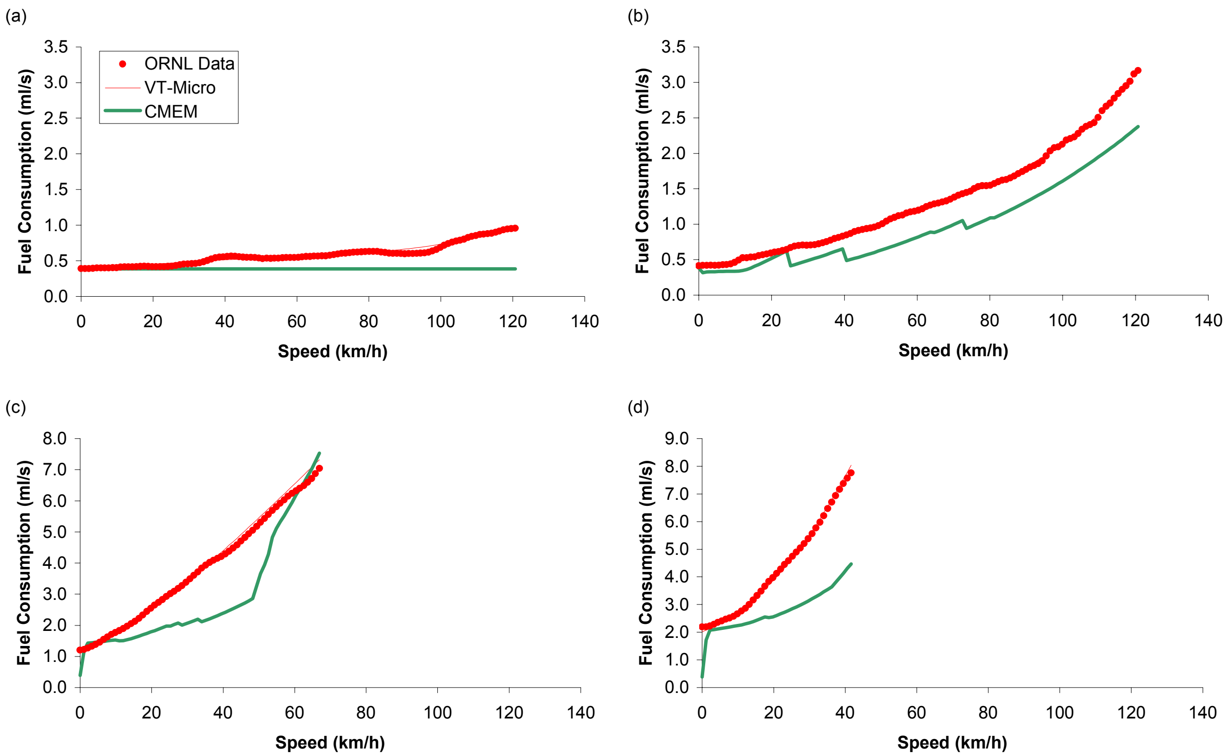
**Table 2: EPA's New Facility-Specific Drive Cycle Characteristics**

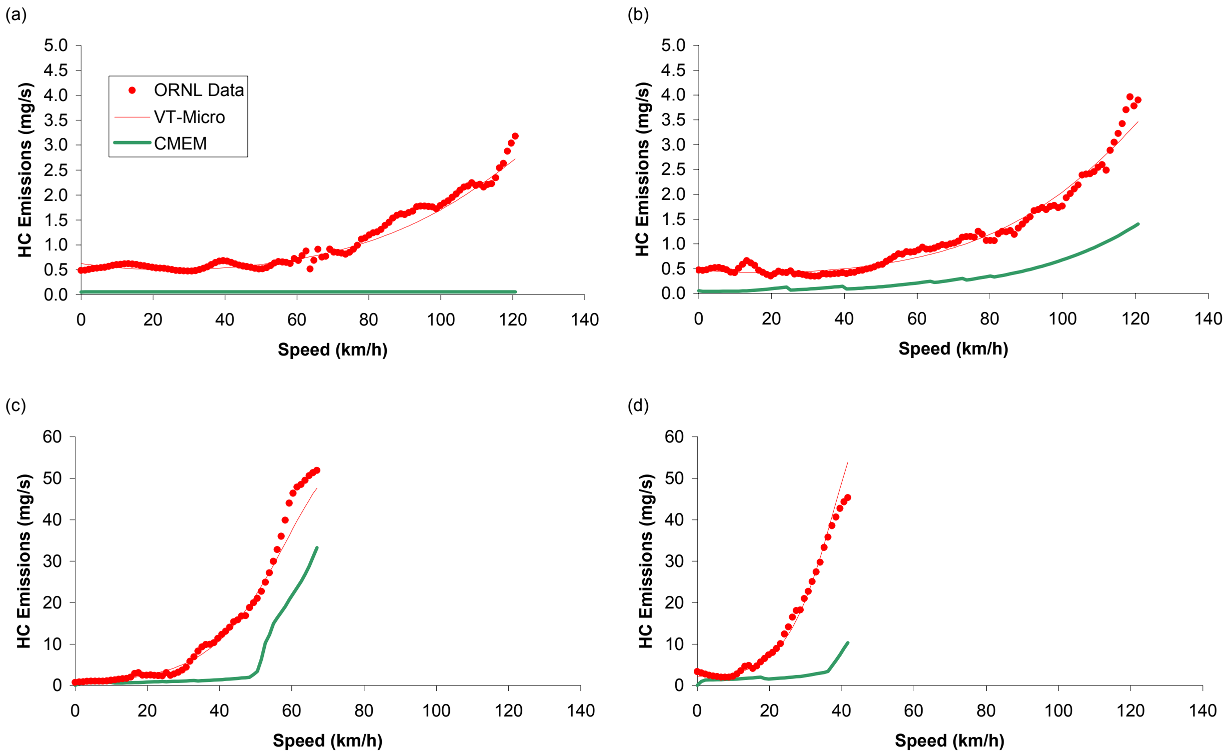
| Cycle | Avg. Spd (km/h) | Max. Spd (km/h) | Max. Accel (km/h/s) | Duration (s) | Length (km) |
|---|---|---|---|---|---|
| Freeway, High Speed (High Speed) | 101.12 | 119.52 | 4.32 | 610 | 17.150 |
| Freeway, LOS A-C (Fwy AC) | 95.52 | 116.96 | 5.44 | 516 | 13.680 |
| Freeway, LOS D (Fwy D) | 84.64 | 112.96 | 3.68 | 406 | 9.540 |
| Freeway, LOS E (Fwy E) | 48.80 | 100.80 | 8.48 | 456 | 6.180 |
| Freeway, LOS F (Fwy F) | 29.76 | 79.84 | 11.04 | 442 | 3.660 |
| Freeway, LOS G (Fwy G) | 20.96 | 57.12 | 6.08 | 390 | 2.270 |
| Freeway Ramps (Ramp) | 55.36 | 96.32 | 9.12 | 266 | 4.100 |
| Arterial/Collectors LOS A-B (Art AB) | 39.68 | 94.24 | 8.00 | 737 | 8.110 |
| Arterial/Collectors LOS C-D (Art CD) | 30.72 | 79.20 | 9.12 | 629 | 5.380 |
| Arterial/Collectors LOS E-F (Art EF) | 18.56 | 63.84 | 9.28 | 504 | 2.590 |
| Local Roadways (Local) | 20.64 | 61.28 | 5.92 | 525 | 2.990 |
| Non-Freeway Area-Wide Urban Travel (Area) | 31.04 | 83.68 | 10.24 | 1348 | 11.600 |
| LA04 (FTP Bag 2 and Bag 3) | 31.36 | 90.72 | 5.28 | 1368 | 11.920 |
| Running 505 | 40.96 | 90.72 | 5.28 | 505 | 5.744 |
| LA 92 | 39.36 | 107.52 | 11.04 | 1435 | 15.696 |
| ST01 | 32.32 | 65.60 | 8.16 | 248 | 2.224 |
| New York Cycle (NY) | 11.36 | 44.32 | 9.6 | 600 | 1.888 |

List of Figures

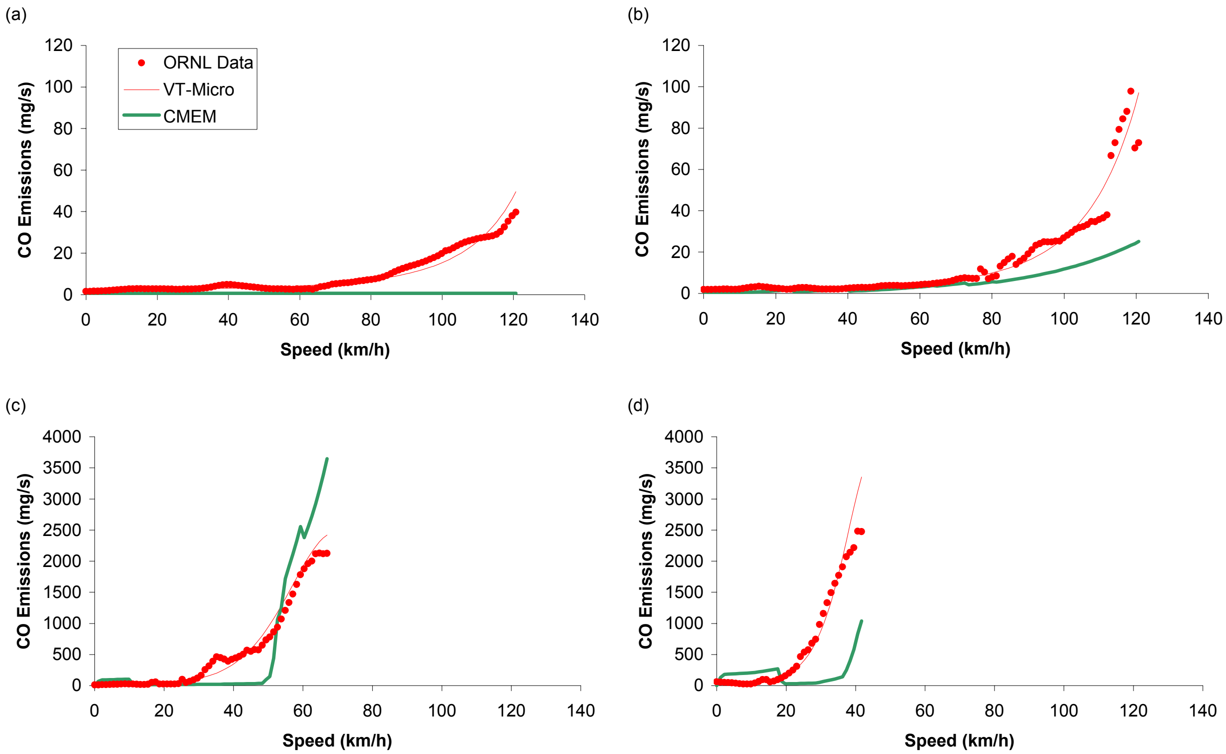

(a)
Fuel Consumption Rate (l/s)
a = 1.8 m/s²
a = 0.9 m/s²
a = 0.0 m/s²
Speed (km/h)
(b)
HC Rate (mg/s)
a = 1.8 m/s²
a = 0.9 m/s²
a = 0.0 m/s²
Speed (km/h)
(c)
CO Rate (mg/s)
a = 1.8 m/s²
a = 0.9 m/s²
a = 0.0 m/s²
Speed (km/h)
(d)
NOx Rate (mg/s)
a = 1.8 m/s²
a = 0.9 m/s²
a = 0.0 m/s²
Speed (km/h)

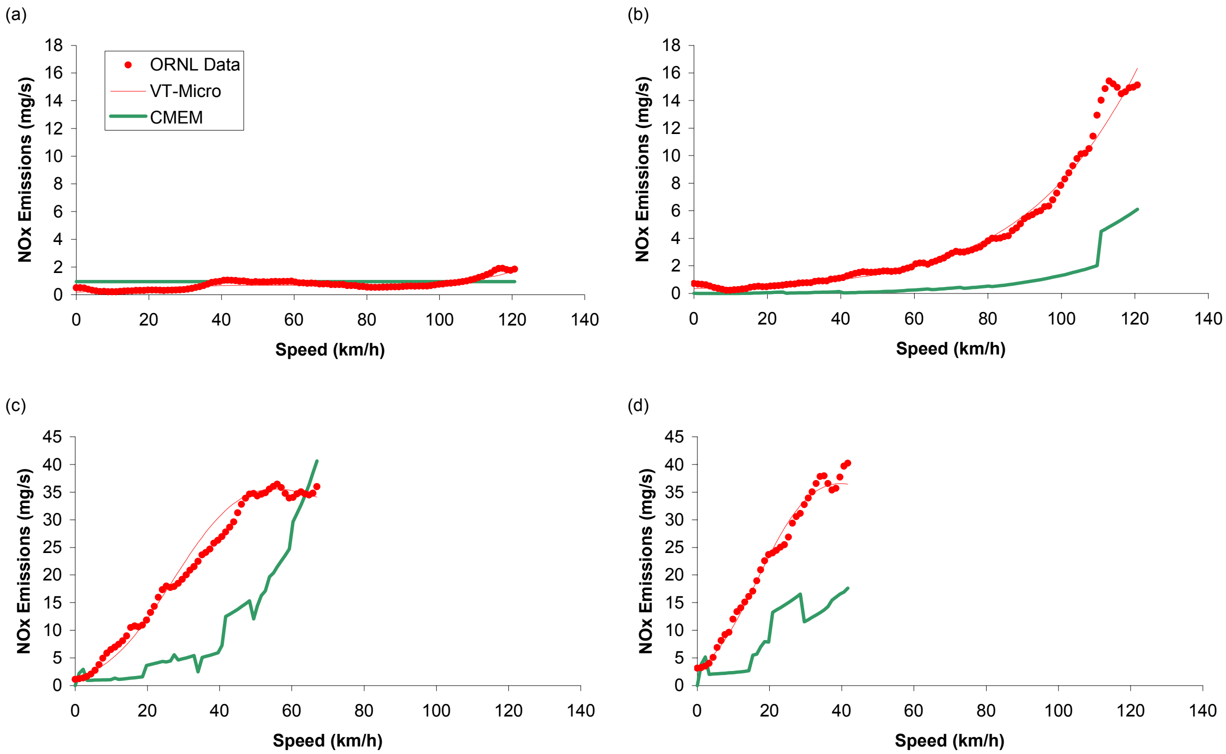
| | | Acceleration (m/s2) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **-1.7** | **-1.4** | **-1.1** | **-0.8** | **-0.6** | **-0.3** | **0.0** | **0.3** | **0.6** | **0.8** | **1.1** | **1.4** | **1.7** | **1.9** | **2.2** | |
| **Speed (km/h)** | **5** | | | 5 | 22 | 55 | 82 | 1322 | 59 | 55 | 32 | 31 | 12 | 21 | 8 | 3 | 1707 |
| | **10** | 3 | 18 | 20 | 26 | 37 | 71 | 84 | 36 | 25 | 24 | 21 | 11 | 13 | 9 | 8 | 406 |
| | **15** | 6 | 16 | 30 | 27 | 33 | 56 | 59 | 39 | 35 | 24 | 20 | 12 | 13 | 8 | 3 | 381 |
| | **20** | 9 | 16 | 27 | 35 | 26 | 50 | 81 | 64 | 55 | 36 | 27 | 11 | 13 | 5 | | 455 |
| | **25** | 11 | 19 | 22 | 26 | 29 | 44 | 48 | 55 | 56 | 53 | 37 | 11 | 2 | 1 | | 414 |
| | **30** | 15 | 15 | 24 | 20 | 33 | 45 | 72 | 63 | 37 | 33 | 31 | 23 | 7 | 1 | | 419 |
| | **35** | 9 | 18 | 20 | 29 | 28 | 43 | 59 | 40 | 52 | 19 | 30 | 14 | 5 | 4 | | 370 |
| | **40** | 6 | 15 | 23 | 22 | 31 | 58 | 93 | 83 | 40 | 34 | 25 | 3 | 3 | | 1 | 437 |
| | **45** | 6 | 6 | 23 | 27 | 30 | 48 | 92 | 88 | 44 | 29 | 17 | | 1 | | | 411 |
| | **50** | 4 | 4 | 13 | 15 | 36 | 70 | 96 | 81 | 42 | 23 | 11 | 3 | | | | 398 |
| | **55** | 4 | 4 | 15 | 18 | 23 | 42 | 98 | 86 | 33 | 14 | 11 | 2 | | | | 350 |
| | **60** | 4 | 3 | 10 | 11 | 16 | 75 | 123 | 87 | 26 | 15 | 4 | 2 | | | | 376 |
| | **65** | 1 | 3 | 6 | 12 | 14 | 33 | 101 | 51 | 27 | 8 | 6 | 1 | | | | 263 |
| | **70** | | | 10 | 7 | 20 | 38 | 81 | 58 | 14 | 14 | 1 | | | | | 243 |
| | **75** | | | 2 | 5 | 13 | 34 | 74 | 44 | 12 | 10 | | | | | | 194 |
| | **80** | 2 | | 2 | 5 | 9 | 32 | 50 | 47 | 9 | 11 | | | | | | 167 |
| | **85** | | 2 | 4 | 4 | 7 | 37 | 78 | 53 | 11 | 4 | | | | | | 200 |
| | **90** | 1 | | 3 | 4 | 10 | 41 | 107 | 63 | 9 | 3 | | | | | | 241 |
| | **95** | | | | 1 | 13 | 52 | 178 | 69 | 5 | 2 | 1 | | | | | 321 |
| | **100** | | 1 | | 3 | 5 | 79 | 210 | 90 | 4 | | 1 | | | | | 393 |
| | **105** | | | 2 | 1 | 5 | 63 | 149 | 66 | 1 | | | | | | | 287 |
| | **110** | | | 1 | | 4 | 48 | 124 | 46 | 1 | | | | | | | 224 |
| | **115** | | | | 1 | 2 | 22 | 29 | 18 | | | | | | | | 72 |
| | **120** | | | | | | 4 | 11 | 3 | | | | | | | | 18 |
| | | 81 | 140 | 262 | 321 | 479 | 1167 | 3419 | 1389 | 593 | 388 | 274 | 105 | 78 | 36 | 15 | 8747 |

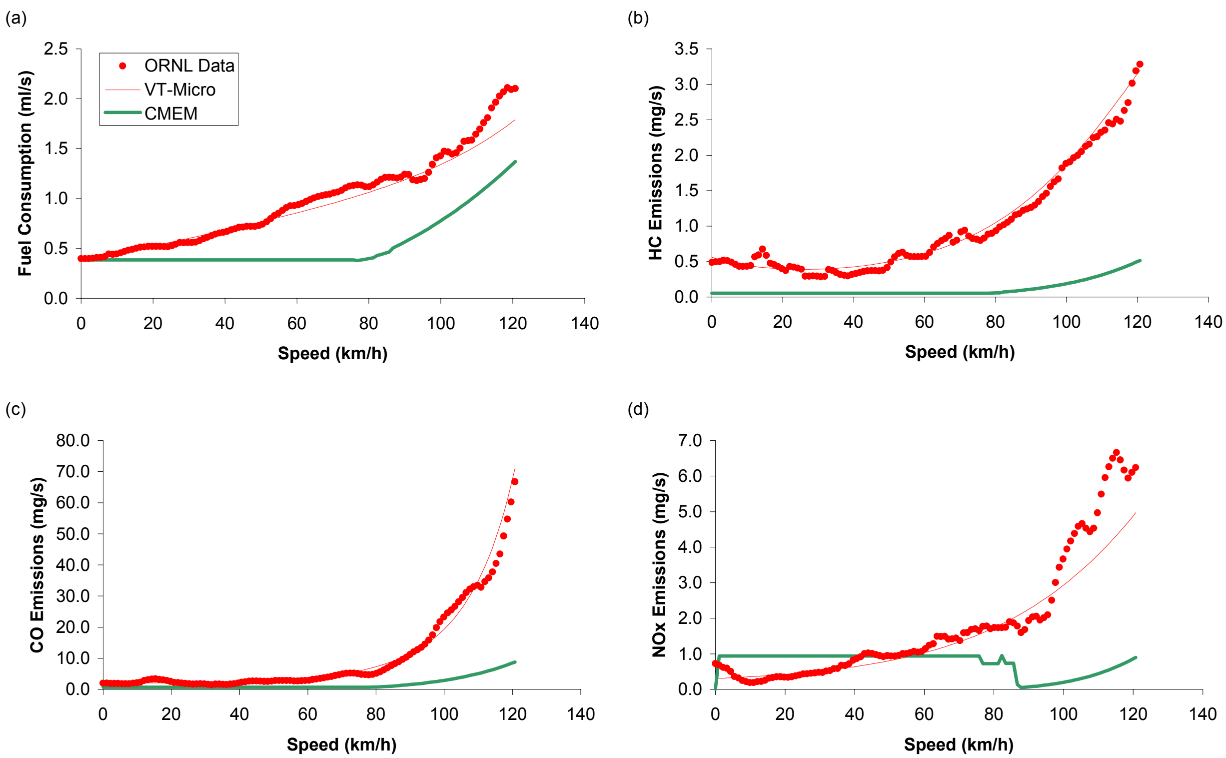

(a)
(b)
(c)
(d)
ORNL Data
VT-Micro
CMEM
Fuel Consumption (ml/s)
Speed (km/h)



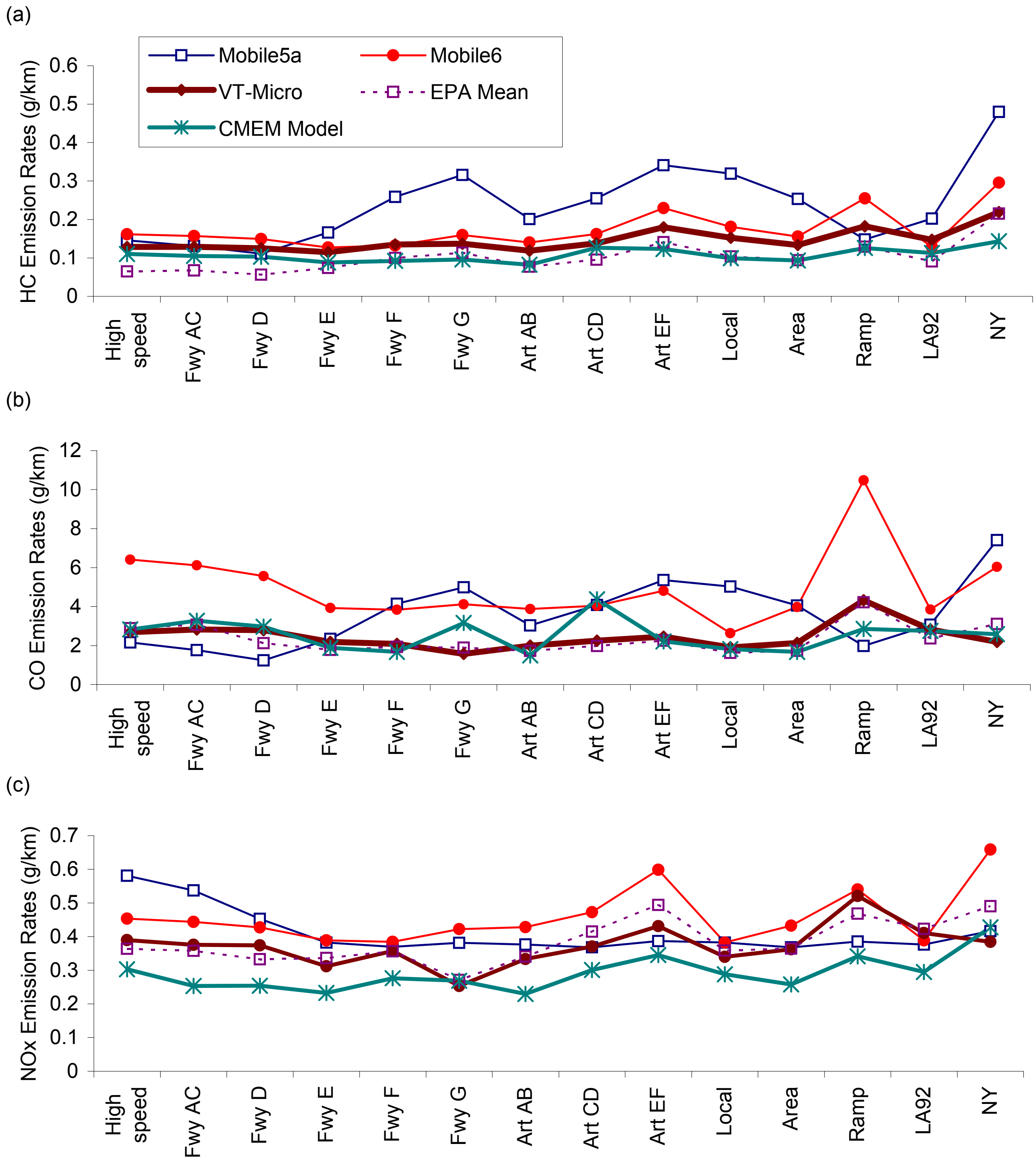
(a)
(b)
(c)
(d)
ORNL Data
VT-Micro
CMEM
HC Emissions (mg/s)
Speed (km/h)


(a)
(b)
(c)
(d)
ORNL Data
VT-Micro
CMEM
CO Emissions (mg/s)
Speed (km/h)


(a)
(b)
(c)
(d)
ORNL Data
VT-Micro
CMEM
NOx Emissions (mg/s)
Speed (km/h)



(a)
ORNL Data
VT-Micro
CMEM
Fuel Consumption (ml/s)
Speed (km/h)
(b)
HC Emissions (mg/s)
Speed (km/h)
(c)
CO Emissions (mg/s)
Speed (km/h)
(d)
NOx Emissions (mg/s)
Speed (km/h)



(a)
Mobile5a
Mobile6
VT-Micro
EPA Mean
CMEM Model
HC Emission Rates (g/km)
0
0.1
0.2
0.3
0.4
0.5
0.6
High speed
Fwy AC
Fwy D
Fwy E
Fwy F
Fwy G
Art AB
Art CD
Art EF
Local
Area
Ramp
LA92
NY
(b)
CO Emission Rates (g/km)
0
2
4
6
8
10
12
High speed
Fwy AC
Fwy D
Fwy E
Fwy F
Fwy G
Art AB
Art CD
Art EF
Local
Area
Ramp
LA92
NY
(c)
NOx Emission Rates (g/km)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
High speed
Fwy AC
Fwy D
Fwy E
Fwy F
Fwy G
Art AB
Art CD
Art EF
Local
Area
Ramp
LA92
NY