Estimating Emissions and Fuel Consumption for Different Levels of Freeway Congestion

MATTHEW BARTH, GEORGE SCORA, AND THEODORE YOUNGLOVE

To improve upon the speed correction factor methodology used by conventional emission models (i.e., MOBILE and EMFAC), the Environmental Protection Agency is introducing in its latest version of MOBILE (version 6) a new set of facility-specific driving cycles. These cycles represent driving patterns for different facility types (e.g., highway and arterial) and congestion conditions. Using a state-of-the-art comprehensive modal emissions model developed under NCHRP Project 25-11, one is able to predict the integrated emissions and fuel use values for these cycles for a wide variety of vehicle-technology categories. These facility-congestion results are then compared with steady-state emissions-fuel use measurements that were made in deriving the modal model. Furthermore, cruise modes that have mild speed perturbations are also investigated. All of these results are then compared with the speed correction equations used in the conventional emissions factor models. It is found that the mild acceleration perturbations at high speeds can lead to significantly higher emissions compared with the steady-state values. Because of this, the new high-speed freeway driving cycles (representing higher levels of service) in many cases have (modeled) emissions higher than those for the cycles that represent lower levels of service. Fuel consumption by speed does not change drastically in the comparisons.

Mobile source emissions estimates used throughout the United States for development of air pollution abatement strategies rely heavily on the regional emission inventory models EMFAC [developed by the California Air Resources Board (*1*)] for California and MOBILE [developed by the Environmental Protection Agency (EPA) (*2*)] for the remaining 49 states. These models produce mobile source emissions inventories based on two processing steps: first, determination of a set of *emissions factors* that specifies the rate at which emissions are generated, followed by determination of an estimate of *vehicle activity*. The emissions inventory is then calculated by essentially multiplying the values obtained in these two steps. The current methods used for determination of emissions factors are based on laboratory-established emissions profiles for a wide range of vehicles with different types of emissions control technologies. The emissions factors are produced on the basis of average driving characteristics embodied in a predetermined driving cycle, known as the Federal Test Procedure (FTP) (*3*). This test cycle was originally developed in 1972 as a certification test and has a specified driving trace of speed versus time, which is intended to reflect actual driving conditions both on arterial roads and on highways. Emissions of carbon monoxide (CO), oxides of nitrogen (NOx), and hydrocarbons (HCs) are integrated and collected for three sections of the cycle (called *bags*) and are used as base emissions rates.

Adjustments are then made to the base emissions rates through a set of correction factors. There are correction factors for each bag, which are used to adjust the basic emissions rates to reflect the observed differences between the different modes of operation. There are also temperature correction factors and speed correction factors, used to adjust the emissions rates for non-FTP speeds. These speed correction factors are derived from limited off-cycle testing [speeds greater than 92 km/h (57 mph), accelerations greater than 5.3 km/h-s (3.3 mph-s)] performed with laboratory dynamometers.

It has been recognized that FTP does not accurately characterize today's actual driving behavior. When FTP was established two decades ago, it was intended to exercise a vehicle in a manner similar to the operation of a typical in-use urban vehicle; however, it did not include off-cycle vehicle operation, a common event in the operation of vehicles today. An additional problem is that the speed correction cycles used to update the current models do not properly represent either facility-specific or areawide travel in urban areas. These speed correction cycles were not developed from data representative of vehicle operation in urban areas.

In the current MOBILE version, only large, regional emissions inventories can be produced. There is no mechanism to produce facility-specific emissions inventories, that is, emissions for specific roadway facilities such as highways, highway ramps, main arterials, residential roads, and so on. This is a critical issue, since driving patterns vary greatly, depending on road type. Two "trips" that have the same average speed will have drastically different emissions results depending on whether the trip was made on arterials or on a freeway.

To address these problems, EPA is introducing into its latest version of MOBILE [MOBILE version 6 (MOBILE6), to be released in late 1999] a new modeling methodology that uses facility-specific driving cycles for inventory development. Several facility-specific cycles have been created for a wide range of roadway types and congestion levels. These cycles are described in further detail in the next section.

Modal emissions models are under development as an alternative to use of the speed correction methodology of the conventional emissions models. Modal emissions models are designed to predict emissions as a function of vehicle operating mode, such as different levels of steady-state cruise, idle, and various acceleration and deceleration levels. If all of the second-by-second vehicle velocity patterns are known for a traffic network, then a comprehensive modal emissions model can be applied to predict overall second-by-second or integrated emissions. However, the computational burden and massive data handling associated with this technique can quickly become unruly for large networks.

One of the key advantages of an accurate modal model is that, for any given driving cycle, one can estimate emissions (and fuel consumption) in place of performing expensive dynamometer testing.

College of Engineering, Center for Environmental Research and Technology, University of California, Riverside, CA 92521.

As an example of this, a state-of-the-art modal emission model was applied to the facility-congestion cycles developed by EPA for MOBILE6. This modal emissions model is being developed for light-duty vehicles (LDVs) under the sponsorship of NCHRP (Project 25-11). The overall objective of this research project is to develop and verify a modal emissions model that accurately reflects LDV (i.e., cars and light trucks) emissions produced as a function of the vehicle's operating mode. In this project, approximately 320 in-use vehicles have been randomly recruited and tested on a single-roll, 1.2-m (48-in.) dynamometer over three different driving cycles: (*a*) the FTP, (*b*) the high-speed US06 cycle (*4*), and (*c*) a specially designed modal emissions cycle [MEC01, which is described elsewhere (*5*):]. For each of these cycles, second-by-second engine-out and tailpipe carbon dioxide (CO_2), CO, NOx, and HC emissions data have been collected. On the basis of these measured emissions data, a modal emissions model is being developed to estimate vehicle emissions under several operating modes.

In the study described in this paper, emissions and fuel consumption were investigated as a function of speed. Steady-state speed modes have been extracted from the emissions data that were measured as part of the vehicle testing used to derive the comprehensive modal emissions model. These modes are then compared to the model emissions results for the facility-congestion cycles. Furthermore, emissions and fuel use associated with cruise modes that have mild speed perturbations are analyzed, and all of these results are compared with the speed correction equations used in the conventional emissions factor models (i.e., EMFAC and MOBILE).

The next section first describes in detail the conventional model's speed correction factor methodology, followed by a description of the facility-congestion cycles developed for MOBILE6. Further details on the NCHRP modal emissions model are then provided. This is followed by a description of the analysis and the corresponding results.

SPEED CORRECTION FACTOR METHODOLOGY

The conventional emissions models use baseline emission factors (in grams per mile) that are modified by several correction factors, such as temperature, fuel type, and speed. The cold- and warm-start emissions measured in Bags 1 and 3 are not corrected with respect to speed; however, the vehicle's hot-stabilized running emissions are corrected by speed normalized to the average speed of the Bag 2 cycle. These speed correction factors (SCFs) are given as:

$$\text{Running emissions factors } (V) = \text{Bag 2 emissions factors} \cdot \text{SCF } (V) \quad (1)$$

FTP's bag 2 driving cycle has an average speed of (26 km/h) (16 mph), and V in Equation 1 is the average trip speed at which the emissions are to be estimated. The SCF equations have been established by measuring emissions factors for a large number of vehicles by using over 12 different driving cycles with average speeds in the range of 4 to 104 km/h (2.5 to 65 mph). Regression analysis is then applied to determine various coefficients associated with the different average speed values.

Both MOBILE and EMFAC apply this SCF methodology for their model vehicle groups. For EMFAC, the SCFs are determined separately for two technology groups: light-duty automobiles (LDAs) and light-duty trucks (LDTs). For post-model-year (post-MY) 1986 vehicles, the SCFs have the following forms (EMFAC):

$$\text{HC: } SCF_{HC}(V) = \exp[A_{HC} \cdot (V-16) + B_{HC} \cdot (V-16)^2 + C_{HC} \cdot (V-16)^3 + D_{HC} \cdot (V-16)^4] \quad (2a)$$

$$\text{CO: } SCF_{CO}(V) = \exp[A_{CO} \cdot (V-16) + B_{CO} \cdot (V-16)^2 + C_{CO} \cdot (V-16)^3 + D_{CO} \cdot (V-16)^4] \quad (2b)$$

$$\text{NOx: } SCF_{NOx}(V) = [A_{NOx} \cdot (V-16) + B_{NOx} \cdot (V-16)^2 + C_{NOx} \cdot (V-16)^3 + 1] \cdot 16/V \quad (2c)$$

where V represents the average speed in miles per hour. The SCFs are normalized on the basis of the Bag 2 average speed of 26 km/h (16 mph). The regression coefficients in Equation 2 differ slightly year by year. For the comparative analysis described in a later section, the following four general vehicles are considered: MY 1989 to 1992 LDAs, MY 1995 to 1997 LDAs, MY 1988 to 1993 LDTs, and MY 1995 to 1997 LDTs. These four categories have the regression coefficients specified in Table 1.

TABLE 1 Coefficients in SCFs of EMFAC7G

89-92 LDA	A	B	C	D
HC	-0.041455954	0.003353255	-0.000155642	0.0000022066
CO	-0.054141297	0.002181699	-0.0000781456	0.0000012643
NOx	0.022648186	-0.000905793	0.0000720429	
95-97 LDA	**A**	**B**	**C**	**D**
HC	-0.043025527	0.003394755	-0.000144306	0.0000019206
CO	-0.061011205	0.00176114	-0.0000357307	0.0000005498
NOx	0.022465859	-0.0009262	0.0000696816	
88-93 LDT	**A**	**B**	**C**	**D**
HC	-0.041653417	0.003358476	-0.000154216	0.0000021706
CO	-0.055005576	0.00212879	-0.0000728095	0.0000011744
NOx	0.022625248	-0.00090836	0.0000717458	
95-97 LDT	**A**	**B**	**C**	**D**
HC	-0.041653417	0.003358476	-0.000154216	0.0000021706
CO	-0.055005576	0.00212879	-0.0000728095	0.0000011744
NOx	0.022625248	-0.00090836	0.0000717458	

NEW FACILITY-SPECIFIC SPEED CORRECTION CYCLES

EPA is introducing into its latest MOBILE6 model a new methodology that uses facility-specific driving cycles for inventory development. Under contract to EPA, Sierra Research (*6*) has created several facility-specific driving cycles on the basis of matching speed-acceleration frequency distributions for a wide range of roadway types and congestion levels. These cycles have been developed on the basis of a large amount of "chase car" and instrumented vehicle data collected in the cities of Spokane, Washington; Baltimore, Maryland; Atlanta, Georgia; and Los Angeles, California. The congestion level was recorded as different level-of-service (LOS) values based on traffic densities observed from the chase car. These LOS measures are similar to those developed by TRB (*7*), which FHWA uses to categorize congestion. For freeways (i.e., noninterrupted flow), LOS is a function of both average vehicle speed and traffic flow rate. Primarily due to intervehicle interaction at higher levels of congestion (corresponding to LOS values of B, C, D, E, and F), vehicles will have substantially different velocity profiles under different LOS conditions. Under LOS A, vehicles will typically travel near the highway's free-flow speed, with little acceleration or deceleration perturbations. As LOS conditions get progressively worse (i.e., LOSs B, C, D, E, and F), vehicles will encounter lower average speeds with a greater number of acceleration and deceleration events.

Six driving cycles have been developed for freeway driving. These cycles range from high-speed driving (LOS A+, where vehicles have little or no interaction with other vehicles) to driving in near gridlock conditions (LOS F–). Cycle lengths range from 4 to 12 min, and the cycles were constructed to optimally match the observed speed-acceleration and specific power frequency distributions of the on-road vehicle data (*6*). These cycles are shown in Figure 1. The general characteristics of these cycles are shown in Table 2. The cycle characteristics include average speed (miles per hour), maximum speed (miles per hour), maximum acceleration rate (miles per hour-second), cycle length in terms of time (seconds) and distance (miles), and K_{max}, the maximum specific energy (defined as 2 · velocity · acceleration, in units of miles per hour squared-second). Other

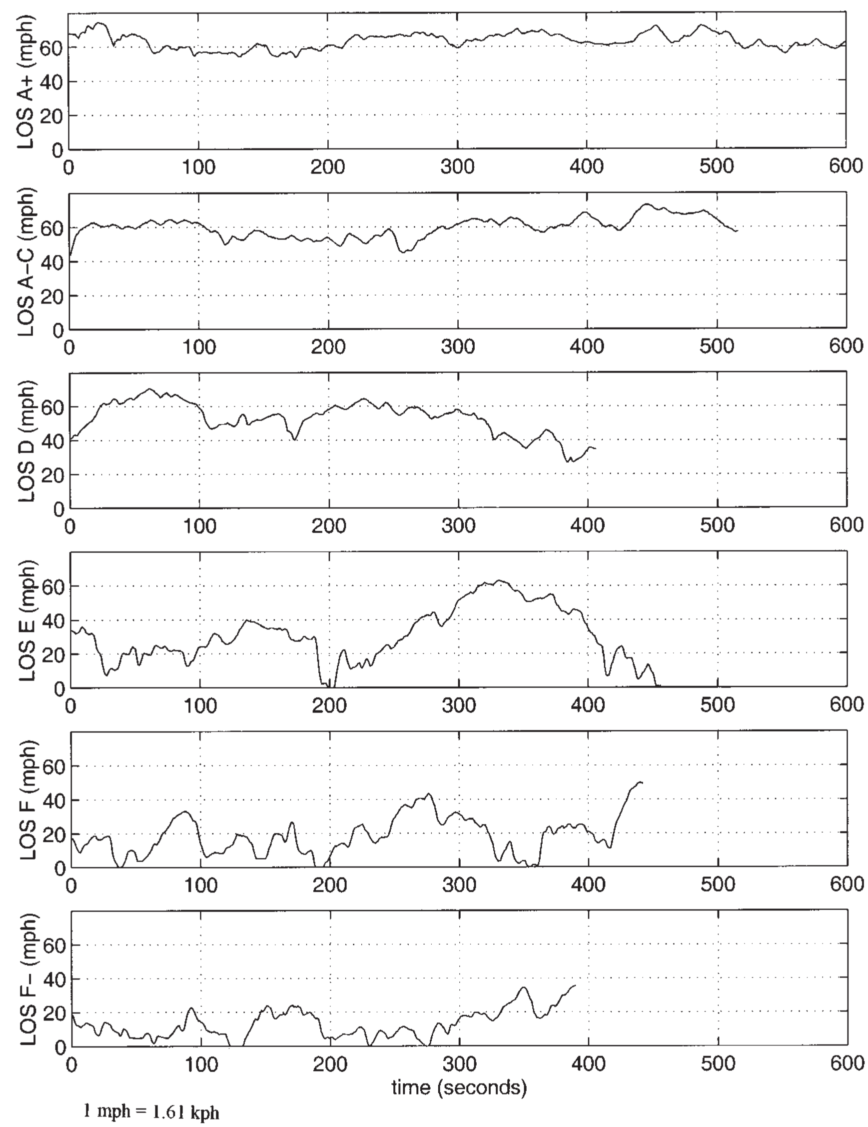


FIGURE 1 Freeway congestion cycles.

TABLE 2 Freeway Congestion Cycle Characteristics

Cycle	Avg Speed mph (kph)	Max Speed mph (kph)	Max Accel mph-s (kph-s)	Length seconds	Length miles (km)	Kmax (mph^2/s)
LOS A+	63.2 (101.7)	74.7 (120.2)	2.7 (4.3)	610	10.72 (17.25)	357
LOS A-C	59.7 (96.1)	73.1 (117.7)	3.4 (5.5)	516	8.55 (13.76)	307
LOS D	52.9 (85.2)	70.6 (113.6)	2.3 (3.7)	406	5.96 (9.59)	233
LOS E	30.5 (49.1)	63.0 (101.43)	5.3 (8.5)	456	3.86 (6.21)	227
LOS F	18.6 (29.9)	49.9 (80.3)	6.9 (11.1)	442	2.29 (3.68)	215
LOS F-	13.1 (21.0)	35.7 (57.4)	3.8 (6.1)	390	1.42 (2.28)	99

driving cycles have been developed for arterial driving patterns; however, those cycles are not included in this analysis.

COMPREHENSIVE MODAL EMISSIONS MODEL

In August 1995 researchers at the University of California–Riverside (along with Marc Ross, University of Michigan, and Tom Wenzel, Lawrence Berkeley National Laboratory) began a 3-year research project, sponsored by NCHRP, to develop a comprehensive modal emissions model. The model is comprehensive in the sense that it will be able to predict emissions for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, or malfunctioning). The model is capable of predicting second-by-second tailpipe (and engine-out) emissions and fuel consumption for a wide range of vehicle-technology categories. Further background on modal emissions modeling is described elsewhere (*5,8–10*).

In Phase 1 of this project, 23 different vehicle-technology categories (Table 3) have been defined to serve as the basis for the model, as well as to guide the vehicle recruitment and testing performed in Phase 2 [details are provided elsewhere (*5*)]. Because the eventual output of the model is emissions, the vehicle-technology categories (and the sampling proportions of each) have been chosen on the basis of a group's emissions contribution as opposed to a group's actual population in the national fleet. The vehicle-technology categories have been chosen on the basis of vehicle class (e.g., car or truck), emissions control technology (e.g., no catalyst or a three-way catalyst), emissions certification standard (e.g., Tier 0 or Tier 1), power-to-weight ratio, and emitter-level category (e.g., normal emitter or high emitter). The high-emitting categories are based on generalized emissions characteristics, as discussed elsewhere in detail (*11*).

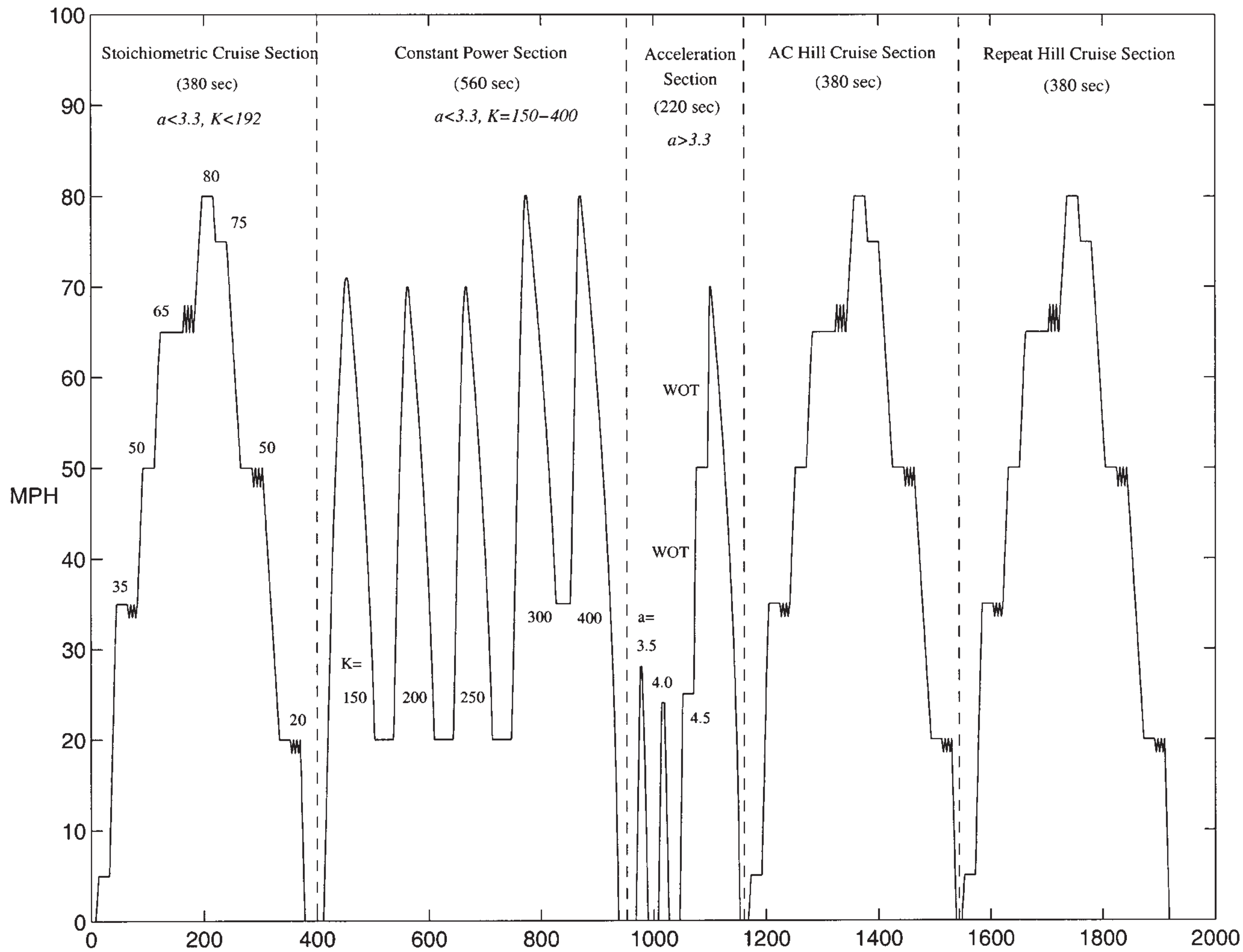
Many in-use vehicles were recruited and tested by a detailed dynamometer testing procedure, resulting in 315 valid vehicle tests. Each vehicle was tested over all three bags of FTP, US06, and a specially designed modal emissions cycle, shown in Figure 2 (*5*). For the purposes of this paper, the focus is on the first stoichiometric cruise section or "hill" that has been designed to measure emissions associated with constant-speed cruises and includes a total of nine steady-state cruise events at different speeds: 8, 56, 80, 104, 128, 120, 80, and 32 km/h, (5, 35, 50, 65, 80, 75, 50, and 20 mph). All of the acceleration rates in this section are below 5.3 km/h-s (3.3 mph-s), the maximum acceleration rate of FTP. Also note that at four of the constant-speed plateaus, there are also "speed fluctuation" events, consisting of mild accelerations and decelerations [approximately ±1.6 kph (±1 mph)], which are common phenomena during in-use driving, particularly when a vehicle is in moderate to heavy traffic.

For all cycles in the NCHRP dynamometer testing protocol, second-by-second engine-out and tailpipe emissions (CO, HC, NOx, and CO_2) data were collected. These emissions data were then used to establish a modal emissions model. The model uses a physical, power-demand modal modeling approach based on a parameterized analytical representation of emissions production. In such a physical model, the entire emissions process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions production (*9*). Each component is then modeled by use of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, and emission technology. The majority of these parameters are stated as specifications by the vehicle manufacturers and are readily available (e.g., vehicle mass, engine size, and aerodynamic drag coefficient). Other key parameters relating to

TABLE 3 Vehicle-Technology Categories Modeled

Category #	Vehicle Technology Category
	Normal Emitting Cars
1	No Catalyst
2	2-way Catalyst
3	3-way Catalyst, Carbureted
4	3-way Catalyst, FI, >50K miles, low power/weight
5	3-way Catalyst, FI, >50K miles, high power/weight
6	3-way Catalyst, FI, <50K miles, low power/weight
7	3-way Catalyst, FI, <50K miles, high power/weight
8	Tier 1, >50K miles, low power/weight
9	Tier 1, >50K miles, high power/weight
10	Tier 1, <50K miles, low power/weight
11	Tier 1, <50K miles, high power/weight
	Normal Emitting Trucks
12	Pre-1979 (<=8500 GVW)
13	1979 to 1983 (<=8500 GVW)
14	1984 to 1987 (<=8500 GVW)
15	1988 to 1993, <=3750 LVW
16	1988 to 1993, >3750 LVW
17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)
18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)
	High Emitting Vehicles
19	Runs lean
20	Runs rich
21	Misfire
22	Bad catalyst
23	Runs very rich

NOTE: 50K mi = 80,450 km.



1 mph = 1.61 kph

FIGURE 2 NCHRP modal cycle.

vehicle operation and emissions production must be estimated from the testing data.

In each vehicle-technology category specified in Table 3, "composite" vehicles have been created by combining the parameter and emissions data for all the vehicles in each category. Furthermore, for each bin in the vehicle-technology matrix in Table 3, a submodel that represents all the vehicles in a category has been created on the basis of the corresponding composite vehicle characteristics. Each submodel reflects the vehicle-technology of that particular category and estimates second-by-second emissions given vehicle operational inputs (i.e., second-by-second velocity, acceleration, grade, accessory loads, etc.). The details of the model parameterization and the compositing techniques used within the vehicle-technology categories are outside the scope of this paper and are presented in a forthcoming NCHRP final report (*10*).

METHODOLOGY

By using the measured emissions data generated for the NCHRP project and the derived modal emissions submodels, it is possible to analyze emissions and fuel consumption characteristics as a function of speed. This analysis investigates

1. Steady-state speed emissions,
2. Emissions associated with mild speed fluctuations,
3. Congestion-based emissions, and
4. Normalized SCF emissions estimates (by using SCF equations from the conventional emission models).

The method for calculating each is described below.

Steady-State Speed Emissions

To show emissions and fuel consumption results at steady-state speeds, the measured emissions values for each of the steady-state cruise modes that make up the stoichiometric cruise section described earlier and shown in Figure 2 were simply extracted. Steady-state events at 8, 32, 56, 80, 104, 120, 128 km/h (5, 20, 35, 50, 65, 75, and 80 mph) last for approximately 30 s each. Two modes exist at 80 km/h (50 mph), one with an acceleration immediately before the mode and the other with a deceleration immediately before the mode. These modes were chosen to determine the effects of previous operating conditions on emissions.

During each of these 30-s modes, the second-by-second composite vehicle emissions values are averaged for the region where the emissions are near constant. For several of the modes, the first several seconds had to be eliminated from the average since there can be significant emissions effects resulting from the previous acceleration-deceleration modes. Fuel consumption is estimated on the basis of a carbon-balance equation with knowledge of CO_2, CO, and HC. It is important to note that the steady-state emissions shown in the following results section are measured values, not modeled values.

Emissions Associated with Speed Fluctuations

Also as described earlier, there are four modes that consist of mild speed fluctuations at average speeds of 32, 56, 80, and 104 km/h (20, 35, 50, and 65 mph). These periods of mild throttle fluctuations (while maintaining speed) last approximately 20 s each. Similar to the steady-state speed emissions modes, the second-by-second composite vehicle emissions values for these periods were averaged within each mode. The results are single average numbers for CO, HC, NOx, and fuel.

Congestion-Based Emissions

To estimate emissions and fuel consumption values for different congestion levels, the six cycles described earlier and shown in Figure 1 were applied to the modal emissions model. This was done for the 23 different submodels that make up the comprehensive modal emissions model.

When showing these congestion-based emissions as a function of speed, the average speed of each congestion cycle is used. As shown in Table 2, the average speed for the cycles are 101 km/h (63 mph) for LOS A+, 94 km/h (59 mph) for LOS A to C, 85 km/h (53 mph) for LOS D, 48 km/h (30 mph) for LOS E, 29 km/h (18 mph) for LOS F, and 21 km/h (13 mph) for LOS F–.

SCF Emissions

It is possible to show plots of the conventional model's SCF equations, normalized around the measured integrated emissions values for FTP Bag 2. FTP Bag 2 emissions data exist for each composite vehicle of the vehicle-technology categories, since FTP was part of the NCHRP testing protocol. These integrated emissions values correspond to emissions at the speed of 26 km/h (16 mph), the average speed of FTP Bag 2. The SCF equations for each emission species are then applied, using the coefficients listed in Table 1.

RESULTS

The methodologies used to obtain speed-based emissions and fuel use values (described earlier) were applied to the modal emission model's vehicle-technology composite vehicles and associated submodels (Table 3). Separate plots were generated for CO, HC, NOx, and fuel for each vehicle-technology category. Because of space limitations, only four vehicle-technology categories that suitably illustrate the data and model results are selected. There are two LDA categories, one for the Tier 0 certification standard and the other for the Tier 1 certification standard (although not officially designated "Tier 0," everything before the Tier 1 certification standard is often considered to be Tier 0). Similarly, a Tier 0 category and a Tier 1 category were selected from the LDT category. The example Tier 0 LDA is represented by Composite Vehicle 5, a generalized vehicle with a three-way catalyst, fuel injection greater than 80 500 km (50,000 mi), and a high power/weight ratio (Figure 3). The example Tier 1 LDA is represented by Composite Vehicle 9, a Tier 1-certified vehicle with greater than 80 500 km (50,000 mi) and a high power/weight ratio (Figure 4). The example Tier 0 LDT is represented by Composite Vehicle 15, MY 1988 to 1993, a truck with a gross vehicle weight (GVW) of less than 3,750 (Figure 5). The example Tier 1 LDT is represented by Composite Vehicle 17, a Tier 1-certified truck with a gross vehicle weight of 3,751 to 5,750. (Figure 6).

These figures contain a wealth of information, which are interpreted below.

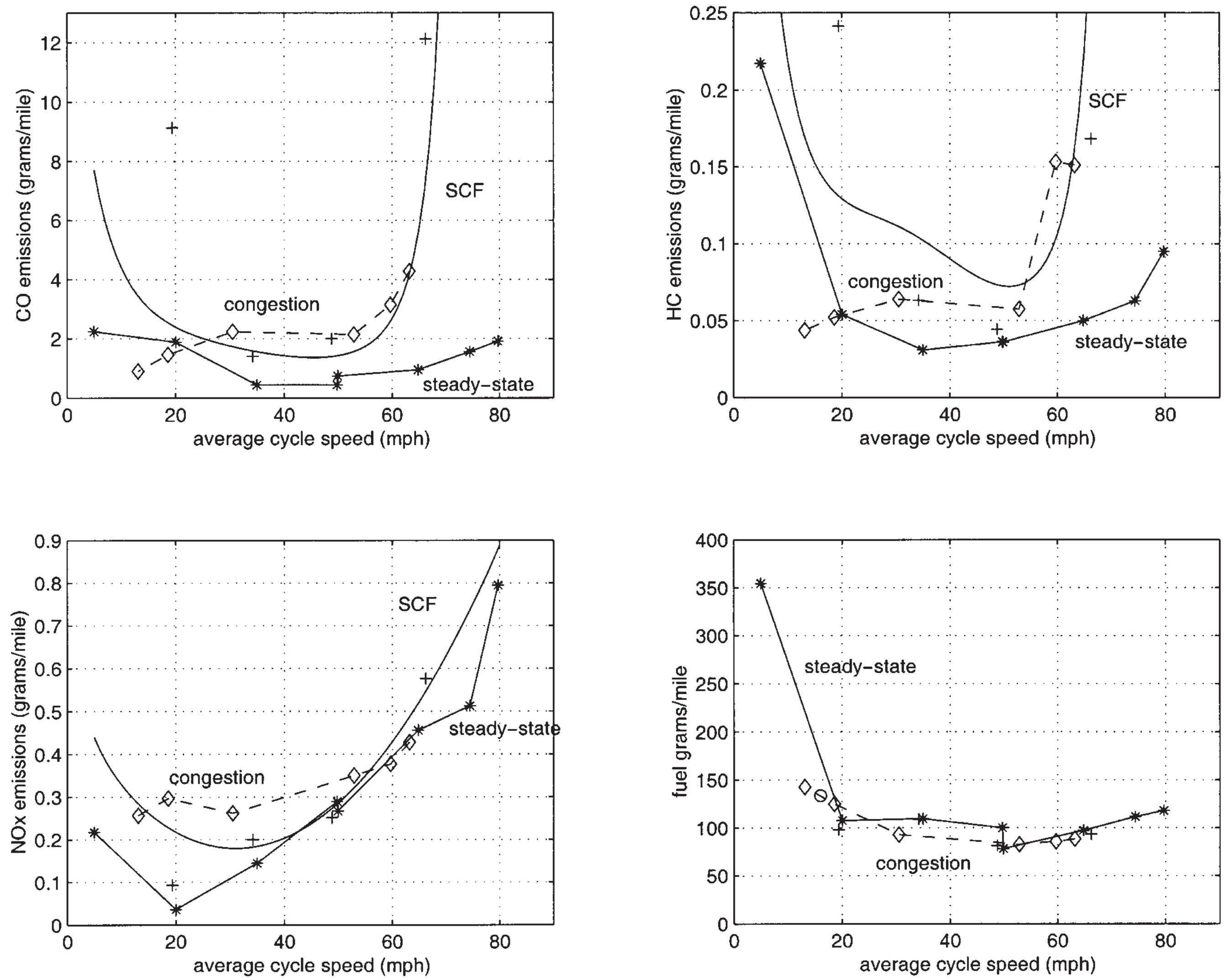
Steady-State Speed Emissions

The steady-state speed emissions are represented by stars and a solid line in the plots in Figures 3 to 6. The steady-state speed emissions in the plots for all of the composite vehicles show the lower bound of what the vehicles produce at any given speed. Since there are no associated accelerations in these modes, the power and, thus, the emissions are minimized at that particular speed. The steady-state speed plots show the typical parabolic shape of a grams-per-mile curve. This parabolic shape (high on both ends, low in the middle) arises from two factors. At low speeds, a vehicle has a relatively low grams-per-second emissions rate; however, because it spends more time on the roadway for a given unit distance, it emits for a longer period of time (i.e., its grams-per-mile rate is higher). At high speeds, much greater loads are placed on the engine, drastically increasing the grams-per-second emissions rate. The vehicle spends less time on the roadway for the given unit distance, but the increased grams-per-second rate overwhelms this effect. Emissions (in grams per mile) are typically lowest at medium speeds [i.e., 48 to 80 km/h (30 to 50 mph)]. Because fuel consumption is not as sensitive to higher speeds as emissions are, it has only a moderate increase at the high end. Both steady-state modes at 80 km/h (50 mph) are shown. It is interesting to note that in most of the plots, the stars at this point are indistinguishable. In some, however, there is a slight offset between the two, indicating that there are indeed emissions differences between the 80-km/h (50 mph) mode immediately preceded by an acceleration and that preceded by a deceleration. The mode preceded by an acceleration usually has the higher value.

Also note that for the LDTs, CO and HC emissions can be extremely high for speeds greater than 120 km/h (75 mph).

Emissions Associated with Speed Fluctuations

Emissions and fuel consumption associated with throttle fluctuations are shown by plus symbols in the plots in Figures 3 to 6. When compared with the steady-state emissions, the emissions associated with throttle fluctuations are significantly higher, particularly at higher speeds. The primary reason for these high levels of emissions at high speeds is due to very short enrichment events that occur when a vehicle accelerates only slightly at high speeds. Even a small acceleration at high speed creates a large enough load to cause a vehicle to operate with a rich mixture, resulting in emissions levels



1 mph = 1.61 kph

FIGURE 3 Emissions and fuel rates (average grams per mile) versus speed for Composite Vehicle 5. In these plots, steady-state emissions are represented by stars, fluctuation emissions by pluses, congestion emissions by diamonds, and SCF emissions by a solid line.

that can be several orders of magnitude greater (albeit short events) than those under controlled, stoichiometric conditions.

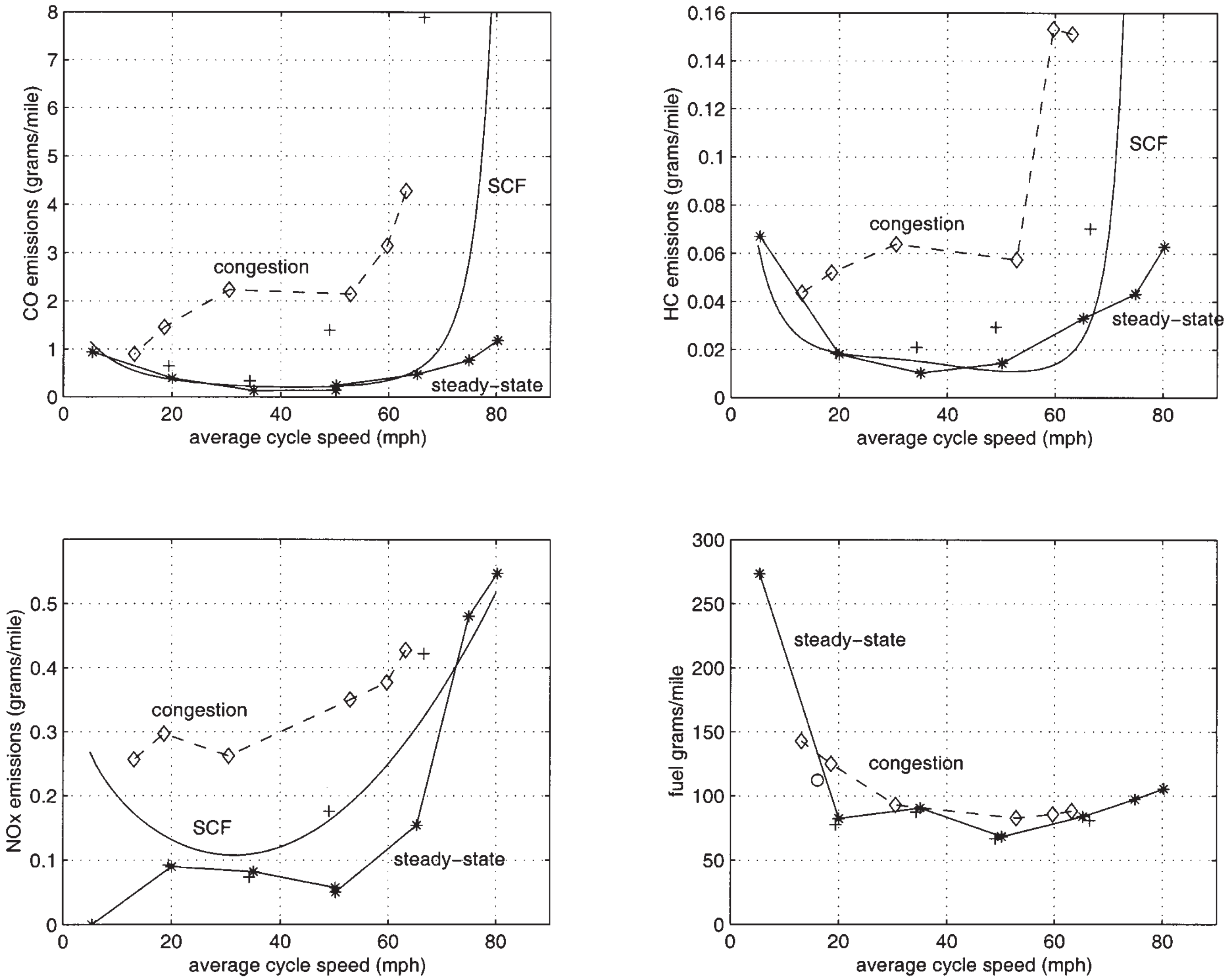
This has large implications for high-speed freeway driving. When there is a lot of traffic traveling at high speeds, small perturbations in speed (i.e., due to relatively small throttle adjustments when one vehicle follows or passes other vehicles) can cause significantly higher emissions compared with those from smoother high-speed driving. When traffic density is sufficiently low, velocity patterns tend to smooth out (e.g., people are more likely to use their cruise control) and emissions are significantly less.

Note that fuel consumption associated with these throttle fluctuations is almost no different from the steady-state speed fuel consumption.

Congestion-Based Emissions

As described earlier the congestion-based cycles (Figure 1) were applied to the modal emissions model, each time calibrated for the appropriate composite vehicle. In each of the congestion-based emissions and fuel use plots in Figures 3 to 6, each datum point (shown by a diamond and connected by a dashed line) represents the emissions or fuel use at a different LOS. The datum point farthest to the right corresponds to LOS A+ [average speed, 101 km/h (63.2 mph)], the next datum point corresponds to LOS A to C [average speed, 96.6 km/h (59.7 mph)], and so on to the farthest point on the left, which corresponds to LOS F− [average speed, 21 km/h (13.1 mph)].

One of the important implications of these curves is that for the majority of vehicles, the emissions rates (in grams per mile) are higher for better flow conditions. This is somewhat counterintuitive. At the free-flow LOS A+ level and at the LOS A to C levels, vehicles travel at high speeds with little or no major transient acceleration or deceleration events. The primary reason for this high level of emissions at high speeds is again due to the very short enrichment events that occur when a vehicle accelerates only slightly at high speeds, very similar to the fluctuation driving described in the previous section. As an example, Composite Vehicle 5 goes into enrichment only for 5 s



1 mph = 1.61 kph

FIGURE 4 Emissions and fuel rates (average grams per mile) versus speed for Composite Vehicle 9. In these plots, steady-state emissions are represented by stars, fluctuation emissions by pluses, congestion emissions by diamonds, and SCF emissions by a solid line.

during the 610-s LOS A+ cycle. This is enough to make the average emissions much higher than those for the lower LOS conditions (LOSs D, E, and F). Note that numerous acceleration and deceleration events also occur for these lower LOS conditions; however, the load placed on the engine is not as great as it is at high speeds, even though the vehicle can undergo greater acceleration events.

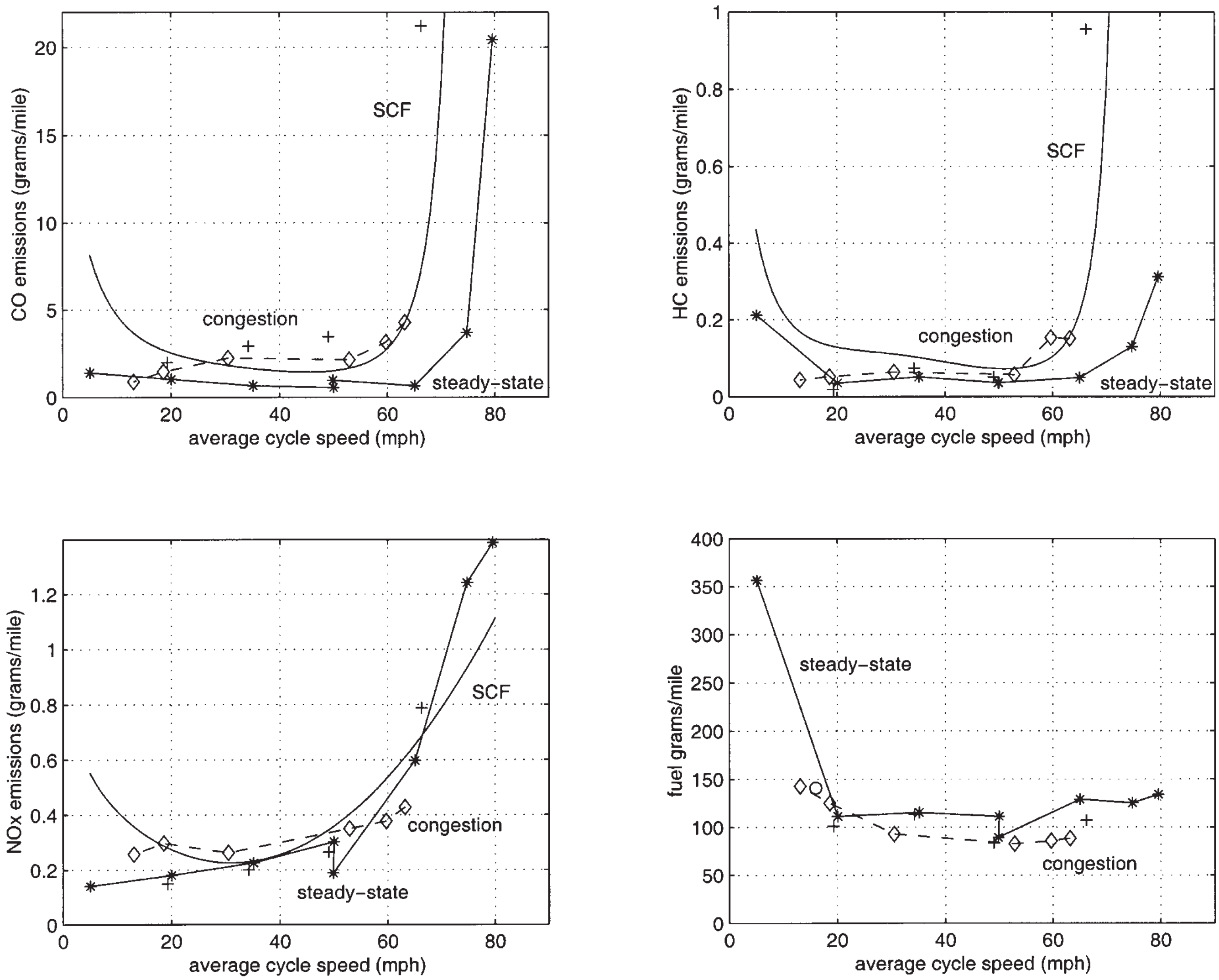
To validate these model results, only a single vehicle was tested thus far at the Vehicle Emissions Research Laboratory at the College of Engineering Center for Environmental Research and Technology, (CE-CERT), University of California–Riverside, by using the new freeway congestion cycles. The measured results for this single vehicle, although in no way a complete validation, did show the same tendencies of having higher emissions for LOS A+ than for the other LOS levels (because of short enrichment events).

Again, fuel consumption is relatively unaffected by enrichment, and the congestion-based fuel rate curves are nearly identical to the steady-state curves.

SCF Curve

The SCF curves show what the conventional emissions models would predict when they are normalized to the FTP Bag 2 emissions values for the composite vehicles. These SCF curves have the very distinctive parabolic shape, particularly for CO and HC. It is important to note that the SCF equations were derived from emissions testing that never exceeded 104 km/h (65 mph), and because these are regression curves, it is inappropriate to estimate emissions above this speed. If SCFs are used to estimate emissions above 104 km/h (65 mph), the estimates will overpredict CO and HC emissions, sometimes by several orders of magnitude.

It is interesting to note that the SCFs for NOx tend to be rather good estimates at almost all speeds, in terms of matching the steady-state emissions and congestion-based emissions. It also appears that the SCF estimates at lower speeds generally overpredict emissions for all species.



1 mph = 1.61 kph

FIGURE 5 Emissions and fuel rates (average grams per mile) versus speed for Composite Vehicle 15. In these plots, steady-state emissions are represented by stars, fluctuation emissions by pluses, congestion emissions by diamonds, and SCF emissions by a solid line.

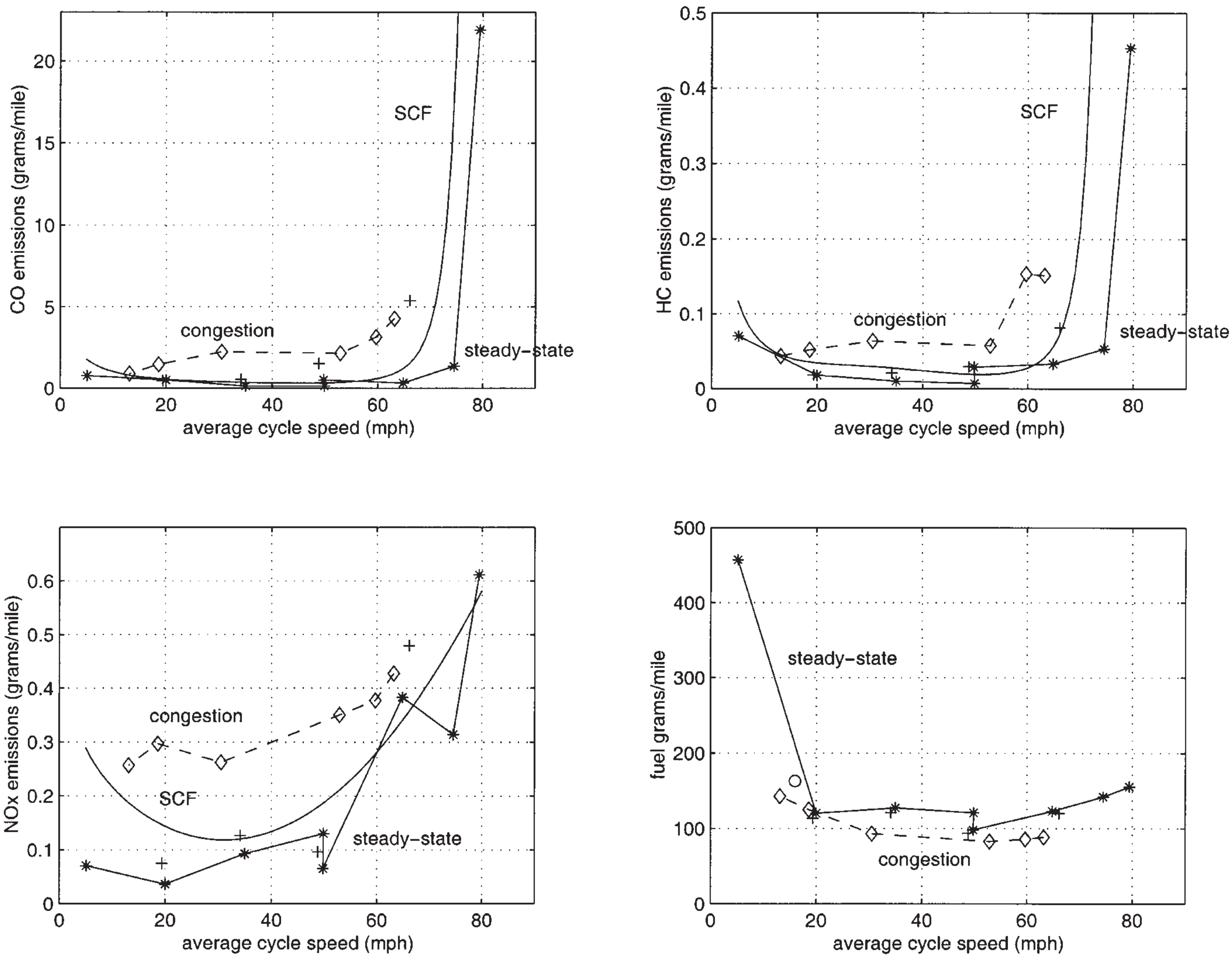
For fuel consumption, only the integrated FTP Bag 2 value is shown with a circle. It can be seen that in all cases this fuel consumption point fits in well with all of the curves.

CONCLUSIONS AND FUTURE WORK

In the present analysis, all 23 vehicle-technology categories that make up NCHRP comprehensive modal emissions model were examined. This paper has illustrated the results for only four composite vehicles, which turn out to be pretty representative of the other categories. For the four composite vehicles and associated submodels, emissions and fuel use characteristics were presented as a function of speed. The steady-state speed characteristics were derived directly from the measured emissions data. Similarly, emissions and fuel use data associated with mild speed fluctuations (while maintaining speed) were derived from measurements. Congestion-based emissions and fuel use were estimated by using facility and congestion cycles derived by EPA for use in its MOBILE6 model. These cycles were directly applied to each submodel to determine their integrated emissions and fuel use results. Lastly, the SCF equations currently used in the conventional emission models were also plotted as a function of speed. The equations were normalized around the FTP Bag 2 value for each composite vehicle.

Some of the key findings of this analysis are as follows:

- As expected, the steady-state emissions are in all cases the lowest emissions that are produced given a particular speed.
- For some of the composite vehicles, the emissions and fuel use at the steady-state modes of 80 km/h (50 mph) differed slightly, depending on whether it was immediately preceded by an acceleration event or a deceleration event.
- Emissions associated with slight speed fluctuations (while maintaining near constant speed) are in most cases significantly higher than the steady-state emissions, particularly at the higher speeds. This is primarily due to brief enrichment events that occur when small accelerations take place at high speeds.



1 mph = 1.61 kph

FIGURE 6 Emissions and fuel rates (average grams per mile) versus speed for composite vehicle 17. In these plots, steady-state emissions are represented by stars, fluctuation emissions by pluses, congestion emissions by diamonds, and SCF emissions by a solid line.

- In many cases, the congestion-based emissions are higher at better LOS flow conditions (in this case, freeway LOS). This is again caused by brief enrichment events that occur with mild accelerations at high speeds. When the vehicles operate under controlled, stoichiometric conditions, their emissions are very low. Only a few seconds of enrichment is enough to bias the integrated cycle results toward higher values.
- In general, the SCF curves match fairly well the steady-state and congestion-based emissions for the middle speeds [16 to 96 km/h (10 to 60 mph)]. The SCF results tended to be slightly high at lower speeds and substantially higher at speeds over 96 km/h (60 mph) (in particular, for CO and HC). The fact that the SCF equations were derived only from data corresponding to a maximum of 104 km/h (65 mph) implies that these SCF curves should not be used for speeds greater than this value.
- The SCF curves tended to be a reasonably good fit for NOx.
- Measured and modeled fuel consumptions for all cases (steady state, fluctuation, congestion, SCF) tend to be essentially the same.

In this modeling project, 315 valid vehicle tests were used to create the composite vehicles and associated submodels. In each vehicle-technology category, the number of vehicle tests that make up each composite vehicle is approximately 15. Statistically, this is a rather small number when considering the variability of vehicles even within the tight categorization. The uncertainty associated with both the measurements and modeling results is being estimated, and in the future these can be shown as error bars on the speed-based plots shown here. To reduce any uncertainty, more vehicles should be tested and included in the compositing and modeling process.

Furthermore, only a single vehicle has thus far been tested at CE-CERT to validate the model results of the facility and congestion driving cycles. Additional testing should be performed to thoroughly validate the model's predictions.

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