Analysis of Modal Emissions From Diverse In-Use Vehicle Fleet

MATTHEW BARTH, THEODORE YOUNGLOVE, TOM WENZEL, GEORGE SCORA, FENG AN, MARC ROSS, AND JOSEPH NORBECK

The initial phase of a long-term project with national implications for the improvement of transportation and air quality is described. The overall objective of the research is to develop and verify a computer model that accurately estimates the impacts of a vehicle's operating mode on emissions. This model improves on current emission models by allowing for the prediction of how traffic changes affect vehicle emissions. Results are presented that address the following points: vehicle recruitment, preliminary estimates of reproducibility, preliminary estimates of air conditioner effects, and preliminary estimates of changes in emissions relative to speed. As part of the development of a comprehensive modal emission model for light-duty vehicles, 28 distinct vehicle/technology categories have been identified based on vehicle class, emission control technology, fuel system, emission standard level, power-to-weight ratio, and emitter level (i.e., normal versus high emitter). These categories and the sampling proportions in a large-scale emissions testing program (over 300 vehicles to be tested) have been chosen in part based on emissions contribution. As part of the initial model development, a specific modal emissions testing protocol has been developed that reflects both real-world and specific modal events associated with different levels of emissions. This testing protocol has thus far been applied to an initial fleet of 30 vehicles, where at least 1 vehicle falls into each defined vehicle/technology category. The different vehicle/technology categories, the emissions testing protocol, and preliminary analysis that has been performed on the initial vehicle fleet are described.

To develop and evaluate transportation policy, agencies at the local, state, and federal levels currently rely on the mobile source emission-factor models MOBILE [Environmental Protection Agency (EPA)] or EMFAC [California Air Resources Board (CARB)]. Both MOBILE and EMFAC predict vehicle emissions based, in part, on average trip speeds and were built on regression coefficients based on a large number of federal test procedure (FTP) bag emission measurements. Since these models are intended to predict emission inventories for large regional areas, they offer little help in evaluating operational improvements that are more microscopic in nature, such as ramp metering, signal coordination, and many intelligent transportation system strategies. What is needed in addition to these regional types of mobile source models is an emissions model that considers at a more fundamental level the modal operation of a vehicle, that is, emissions that are directly related to vehicle operating modes, such as idle, steady-state cruise, various levels of acceleration/deceleration, and so forth.

The authors are developing a comprehensive modal emissions model under sponsorship of the National Cooperative Highway Research Program. This paper describes the initial phase of a long-term project with national implications for the improvement of transportation and air quality. The overall objective of the research is to develop and verify a comprehensive modal emissions model that accurately reflects the impacts of a vehicle's operating mode. The model is comprehensive in the sense that it will be able to predict emissions for a wide variety of light-duty vehicles (LDVs, i.e., cars and trucks) in various states of condition (e.g., properly functioning, deteriorated, malfunctioning). Other efforts and further background on modal emission modeling have been described elsewhere (*1*) and elsewhere in this Record by An et al.

A specific modal emissions testing protocol has been developed that reflects both real-world driving and specific modal events associated with different levels of emissions. This testing protocol (described later in this paper) is being applied to more than 300 vehicles to provide the foundation for the modal emissions model. As a preliminary step, the test cycle has been applied to an initial fleet of 30 vehicles, where at least 1 vehicle falls into each of the 28 defined vehicle/technology categories. The preliminary analysis of the initial test fleet is described.

VEHICLE/TECHNOLOGY CATEGORIZATION

The conventional emission inventory models are based on bag emissions data (FTP) collected from certification tests of new cars, surveillance programs, and inspection/maintenance programs. These large sets of emissions data provide the basis for the conventional emission inventory models and are indexed primarily by model year. For LDVs, groupings are based on a few different vehicle classes and technology groups.

In developing a modal emission model, we cannot base the model on these bag data and must collect second-by-second emissions data from a sample of vehicles to build a model that predicts emissions for the national fleet. The choice of vehicles for this sample is therefore crucial, since only a small sample (300+ vehicles) will be the basis for the model.

The determination of the vehicle/technology categories in the modal model is a critical task, not only for vehicle recruitment and testing but also for the development of the model. Because the eventual output of the model is emissions, the vehicle/technology categories and the sampling proportions of the major vehicle/technology groups (normal versus high emitter, and carbureted versus fuel injected versus Tier 1) have been chosen based on each major category's contribution to total emissions, as opposed to a group's actual population in the national fleet. Recent results from both remote sensing and surveillance studies have indicated that a small population of vehicles contribute a substantial fraction of the total emissions

M. Barth, T. Younglove, G. Scora, F. An, and J. Norbeck, College of Engineering, Center for Environmental Research and Technology, University of California, Riverside, Calif. 92521. T. Wenzel, Lawrence Berkeley National Laboratory, Berkeley, Calif. 94720. M. Ross, Physics Department, University of Michigan, Ann Arbor, Mich. 48109.

inventory. With this approach, more emphasis is put on testing and modeling high emitters than if based strictly on population numbers. These vehicles are not well understood, and the data and models developed here should improve this aspect of the emissions inventory modeling procedure.

A matrix of 28 vehicle/technology groups has been determined based on LDV emission certification levels and the major technology groups within these levels, as presented in Table 1. The non–Tier 1 vehicles manufactured between 1981 and 1993 are commonly referred to as Tier 0 vehicles with their corresponding Tier 0 certification standards. Tier 1 emission certification standards were introduced in 1994, as presented in Table 2. These standards for cars were phased in over a 3-year period: 40 percent of 1994 cars sold met the standards, 80 percent of 1995 cars, and 100 percent of 1996 cars.

The pre–Tier 1 (primarily Tier 0) cars were divided into groups on the basis of their emission control and fuel system technology. These groups include noncatalyst cars, two-way catalyst cars, three-way catalyst cars that are carbureted, and three-way catalyst cars with fuel injection (FI). Further, the Tier 0, three-way catalyst FI cars, as well as the Tier 1 cars, have been divided into subgroups on the basis of power/weight ratio and mileage, because these vehicle categories will dominate future emissions. Two power/weight classes have been created for each category. Different limits were selected to reflect the increase in vehicle power to weight ratios during the time these cars were available (*2*). The dividing point between low power/weight and high power/weight for the three-way catalyst, FI pre–Tier 1 groups was set at the average ratio over the 1983–1993 period (0.038 hp/lb); the average for the 1993 model year (0.043 hp/lb) was used for the Tier 1 cars.

Unlike emissions standards for cars, the federal truck emissions standards have changed several times since 1981. These changes were substantial for all three pollutants, reducing the allowable emissions of each by almost one-half. As the emissions standards changed, so did the classification of trucks by weight; the Tier 1 standards include four separate light-duty truck (LDT) standards, based on a combination of gross vehicle weight (GVW, which includes maximum payload) and loaded vehicle weight (LVW, or test weight, which is the empty or "curb" weight plus 300 lb). Since the Tier 1 LDT1 standards are identical to those for cars, these trucks (up to 3,750 GVW) will be included in the car Tier 1 categories. The LDT2 and LDT3 standards are nearly identical, so these categories have also been combined.

Data have been collected from several sources to estimate the emission contribution from each of the groupings in Table 1. Fuel system and catalyst technology distributions, along with travel fractions by model year from MOBILE5a, were multiplied by average emission rates by technology grouping. These emission rates are based on recent in-use surveillance data from CARB.

CARB regularly conducts dynamometer testing of in-use vehicles under its Light-Duty Vehicle Surveillance program (LDVSP) (*3*). For this analysis, data were used from the most recent survey, LDVSP-12, which was conducted in 1992. The vehicles tested in this survey were randomly selected by stratified random sampling on vehicle model year from the South Coast Air Basin and brought in for testing. There are several benefits of using this data source: the vehicles were tested in the condition they were received, rather than after adjustments or repairs were made that might reduce emissions; there are extensive and accurate data on the characteristics of each vehicle, including the odometer reading; and the vehicles are subject to dynamometer testing, which provides a more accurate and in-depth picture of their in-use emissions. In addition, the vehicles in LDVSP-12 were tested on CARB's new unified cycle, which was designed to be more representative of real-world driving behavior than the FTP. The only limitations with the LDVSP data are that the sample size is small (only 165 cars and light-duty trucks), and that no vehicles prior to MY83 were tested.

The CARB LDVSP-12 testing results indicate that understanding the emissions behavior of the high-emitting vehicles is critical in

TABLE 1 Vehicle Technology Matrix

Vehicle Technology Category	Phase I Test Vehicle Recruitment Targets	
Cars	**Normal emitting**	**High-emitting**
No Catalyst	1	1
2-way Catalyst	1	1
3-way Catalyst, Carburated	1	1
3-way Catalyst, FI, >50K miles, low power/weight	1	
3-way Catalyst, FI, >50K miles, high power/weight	1	1
3-way Catalyst, FI, <50K miles, low power/weight	1	
3-way Catalyst, FI, <50K miles, high power/weight	1	
Tier 1, >50K miles, low power/weight	1	
Tier 1, >50K miles, high power/weight	1	1
Tier 1, <50K miles, low power/weight	1	
Tier 1, <50K miles, high power/weight	1	
Total Cars	11	5
Trucks		
Pre-1979 (<=8500 GVW)	1	1
1979 to 1983 (<=8500 GVW)	1	1
1984 to 1987 (<=8500 GVW)	1	1
1988 to 1993, <=3750 LVW	1	1
1988 to 1993, >3750 LVW	1	
Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	1	1
Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	1	
Total Trucks	7	5

TABLE 2 Vehicle Emissions Standards and Phase-Ins

Vehicle Type	Emissions Standard	New Car Standards, grams per mile HC	NMHC	CO	NOx	Standards Phase-In Schedule, Model Year 1993	1994	1995	1996	1997
LDVs (0-6,000 GVW)										
Cars	0-3,750 LVW									
	California	0.41	0.39	7.0	0.4	100%	60%	20%		
	Federal Tier 0	0.41		3.4	1.0	100%	60%	20%		
	Federal Tier 1		0.25	3.4	0.4		40%	80%	100%	100%
Trucks	LDT1: 0-3,750 LVW									
	CA	0.41	0.39	9.0	0.4	100%	60%	20%		
	Federal Tier 0	0.80		10.0	1.2	100%	60%	20%		
	Federal Tier 1		0.25	3.4	0.4		40%	80%	100%	100%
	LDT2: 3,751-5750 LVW									
	CA	0.50	0.50	9.0	1.0	100%	60%	20%		
	Federal Tier 0	0.80		10.0	1.7	100%	60%	20%		
	Federal Tier 1		0.32	4.4	0.7		40%	80%	100%	100%
LDTs (6,001-8,500 GVW)										
	LDT3: 3,751-5,750 ALVW									
	CA	0.50	0.50	9.0	1.0	100%	100%	100%	50%	
	Federal Tier 0	0.80		10.0	1.7	100%	100%	100%	50%	
	Federal Tier 1		0.32	4.4	0.7				50%	100%
	LDT4: Over 5,750 ALVW									
	CA	0.60	0.60	9.0	1.5	100%	100%	100%	50%	
	Federal Tier 0	0.80		10.0	1.7	100%	100%	100%	50%	
	Federal Tier 1		0.39	5.0	1.1				50%	100%

Notes:
- Standards for cars and LDT1s are identical
- 50,000 mile standards for LDT2 and LDT3 are identical; however, higher mileage standards differ slightly
- GVW = gross vehicle weight
- curb weight = unloaded weight
- LVW = loaded vehicle weight, or test weight (curb weight + 300 lbs)
- ALVW = adjusted LVW, (GVW + curb weight) / 2

modeling vehicle emissions from the on-road vehicle population. In addition to higher total emissions, the variance of the emissions from the high-emitting part of the population is much higher than that of the rest of the population. For example, the vehicle-to-vehicle variance in the unified cycle carbon monoxide (CO) emissions of the highest emitting quintile was about 20 times that of the next highest emitting quintile. Thus, from a statistical sample allocation perspective, it is also important to assign more of the sample to the more variable high-emitting portion of the population.

The distribution of the 300 test vehicles among the 28 cells in the testing matrix in Table 3 is based in part on the estimated emissions contribution of the major vehicle/technology groups in 2000. Average emission rates are taken from the LDVSP-12 data. Average emission rates were calculated for CO, hydrocarbons (HC), and nitrogen oxide (NO_X), over both the FTP and the unified cycle for each vehicle technology category. The appropriate standard level for Tier 1 vehicles under 50,000 mi was used for Tier 1 cars over 50,000 miles, the observed increment due to mileage observed in the LDVSP-12 data for three-way catalyst/fuel-injected cars was used. LDVSP-12 did not include vehicles in the pre-MY79 LDT category; the emission rate from MY79-83 was used as a conservative estimate for this category.

Since California CO standards for cars were much higher than federal standards, average CO emissions cannot be used as representative of U.S. emissions. Since Tier 1 LDT average emissions are based on U.S. standard levels, averages based on the unified cycle cannot be used because the standards are based on FTP driving. Therefore, analysis is restricted to HC and NO_X emissions over the FTP.

Travel fractions are taken from MOBILE5. The LDV technology weights in MOBILE were also used; the LDT weights by model year are from corporate average fuel economy (CAFE) certification data of the sales of individual LDT models, provided by NHTSA. The Tier 1 LDT standards are based on a combination of GVW and LVW; however, the CAFE files provide only LVW. No other source of data could be identified that would allow sales of LDTs to be determined by the four emission standards. In the absence of such data, LDT sales were divided into three groups: LVW up to 3,750 lbs (LDT1, which are included in the car categories), horsepower up to 170 (LDT2 and LDT3), and horsepower over 170 (LDT4), on the basis of the finding that maximum horsepower increases as LVW increases. On the basis of this classification, LDT1s represent 25 percent of truck sales in 1994 and the remaining sales are split evenly between trucks over and under 170 maximum horsepower.

The HC and NO_X emissions contribution, based on LDVSP-12 results, of each cell are given in Table 3. The emissions contributions are used as a rough guide for allocation of the test vehicles between the normal- and high-emitter groups, and among the three major technology groups (carbureted, fuel injected, and Tier 1). In 2000, there will be very few Tier 0 fuel-injected cars with less than 50,000 mi, so the table indicates no contribution to year 2000 emissions from this class. Cars in this category should be tested, however, to model deterioration of emissions controls in Tier 0 cars.

Because of the significant emissions contribution of high-emitting vehicles, both normal-emitting vehicles (i.e., properly functioning) and malfunctioning vehicles (i.e., high emitters) are to be sampled within each cell of the matrix. For the first three categories of cars

TABLE 3 Vehicle Technology Matrix Sampling Allocation

Vehicle Technology Category	Contribution to Total Year 2000 Emissions		Target Recruitment of Test Vehicles	
Cars	**HC**	**NOx**	**Normal emitting**	**High-emitting**
No Catalyst	0%	0%	5[b]	
2-way Catalyst	6%	4%	10[b]	
3-way Catalyst, Carbureted	8%	6%	15[b]	
3-way Catalyst, FI, >50K miles, low power/weight	56%	55%	15	15
3-way Catalyst, FI, >50K miles, high power/weight			15	
3-way Catalyst, FI, <50K miles, low power/weight	0%	0%	15	
3-way Catalyst, FI, <50K miles, high power/weight			15	
Tier 1, >50K miles, low power/weight	9%[a]	7%[a]	15	15
Tier 1, >50K miles, high power/weight			15	
Tier 1, <50K miles, low power/weight	20%[a]	27%[a]	15	
Tier 1, <50K miles, high power/weight			15	
Total Cars			150	30
Trucks				
Pre-1979 (<=8500 GVW)	5%	2%	5[b]	
1979 to 1983 (<=8500 GVW)	11%	4%	10[b]	
1984 to 1987 (<=8500 GVW)	18%	16%	15[b]	
1988 to 1993, <=3750 LVW	30%	32%	15	15
1988 to 1993, >3750 LVW	14%	9%	15	
Tier 1 LDT2/3	7%[a]	12%[a]	15	15
Tier 1 LDT4	9%[a]	18%[a]	15	
Total Trucks			90	30

[a] emissions contribution based on applicable emission standard, rather than measured in-use emissions
[b] malfunctioning vehicles recruited at random, rather than specifically targeted

and trucks, malfunctioning vehicles are not specifically targeted for recruitment; rather, it is assumed that a large fraction of the vehicles randomly selected will be malfunctioning. For the later categories, malfunctioning vehicles will be recruited within broader technology classes. If no malfunctioning vehicles are randomly recruited in the older categories, this recruitment strategy will result in a minimum of 60, or 20 percent, malfunctioning vehicles recruited and tested. Experience in the recruitment of older vehicles for the 28-vehicle test fleet indicates that there is a very small chance that no malfunctioning vehicles will be located randomly.

EMISSIONS TESTING PROTOCOL

In recent years, a great amount of research has been conducted in developing driving cycles that better reflect today's actual driving than the federal test procedure. The most significant study has been the FTP revision project, where real-world driving activity data have been collected from instrumented vehicles driven in Los Angeles, Atlanta, Baltimore, and Spokane (*4,5*).

From these real-world driving data, EPA has established a supplemental federal test procedure (SFTP) starting for model year (MY) 2000. The SFTP includes two single-bag emission test cycles: a new start control cycle (SC03), which is performed following a new 60-min soak; and a new aggressive driving cycle (i.e., the US06), which is performed while a vehicle is in the hot-stabilized condition and often referred to as Bag 4 testing. EPA recommends using a 48-in. single-roll dynamometer with electronic control of power absorption.

For the development of this modal emissions model, the capture of modal emission events characteristic of in-use driving is essential. Some of these events occur within the standard FTP and US06 driving cycles. However, these driving cycles still are not true modal cycles in that they do not provide clear-cut modal emission results, that is, emissions that can easily be matched to specific speeds, accelerations, or power rates. Therefore, in addition to testing vehicles over the FTP and US06, vehicles will be tested over a new modal emission test cycle that has been developed as part of this project.

The entire testing protocol consists of

- A complete three-bag FTP test;
- EPA's proposed high-speed cycle (US06); and
- The new modal emission cycle (MEC01) developed by the research team.

A complete FTP test is necessary for two reasons. First, it is the standard certification testing procedure and provides baseline information about a vehicle's emissions, which can be used as a reference for comparison with existing tests of other vehicles. Second, FTP Bag 1 testing provides information on catalyst efficiency during cold starts, which is very useful in developing the model (FTP Bag 3 consists of the standard warm-start operating condition; FTP Bag 2, the US06, and the modal emissions cycle are all performed when the vehicle is operating in the hot-stabilized mode).

The modal emission cycle, or MEC01, has been designed to include various levels of acceleration and deceleration, a set of constant speed cruises, speed fluctuation driving, and constant power driving. The MEC01 cycle is presented in Figure 1 and consists of five sections.

Stoichiometric Cruise Section

The stoichiometric cruise section or "hill" has been designed to measure emissions associated with cruises at seven constant speeds:

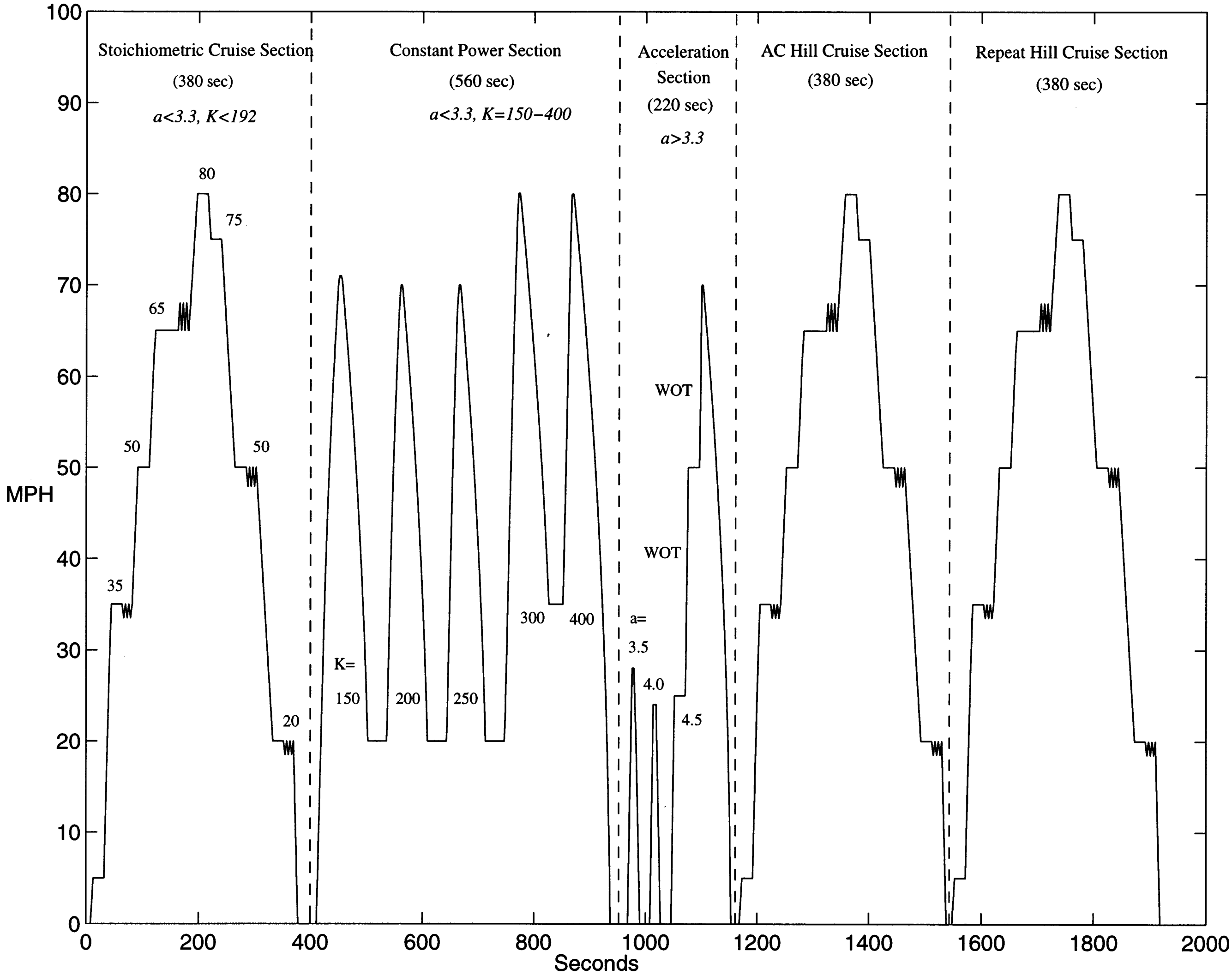

FIGURE 1 Modal emission cycle MEC01v5.0.

35, 50, 65, 80, 75, 50, and 20 mph. Each of these events lasts approximately 20 sec, except the 65-mph cruise, which lasts 40 sec. All of the acceleration rates in this section are below 3.3. mph/s, the maximum acceleration in the FTP. At four of the constant-speed plateaus, there are also speed-fluctuation events, which are common phenomena during in-use driving and may induce transient enrichment spikes. The speed fluctuation is simulated by initially coasting down for 3 sec, followed by a mild acceleration back to the initial speed level. This is repeated three times.

It is important to note that there are two 50-mph cruises: one immediately preceded by an acceleration event, the other preceded by a deceleration event. Comparisons between the two will help establish what impact, if any, recent driving history has on emissions. This analysis will be covered in future work and has not been completed for this paper.

Constant Power Section

In the constant power section, there are five constant specific-power subcycles, with specific power (SP) ranging from 150 to 400 mph^2/s. Specific power is approximated as two times the product of velocity (v) and acceleration (a):

$$SP = 2 * v * a$$

The units of v are mph, a is mph/s, and SP is mph^2/s. Because the specific power multiplied by the vehicle mass is the kinetic power, the specific power measures kinetic energy used during a driving episode. In the case of the FTP, the maximum SP is 192 mph^2/s. In the US06, the maximum specific power is much greater, reaching 480 mph^2/s. During high-power episodes, the kinetic power required to overcome vehicle inertia typically dominates the total power requirements. Thus, during high-power operation, a constant specific power approximately represents constant total power. The specific power levels from 200 to 300 mph^2/s represent moderately high-power driving, while a level of 150 is within the power range of the FTP, and a level of 400 requires wide-open-throttle (WOT) operation in most vehicles. This section allows us to detect the thresholds at which vehicles enter a power enrichment state. Determining the threshold at which modern vehicles enter a power enrichment mode is critical for predicting the vehicle emissions due to the extreme nonlinear behavior (An et al., elsewhere in this Record).

Constant Acceleration Section

Five acceleration episodes are included in the constant acceleration section: The first goes from 0 to 25 mph with a constant acceleration rate of 3.5 mph/s, the second from 0 to 20 mph at a constant rate of 4 mph/s. These first two acceleration rates are slightly above the FTP limit of 3.3 mph/s, again intended to capture any onset of enrichment. The third acceleration episode is from 20 to 40 mph at 4.5 mph/s, followed by two events at wide-open throttle: one from 40 to 55 mph and another from 55 to 75 mph. The last two episodes are designed to test emissions associated with the maximum enrichment level and the application of maximum power of the vehicle.

Air Conditioning Hill Section

The stoichiometric cruise section is repeated in the cycle, this time with the air conditioner (AC) on if the vehicle is so equipped. It is still unclear what effect vehicle accessories (e.g., air conditioning) have on emission rates on most vehicles; this section of the cycle will allow direct comparison with the initial steady-state cruise section. The ambient air temperature during these tests is generally lower than that typically found when vehicle AC use is likely. This may result in a smaller load on the engine and an underestimation of emissions.

Repeat Hill Cruise Section

To determine emissions variance for each vehicle within a single test, the stoichiometric cruise section is again repeated (this time with AC off). This repeat hill allows us to directly compare the modal events within the hill or the composite emissions for both hills.

The time intervals between all high acceleration/deceleration modal events in the cycle are at least 30 sec, allowing the catalytic converter enough recovery time (the interval between modal events was initially smaller; however, after examining the results of the first few vehicles, it was determined that 30 sec was needed for spacing of the events). Also, there are various deceleration rates in the cycle; however, these rates are rather mild in order to avoid brake overheating during the testing.

RESULTS

The testing protocol has been used for preliminary testing of 30 vehicles, one for each of the 28 bins of the vehicle/technology matrix (two additional vehicles from the three-way catalyst, fuel-injected malfunction group were also tested). The vehicles tested are shown in Table 4; the odometer reading of each vehicle is listed in the bottom right of each cell, while the order in which the vehicles were tested is bracketed at the bottom left of each cell. The high-emitter vehicles that were tested were identified through several methods: remote sensing measurements, recent failure to pass state smog check tests, inquiries with auto repair shops, and observed poor maintenance and high mileage. Occasionally, a suspected high emitter turned out to be a normal emitter during our dynamometer testing. Such a vehicle was shifted to the properly functioning cell, and a new potential malfunctioning vehicle was recruited and tested in its place. For these initial vehicles, the sample was recruited from representative vehicles in the Riverside, California, area; however, for the 300-vehicle sample in the next phase of the project, vehicles within each category will be recruited randomly from the population of vehicles registered in southern California to minimize selection bias.

Cumulative FTP Results

The cumulative FTP bag emission results of the vehicles are given in Table 5. Examination of these results indicates clear differences in CO and HC results between vehicle/technology groups and between properly functioning and malfunctioning cars. There are clear trends in both the normal operating vehicles and the malfunctioning vehicles, with the older, lower-technology vehicles having higher emissions. Newer malfunctioning vehicles have much lower emission rates on the FTP cycle than the older malfunctioning vehicles. Differences in NO_X emission levels among technology groups are not as pronounced. NO_X emission rates are higher for the malfunctioning vehicles in some, but not all, technology categories.

Steady-State Cruise Modal Analysis

The MEC01 driving cycle contains more than 60 distinct modes of operation. These modes consist of various levels of steady-state cruise, idle, and different levels of acceleration and deceleration. Preliminary analysis has been carried out on these modes primarily for model building purposes. As an example of modal analysis across several vehicles, the emission rates (g/mi) at each of the steady-state cruises were extracted and plotted as a function of speed for several vehicles. While steady-state driving does not account for a large percentage of in-use driving time, it is important for developing the model. Integrated emissions during each 30-sec cruise event for CO, HC, and NO_X are presented in Figures 2, 3, and 4, respectively. Care was taken to avoid any transients resulting from a preceding acceleration or deceleration.

These example vehicles were chosen to illustrate the emissions variation between vehicle/technology categories. Both CO and HC have been plotted on a log scale to see the differences between vehicles. The MY83 Ford van has very high emission rates compared with the other vehicles. It is interesting to note that the general shape of all of these curves for these vehicles matches the shapes of the speed correction factor curves of the EMFAC and MOBILE models. For CO and HC, the emission rates (g/mi) tend to be lowest at the medium speeds (30 to 50 mph).

The NO_X emissions are plotted on a linear scale, and for the steady-state cruises, the emissions are very well behaved. The NO_X emission rates for each of these vehicles are small at low speeds and then increase significantly at higher speeds; these higher speeds (55+ mph) are not part of the FTP regime.

Air Conditioning Analysis

We have compared the cumulative emissions during the cruise hill with both the AC off and the AC on for most of the initial vehicle fleet (some of the older vehicles were unable to make the more difficult parts of the test sequence; therefore, modal data are not available for

TABLE 4 Vehicles Tested in Preliminary Testing Phase

Vehicle Technology Category	Test Vehicles	
Cars	**Normal emitting**	**High-emitting**
No Catalyst	76 Honda Civic [15] 188716	73 Datsun [21] 142843
2-way Catalyst	82 Honda Prelude [19] 191203	79 Oldsmobile [25] 136436
3-way Catalyst, Carbureted	85 Honda Accord [27] 222528	81 Toyota Celica [13] 124601
3-way Catalyst, FI, >50K miles, low power/weight	91 Honda Civic [16] 73558	84 Cadilac deVille [23] 114966
3-way Catalyst, FI, >50K miles, high power/weight	89 Oldsmobile [26] 112403	86 Buick Century [20] 74020
3-way Catalyst, FI, <50K miles, low power/weight	91 Dodge Spirit [24] 13681	
3-way Catalyst, FI, <50K miles, high power/weight	91 Ford Taurus [1] 43167	91 Ford Taurus [4] 44024
Tier 1, >50K miles, low power/weight	95 Honda Civic [37] 49825	
Tier 1, >50K miles, high power/weight	95 Jeep Cherokee [35] 50552	
Tier 1, <50K miles, low power/weight	95 Toyota Tercel [17] 23260	
Tier 1, <50K miles, high power/weight	96 Cadillac DeVille [32] 13287	96 Buick LeSabre [34] 22651
Trucks		
Pre-1979 (<=8500 GVW)	72 Ford F250 [5] 163510	68 Chevrolet Pickup [3] 173311
1979 to 1983 (<=8500 GVW)	82 Ford Bronco [14] 61695	83 Ford Econoline Van [9] 138812
1984 to 1987 (<=8500 GVW)	86 Ford Aerostar [31] 114359	87 Chevy Suburban [22] 96394
1988 to 1993, <=3750 LVW	90 Toyota Pickup [18] 91102	88 Plymouth Voyager [28] 169993
1988 to 1993, >3750 LVW	94 Chevrolet Suburban [29] 38640	
Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	96 GMC Safari [30] 8136	95 Dodge Caravan [36] 23403
Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	95 Ford F350 Van [38] 46266	

TABLE 5 Vehicle Technology Matrix with FTP Cumulative Results for CO, HC, and NO_X

Vehicle Technology Category	FTP Bag Analysis Results (g/mi)	
Cars	**Normal emitting**	**High-emitting**
	CO - THC - NOx	CO - THC - NOx
No Catalyst	4.61 - 1.00 - 1.02	45.55 - 8.17 - 3.47
2-way Catalyst	7.26 - 1.71 - 2.26	65.62 - 3.69 - 2.19
3-way Catalyst, Carburated	6.87 - 0.54 - 0.76	21.01 - 3.63 - 2.37
3-way Catalyst, FI, >50K miles, low power/weight	3.92 - 0.31 - 0.41	16.37 - 1.30 - 4.93
3-way Catalyst, FI, >50K miles, high power/weight	4.37 - 0.50 - 1.70	5.60 - 0.79 - 0.62
3-way Catalyst, FI, <50K miles, low power/weight	2.99 - 0.26 - 0.21	
3-way Catalyst, FI, <50K miles, high power/weight	1.85 - 0.18 - 0.30	13.18 - 2.70 - 2.41
Tier 1, >50K miles, low power/weight	1.41 - 0.26 - 0.29	
Tier 1, >50K miles, high power/weight	2.09 - 0.23 - 0.49	
Tier 1, <50K miles, low power/weight	1.76 - 0.23 - 0.10	
Tier 1, <50K miles, high power/weight	0.97 - 0.18 - 0.20	3.59 - 0.33 1.86
Trucks	CO - THC - NOx	CO - THC - NOx
Pre-1979 (<=8500 GVW)	82.12 - 5.35 - 1.94	117.85 - 6.16 - 0.94
1979 to 1983 (<=8500 GVW)	9.40 - 2.02 - 2.01	79.48 - 2.00 - 0.86
1984 to 1987 (<=8500 GVW)	8.22 - 0.52 - 0.91	7.12 - 0.86 - 0.64
1988 to 1993, <=3750 LVW	2.90 - 0.33 - 0.20	7.45 - 1.59 - 2.29
1988 to 1993, >3750 LVW	8.44 - 0.54 - 0.78	
Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	2.12 - 0.25 - 0.31	3.95 - 0.35 - 1.31
Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	4.55 - 0.24 - 0.36	

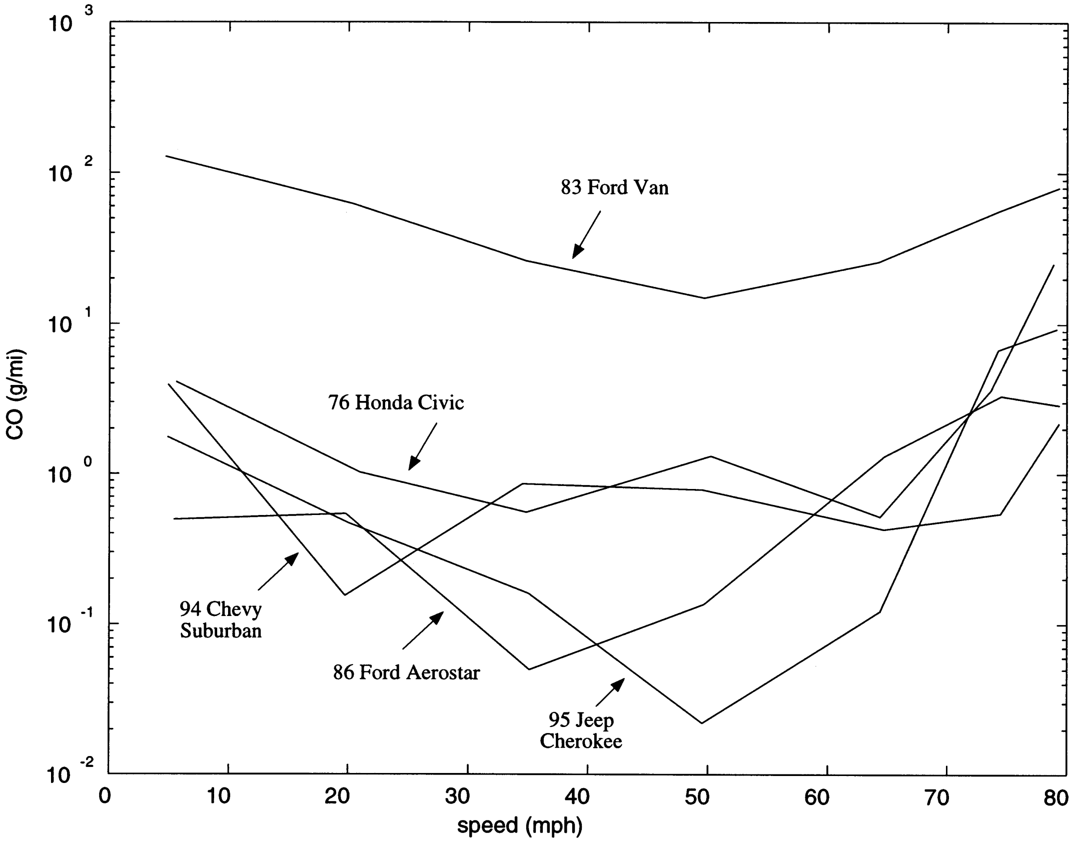

FIGURE 2 CO steady-state cruise results for several vehicles.

these vehicles). The results for normally operating vehicles are shown in Figure 5, and for the high-emitting/malfunctioning vehicles in Figure 6.

Emission changes due to AC operation in normally operating vehicles ranged from a decrease of 64 percent to an increase of 394 percent for CO, –25 to 259 percent for HC, –14 to 594 percent for NO_X, and 4 to 23 percent for carbon dioxide (CO_2). Integrated emission rates for the initial cruise hill (AC off) and the repeat AC cruise hill (AC on) were averaged across vehicles; the mean increase in emissions due to AC operation were 97 percent for CO, 52 percent for HC, 68 percent for NO_X, and 14 percent for CO_2. In previous research (*6*), average increases in tailpipe NO_X emissions of over 80 percent were reported during AC operation. The results were compared across vehicles using a paired *t*-test. The null hypothesis of no significant difference in emission rates between AC off and AC on was rejected at the 5 percent level of significance for CO, NO_X, and CO_2, indicating that there was a significant increase in these emissions due to AC operation. The increase in HC emissions was not significant at the 5 percent level. Some of the vehicles exhibited increases in HC emissions on the AC hill, while others had reductions in HC emissions. While the mean difference for CO_2 was smaller than that for HC, it was more consistent across vehicles. As additional vehicles are tested, we will test for whether this is a random vehicle-to-vehicle difference or whether there is an interaction between our technology groups and the effect of AC on HC emissions.

Malfunctioning vehicles did not indicate consistent increases (or decreases) in any pollutant due to AC operation. Changes in CO, HC, NO_X, and CO_2, emissions ranged from –14 to 128 percent, –29 to 105 percent, –59 to 19 percent, and –4 to 22 percent, respectively. The differences in average emissions of each of the four pollutants were not statistically significant (at the 5 percent level of significance). Integrated emission rates for the initial cruise hill (AC off) and the repeat AC cruise hill (AC on) were averaged across vehicles; the mean increase in emissions due to AC operation were 39 percent for CO, 18 percent for HC, –9 percent for NO_X, and 6 percent for CO_2.

Repeatability Analysis

Similar to the AC analysis, the initial cruise hill was compared with the repeat cruise hill at the end of the MEC01 cycle. The results are presented in Figures 7 and 8 for the normally operating and high-emitter vehicles, respectively. The differences in average emissions of each of the four pollutants were not statistically significant. Integrated emission rates for the initial cruise hill and the repeat cruise hill were averaged across vehicles; the mean increase in emissions for the repeat hill were –92 percent for CO, –19 percent for HC, 30 percent for NO_X, and 0.02 percent for CO_2. Integrated emission rates for the cruise hill and the repeated cruise hill were compared using the paired *t*-test at the 5 percent level of significance across vehicles. The repeated hill had significantly higher NO_X emissions, significantly lower CO and HC emissions, and no significant difference in CO_2 emission rates.

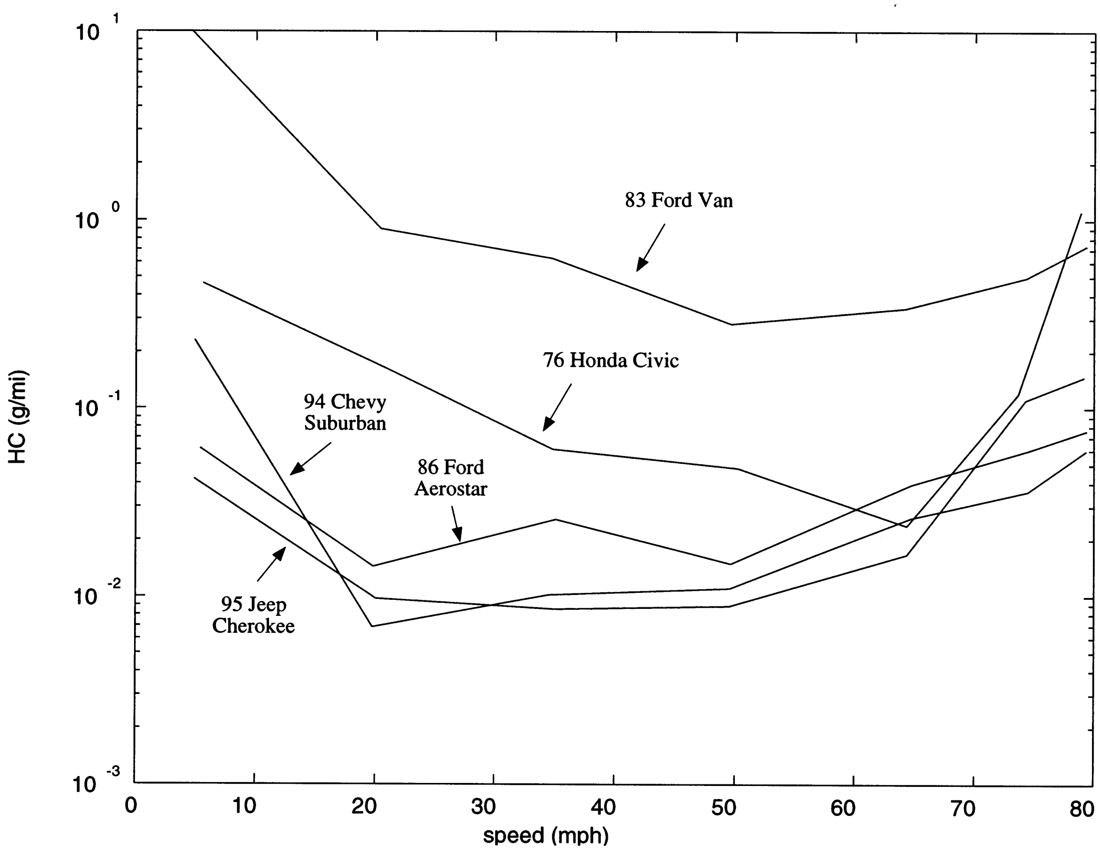

FIGURE 3 HC steady-state cruise results for several vehicles.

Malfunctioning vehicles did not indicate consistent increases (or decreases) in any pollutant for the repeat hill. The differences in average emissions of each of the four pollutants were not statistically significant (at the 5 percent level of significance). The mean increase in emissions for the repeat hill were 31 percent for CO, 24 percent for HC, 19 percent for NO_X, and 0.02 percent for CO_2.

The overall process error for a driving segment can be estimated as one-half the variance of the difference between the first cruise hill and the repeat cruise hill. At this level of resolution (specific driving segment), many factors can affect repeatability, including shift points, throttle fluctuations, vehicle operating conditions, and so forth. The finding of significant differences between the first cruise hill and the repeat hill in the normally operating vehicles indicates that for these vehicles this analysis may not be suitable. In addition, an analysis of this type should be done within vehicle/technology group because of the large emission rate differences involved. This will be done when the 300-vehicle testing provides the necessary data.

CONCLUSIONS AND FUTURE WORK

For this analysis, 30 vehicles have been tested in the 28 vehicle/technology categories. With only one vehicle tested for most technology groups, statistical testing is restricted to simple tests with narrow assumptions. However, a number of interesting observations can be made at this time. Large differences in emissions rates have been observed between the various vehicle/technology groups. In addition, differences were observed between the normally operating and malfunctioning vehicles. Distinct differences in emission rates were observed between different driving modes for individual vehicles. Emission rates with AC on were significantly higher across technology groups for CO, NO_X, and CO_2 for normally operating vehicles, but no significant differences were observed for the malfunctioning vehicles.

The second phase of the project involves testing 300 vehicles. Extra effort will be made to recruit 49-state certified vehicles for the 300-vehicle sample. Given that 15 to 20 percent of the vehicle population in southern California are 49-state certified, we anticipate that a minimum of 20 percent of the test vehicles will be 49-state vehicles. Some refinements have been made to the modal cycle to shorten the overall test protocol to ensure that the entire sample is tested in a timely manner. Larger samples of vehicles in each technology group will allow us to assess the utility of the current groupings. At this point, the vehicle/technology groups are merely a guide for modeling and sampling of the vehicles; the groups can be split and/or recombined across different variables if analysis indicates that other variables have more explanatory power. As more vehicles are tested, it will be possible to determine whether the differences in emissions due to vehicle operation mode, emitter category, technology group, and AC operation are statistically significant. Analysis will also be conducted on the effect of prior driving conditions on the 50-mph steady-state cruise emissions.

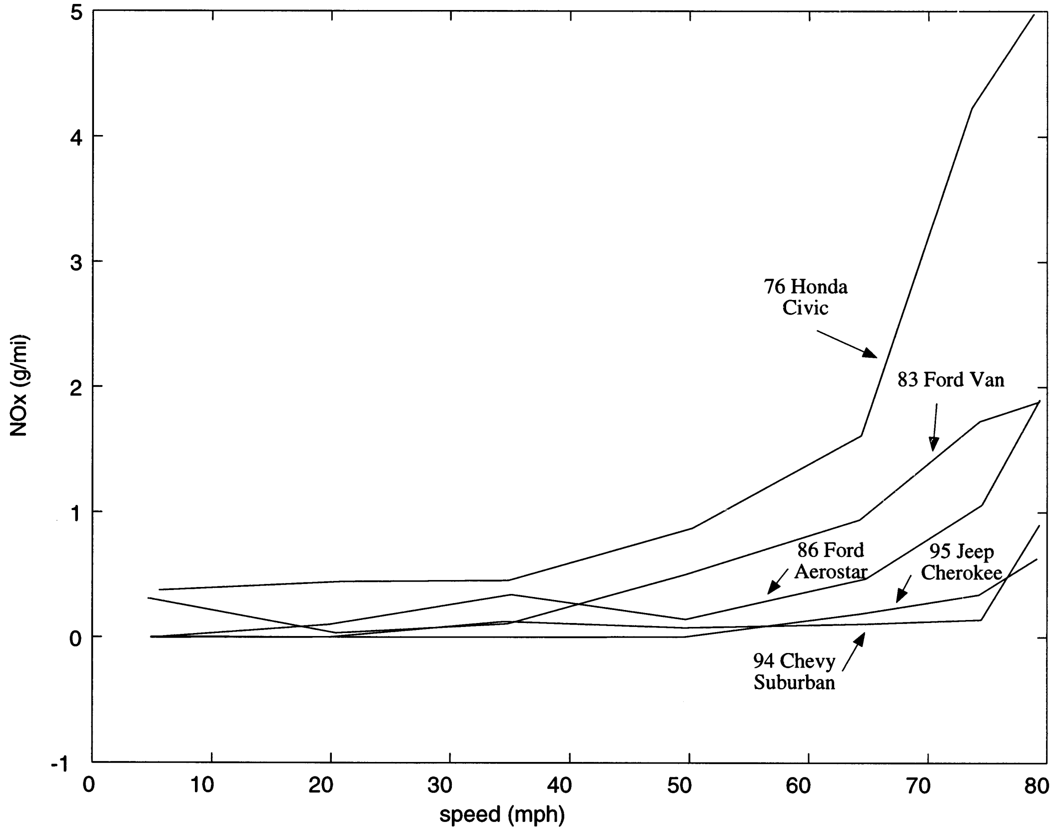

FIGURE 4 NO_X steady-state cruise results for several vehicles.

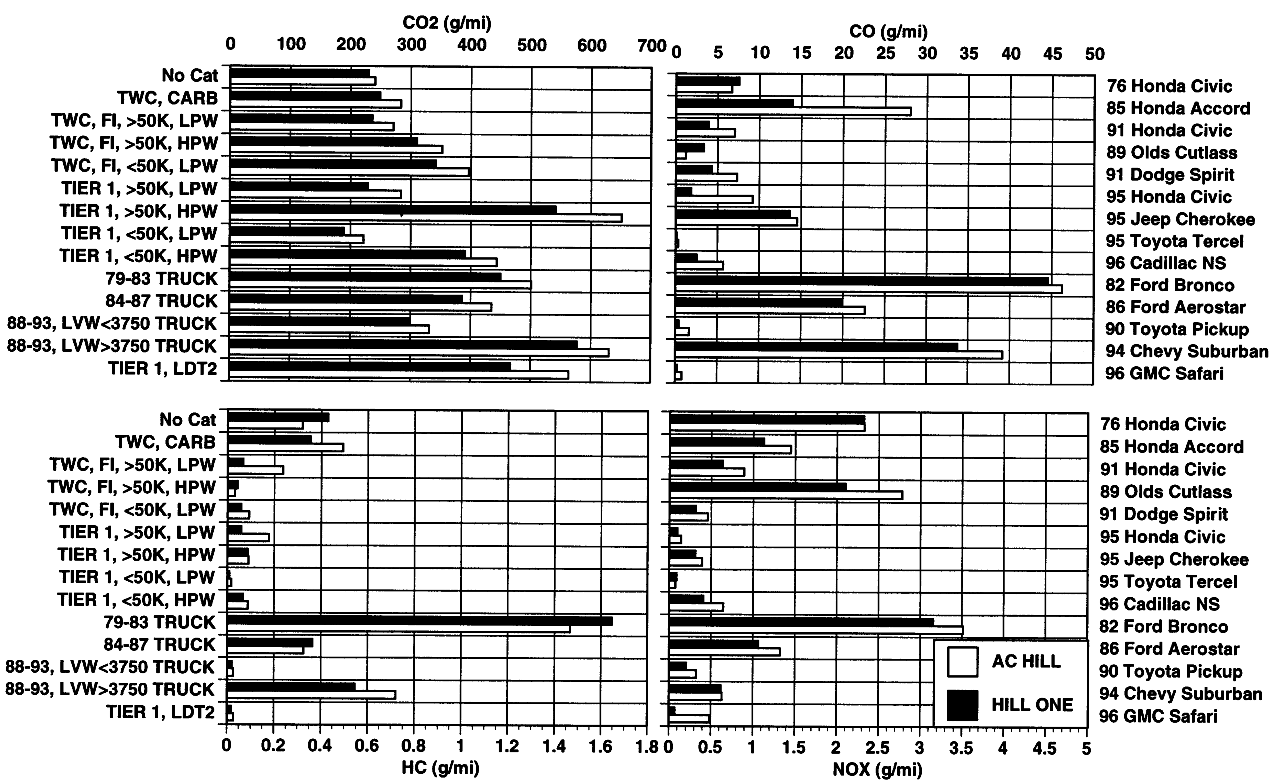

FIGURE 5 CO_2, CO, HC, and NO_X emissions for normal emitting vehicles, for both cruise and AC hills.

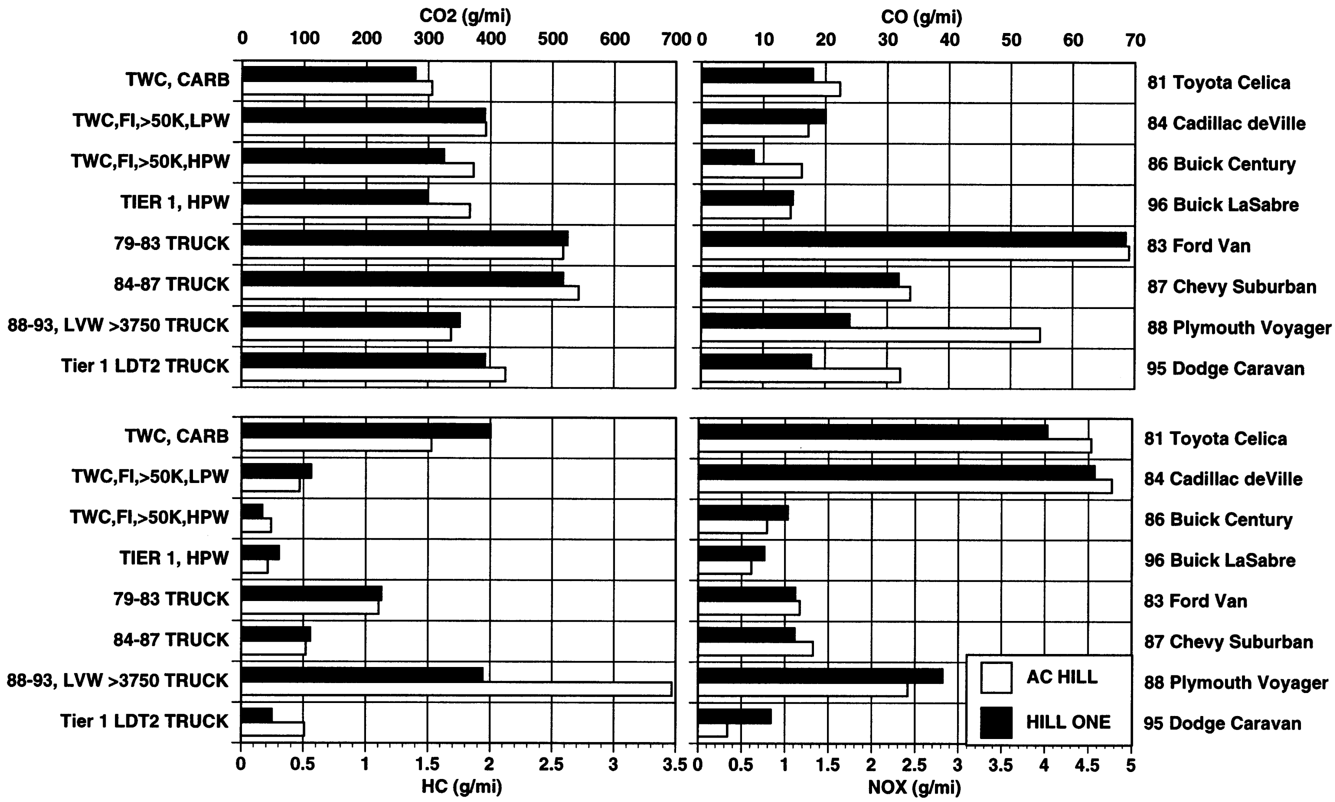

FIGURE 6 CO_2, CO, HC, and NO_X emissions for high-emitting/malfunctioning vehicles, for both cruise and AC hills.

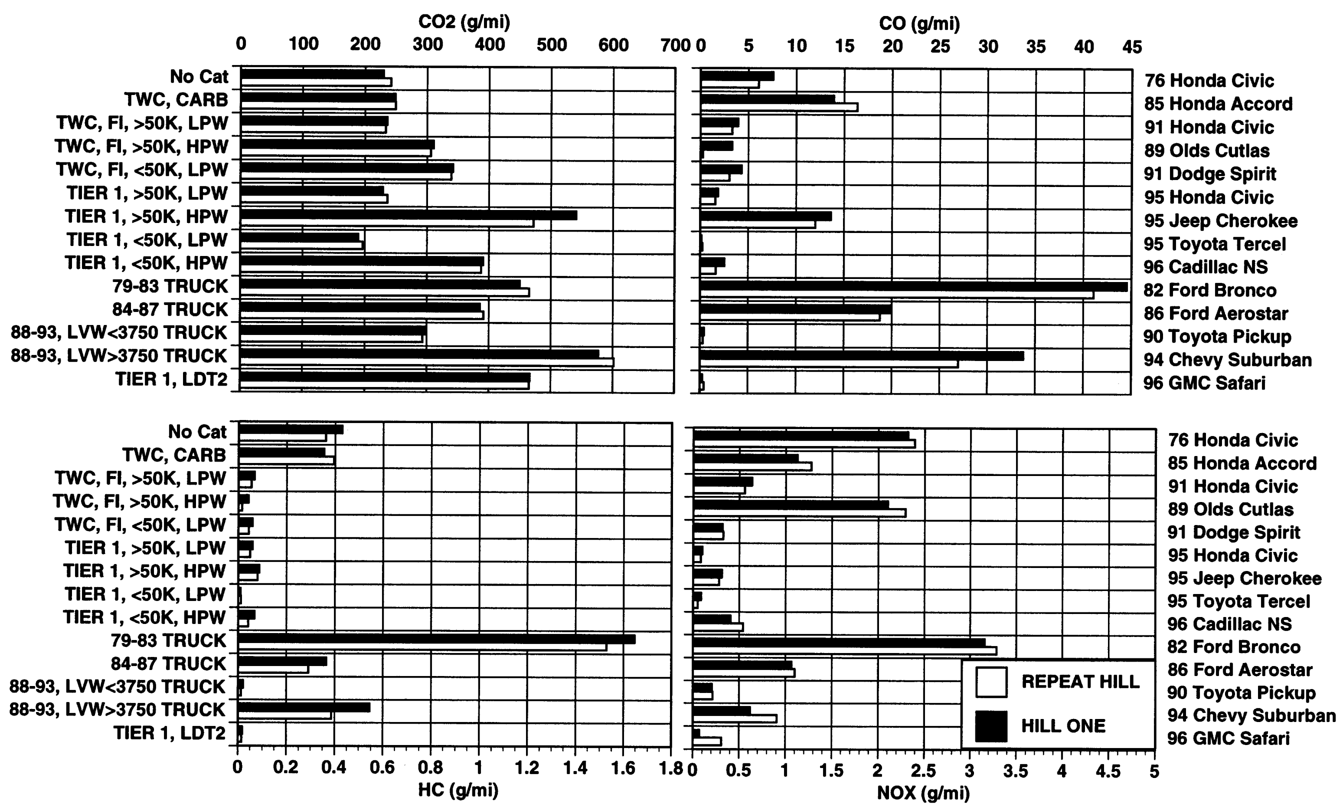

FIGURE 7 CO_2, CO, HC, and NO_X emissions for normal emitting vehicles, for both cruise and repeat hills.

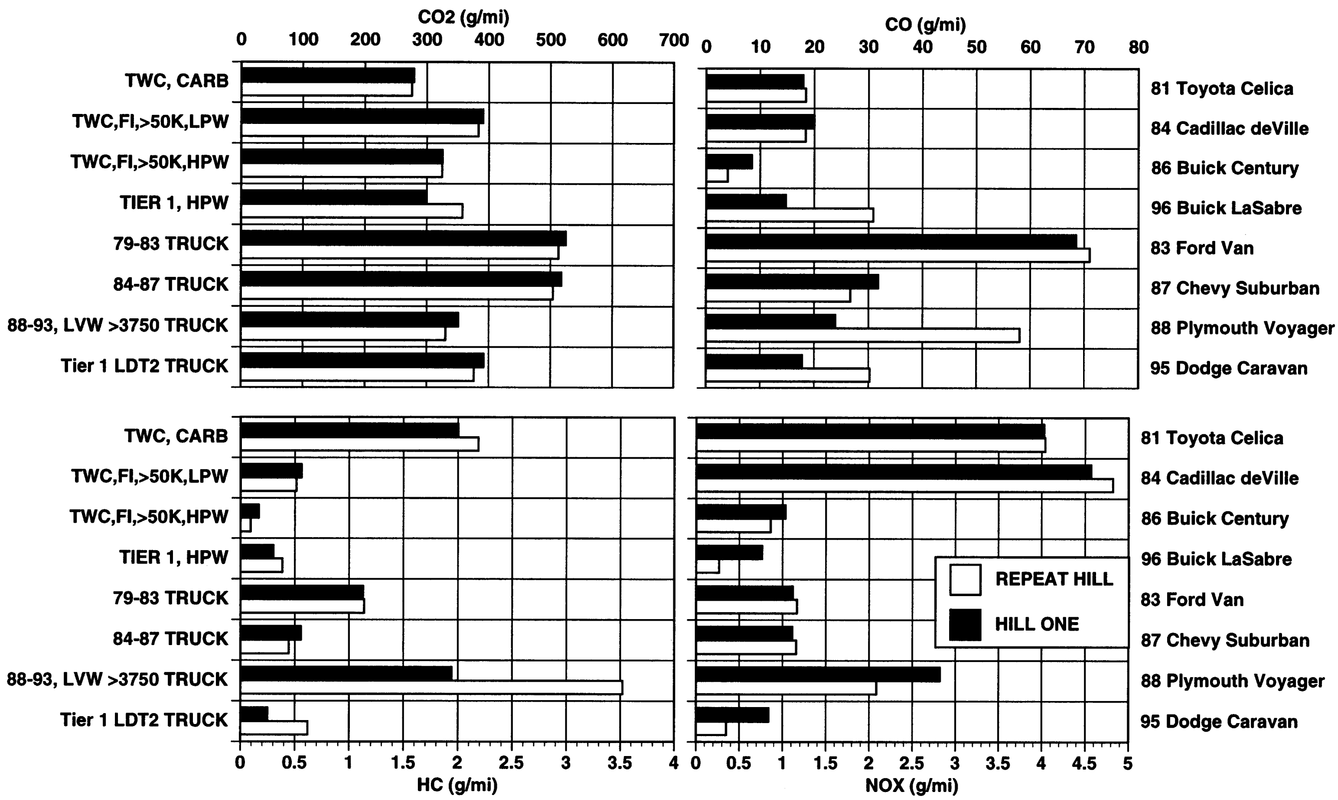

FIGURE 8 CO_2, CO, HC, and NO_X **emissions for high-emitting/malfunctioning vehicles, for both cruise and repeat hills.**

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