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ABSTRACT

A methodology for developing modal vehicle emissions and fuel consumption models is described. These models, in the form of look-up tables for fuel consumption and emissions as functions of vehicle speed and acceleration, are designed for simulations such as the Federal Highway Administration's TRAF-series of models. These traffic models are used to evaluate the impacts of roadway design on emissions and fuel consumption. Vehicles are tested on-road and on a chassis dynamometer to characterize the entire operating range of each vehicle.

As a verification exercise the models were used to predict cycle emissions and fuel consumption, and the results were compared to certification-type tests on a different population of vehicles. Results of the verification exercise show that the developed models can generally predict cycle emissions and fuel consumption with error comparable to the variability of repeat dynamometer tests.

INTRODUCTION

There are numerous computer models for predicting motor vehicle emissions, each with its own approach, and intended purpose. The MOBILE and EMFAC series of models are macroscopic in nature, intended to predict emissions of thousands of vehicles over thousands or millions of kilometers of travel for large areas. Microscopic models are generally those that model individual vehicles in traffic. Examples of microscopic models are the TRAF-series of models (CORSIM, NETSIM, and FRESIM) developed by the Federal Highway Administration (FHWA) of the U.S. Department of Transportation. The FHWA uses traffic models to evaluate the impact of roadway design on traffic, emissions, and fuel consumption.

In the early 1980s Oak Ridge National Laboratory (ORNL) developed fuel consumption models for TRAF based on testing of fifteen light-duty vehicles. The vehicles were tested on-road and on a chassis dynamometer to develop the models, which were presented in the form of lookup tables. Emissions measurements were also made on six of the fifteen vehicles, and these results used to develop lookup tables for hydrocarbon (HC), oxides of nitrogen (NO_x) and carbon monoxide (CO) emissions. The tables provide fuel consumption (or emissions) as functions of vehicle speed and acceleration [1].

Given the advances in automotive technology since the early 1980s, the FHWA decided that the tables needed to be updated. This paper describes the measurement and mapping procedures used to develop these tables, verification of the final results, and outlines continued work in this area.

EXPERIMENTAL METHODS

In the early 1980s study [1], the researchers developed a unique method of "mapping" dynamometer-based measurements onto road-based measurements. Due to advances in automotive, data collection, and computer technology, this methodology was improved for the reported work. Vehicles are first tested on-road to obtain the most realistic road loads. The on-road data provide engine conditions as functions of vehicle speed and acceleration. These engine conditions are then duplicated on the chassis dynamometer while making emissions measurements. The data sets are merged to provide the desired results of emissions as functions of speed and acceleration. The instantaneous on-road fuel consumption is measured by calibrating the fuel delivery system on the dynamometer.

VEHICLE SELECTION - The eight vehicles tested were selected based on their weight, engine size, and availability. Expectations were that more vehicles would be tested in subsequent years, to provide a more statistically significant sample. Recognizing that there was at least a possibility that budget constraints might preclude additional vehicle testing, attempts were made to make the eight vehicle list representative of mainstream vehicles. Sales volume, vehicle weight, and engine data were consulted to assist in the selection. Since pickup trucks, sport utility vehicles, and minivans (grouped together in the industry as light-duty trucks, LDT) have gained popularity in recent years, it was felt that a vehicle mix should contain at least one light truck of each type. All vehicles were model year 1993 or later (except for the first "mule" test vehicle), and all had less than 80,000 km (50,000 miles) on their odometers. With the approval of the sponsor, each of the vehicles shown in Table 1 was acquired and tested. Note that the average engine displacement of the 8 vehicles is 3.3 liters, the average number of cylinders is 5.8, and the average curb weight is 1500 kg (3300 lbs). Although a small sample, the average is very representative given that industry reports show that the average sales-weighted domestic engine displacement for 1995 was 3.5 liters, with an average of 5.8 cylinders (the sales weighted averages for cars were 2.9 liters, 5.4 cylinders, and for trucks 4.6 liters and 6.5 cylinders) [2-5]. The sales-weighted average curb weight of passenger cars has been steady at around 1320 kg (2900 lbs) for a number of recent years [6]. Light trucks are generally classed by Gross Vehicle Weight Rating (GVWR) as opposed to curb weight. In 1995, 73% of the over 6 million light trucks sold were under 2720 kg (6,000 lb) GVWR. Light trucks have accounted for some 38-44% of total light vehicle sales in recent years [2-5]. Of the three light trucks in Table 1 only the Chevrolet's GVWR is over 2720 kg (6000 lbs).

ON-ROAD - Vehicles were first instrumented, using as many on-board sensors as possible to minimize setup time. A Davit Lightspeed optical fifth wheel was used to sense vehicle speed, and all data were collected using an Advance Electronic Diagnostics Rough Ryder PC and VMS 1220 datalogger. After installation of the datalogger and optical fifth wheel, each vehicle was road tested at steady speeds from 32 to 105 km/h (20 to 65 mph), in nominal 4 km/h (2.5 mph) increments on public roads with minimal grade. Since the East Tennessee area is somewhat hilly, all data were gathered in opposite directions on the same road to reduce grade (and wind) effects. Cruise control was used whenever possible during steady speed data collection.

Following steady speed road testing, the vehicle was tested on a 1.5 km (5000 ft) airport runway. The airport runway was used for very low and very high speed runs, and acceleration and deceleration runs which cannot be safely conducted on public roads. Acceleration runs were typically performed at 10 different throttle settings ranging from 10% throttle to wide-open-throttle (WOT). All data on the runway were also gathered in both directions to reduce wind and grade effects, and typically two full sets of data were gathered. The runway has a maximum grade of 1%. Parameters typically collected on-road are shown in Table 2.

DYNAMOMETER - Following on-road data collection, the test vehicle was brought to the chassis dynamometer at the University of Tennessee for emissions and fuel consumption measurements. The same datalogger is used for collecting data similar to that collected on-road. In addition, fuel consumption and engine-out and tailpipe emissions constituents are measured and logged (HC, CO, NO_x, CO_2, O_2). The two parallel raw exhaust streams are pumped and cooled by a two-head ADI teflon/stainless steel diaphragm pump and a Baldwin Environmental thermoelectric chiller, respectively. Two identical emissions benches measure the exhaust species using Rosemount NGA 2000 gas analyzers. The analyzers include flame ionization detectors for hydrocarbons, non-dispersive infrared detectors for CO and CO_2, chemiluminescence detectors for NO_x, and paramagnetic detectors for oxygen.

The fuel consumption is measured using a Max Machinery 710 Fuel Flow Measurement System. The Max system contains a positive-displacement fuel flowmeter, heat exchanger, pumps, level controller, pressure regulators, and vapor eliminators to facilitate measuring the net fuel consumed by fuel injected engines. The fuel flow measurement system is accurate to ±0.5% with a turndown ratio of 200:1, however it can take several seconds for it to respond to a transient event. As such, the flowmeter was used to measure flow under steady conditions on the dynamometer while recording fuel injector pulsewidth (PW) and frequency (FR). A fuel injection calibration curve was developed for each vehicle tested so that on-road pulsewidth and frequency data could be used to infer fuel consumption on-road. The fuel flow (cc/s) is divided by the injector frequency (s^{-1}) to yield fuel injected per pulse (cc). A curve is then fit to predict fuel injected per pulse as a function of pulsewidth. A sample fuel calibration curve for a 1994 Oldsmobile Eighty Eight is shown in Figure 1.

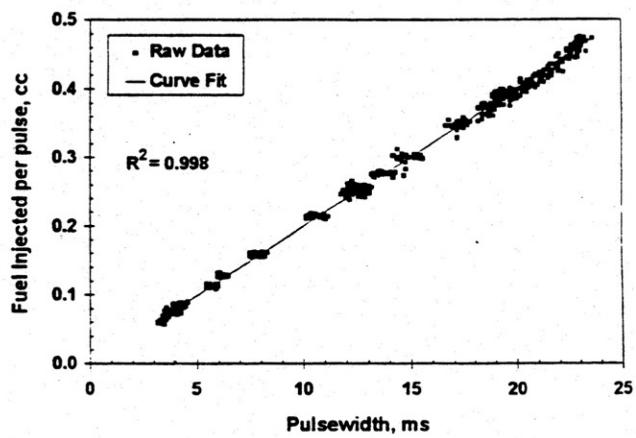

Figure 1. Fuel calibration curve for Oldsmobile 88

The improved response time of the PW-based fuel flow over the instantaneous flowmeter measured value is shown in Figure 2 for a 1994 Jeep Grand Cherokee. To obtain instantaneous fuel flow, the fuel injected per pulse is multiplied by the injector frequency.

The chassis dynamometer used is a twin-roll, eddy-current Sun Roadamatic. For transient testing, the

Table 1. Test Vehicle and Industry Average Specifications						
Year	**Make/Model**	**Engine** PFI=Port Fuel Injection TBI=Throttle Body Injection	**Transmission** M=Manual, L=Automatic with lockup	**Curb Weight** lbs (kg)	**Rated hp** (kW)	**EPA Fuel Economy** city/hwy mpg (km/L)
	Light-Duty Cars					
1988	Chevrolet Corsica	2.8 L pushrod V6, PFI	M5	2665 (1209)	130 (97)	19 / 29 (8/12)
1994	Oldsmobile Cutlass Supreme	3.4 L DOHC V6, PFI	L4	3290 (1492)	210 (157)	17 / 26 (7/11)
1994	Oldsmobile Eighty Eight	3.8 L pushrod V6, PFI	L4	3360 (1523)	170 (127)	19 / 29 (8/12)
1995	Geo Prizm	1.6 L OHC I4, PFI	L3	2460 (1116)	105 (78)	26 / 30 (11/13)
1993	Subaru Legacy	2.2 L DOHC flat 4, PFI	L4	2800 (1270)	130 (97)	22 / 29 (9/12)
	5-car average	2.8 L, 5.2 cyl.		2915 (1322)	149 (111)	21 / 29 (9/12)
1995	**LDV industry average**	2.9 L, 5.4 cyl		2900 (1315)		
	Light-Duty Trucks					
1994	Mercury Villager Van	3.0 L pushrod V6, PFI	L4	4020 (1823)	151 (113)	17 / 23 (7/10)
1994	Jeep Grand Cherokee	4.0 L pushrod I6, PFI	L4	3820 (1732)	190 (142)	15 / 20 (6/9)
1994	Chevrolet Silverado Pickup	5.7 L pushrod V8, TBI	L4	4020 (1823)	200 (149)	14 / 18 (6/8)
	3-truck average	4.2 L, 6.7 cyl.		3953 (1793)	180 (134)	15 / 20 (6/9)
1995	**LDT industry average**	4.6 L, 6.5 cyl.				
	8-vehicle average	3.3 L, 5.8 cyl.		3300 (1497)	160 (119)	19 / 26 (8/11)
1995	**LDV+LDT, industry avg**	3.5 L, 5.8 cyl				
	Federal Test Procedure Revision Program (FTPRP) Average (5/8 LDV + 3/8 LDT)	3.4 L, 5.7 cyl		3430 (1560)	160 (119)	

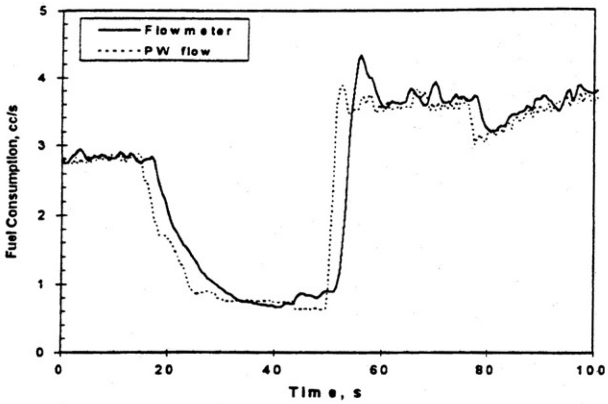

Figure 2. Transient response of flowmeter and PW-based fuel flow for Jeep Grand Cherokee

dynamometer's discrete mass and drag coefficient times frontal area (C_dA) settings were adjusted to match on-road data. The C_dA was adjusted at high speed cruise until the engine condition (MAP (manifold absolute pressure) and RPM (engine speed, revolutions per minute) matched that measured on-road at the same speed. Wide-open-throttle (WOT) rolling acceleration runs were then used to set the inertia weight that matched the on-road time required to accelerate from 32 to 97 km/h (20 to 60 mph). This process ensured that transients on the dynamometer most closely matched similar on-road conditions. During steady-state testing on the dynamometer, the load was manually adjusted to obtain the desired RPM and MAP.

Table 2. Data Collected On-Road

Parameter	Units
Speed	m/s
Ambient Temperature	°C
Engine Speed	RPM
Manifold Absolute Pressure (MAP)	kPa, Volts
Mass Air Flow (MAF)	g/s, Volts
Fuel Injector Pulse Width (PW)	ms
Fuel Injector Frequency (FR)	Hz
Fuel Temperature	°C
Throttle Position (TPS)	%, Volts
Exhaust Temperatures (before and after catalyst)	°C

The on-road MAP and RPM data were plotted to provide a guide or "roadmap" for dynamometer measurements, so that on-road engine conditions could be duplicated on the dynamometer. On-road MAP vs RPM for the Chevrolet Silverado pickup truck is shown in Figure 3. On the dynamometer, engine conditions were held steady for about 10 seconds while emissions data were recorded.

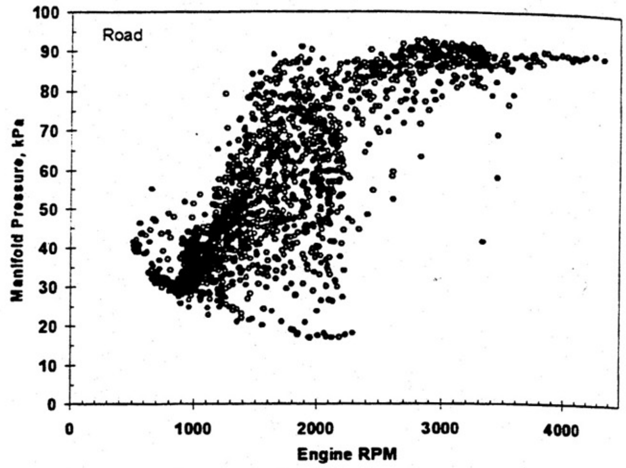

Figure 3. On-road MAP vs RPM for Chevrolet Truck

Transient data were recorded between the steady set points. Data were gathered until the on-road MAP vs RPM plot was adequately covered with steady-state dynamometer data. Transients were also recorded from idle to 120 km/h at various throttle settings, to ensure full coverage of the engine map, and to provide the resulting models with a composite of transient and steady-state data. Figure 4 shows the dynamometer MAP vs RPM. Note that the dynamometer coverage is more extensive than the on-road coverage due to the wider range of control on the dynamometer.

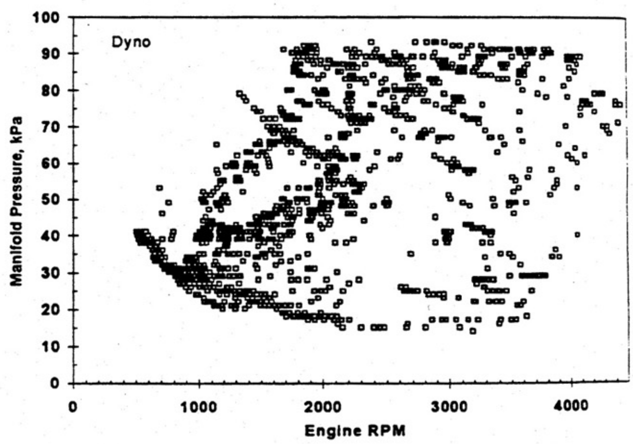

Figure 4. Dynamometer MAP vs RPM for Chevrolet Truck

DATA PROCESSING - The on-road and dynamometer data were processed using desktop personal computers, and commercially available software. Custom FORTRAN programs were used to smooth the on-road data and put it into a more manageable size using a moving window average technique [7]. On-road data were collected at 10 Hz (10 samples per second), so it was not unusual for the conglomerate on-road data file to contain over 30,000 lines of data. The smoothing routine reduced the file size to one fourth its original size.

The dynamometer data were collected at 2 Hz because the response of the gas analyzers and fuel flowmeter were on the order of seconds. Output from each gas analyzer was offset by a measured amount from realtime measurements of engine parameters to allow for transport of the gas and analyzer response time. Following computation of emissions rates (g/s), surface maps of emissions were generated as functions of engine speed and MAP.

On-road data were used to generate surface maps of RPM, MAP, and fuel consumption as functions of vehicle speed and acceleration. Using the RPM and MAP surface maps, for any given speed and acceleration one can compute the engine condition. Given RPM and MAP, one can then go to the dynamometer maps and compute the emissions. The resulting maps, or lookup tables, provide emissions and fuel consumption as functions of vehicle speed and acceleration. Graphical representations of the lookup tables are shown in surface plots of the modal fuel consumption, CO, HC and NO_x emissions in Figures 5, 6, 7, and 8, respectively. These plots are for the average of the eight vehicles, or for a composite vehicle. The onset of enrichment is very clearly seen in the CO and HC plots, when the emissions increase drastically. The NO_x emissions are shown on the same scale as the HC emissions.

It is important to point out that most vehicles cannot operate in every mode represented here. For almost any vehicle the maximum obtainable acceleration rate decreases at higher speeds. Since the lookup tables are provided on a rectangular matrix, the unobtainable cells are filled with their nearest neighbor. That is, the emissions or fuel consumption value at the maximum acceleration for any given speed is used to fill the remainder of the lookup table for that speed.

VERIFICATION

A recent government/industry cooperative research program has made publicly available emissions and fuel consumption data for a number of light-duty vehicles driven over four different cycles [8,9]. The purpose of the program was to examine the effects of "off-cycle" driving on vehicle emissions. "Off-cycle" here designates those vehicle speeds and accelerations not represented by the current Federal Test Procedure (FTP) for compliance testing of motor vehicle emissions. Three new test cycles were developed based on driving pattern studies [10-12], and each vehicle tested in the FTP Revision Program (FTPRP) was tested at least twice on each of the three cycles as well as the current FTP. The other three cycles were designated ARB02, REP05, and HL07. For a thorough explanation of the intent of these other cycles, the reader is encouraged to consult the literature [8].

To verify the utility of the resulting data-based models, driving cycle emissions and fuel consumption were computed for the four driving cycles in the FTPRP (FTP, ARB02, REP05, and HL07) using the composite vehicle maps to obtain a per-vehicle estimate for each cycle. The model results were compared to actual cycle-derived emissions and fuel consumption from the FTPRP. The FTPRP results were obtained by adding 5/8 of the light duty car average and 3/8 of the light-duty truck average

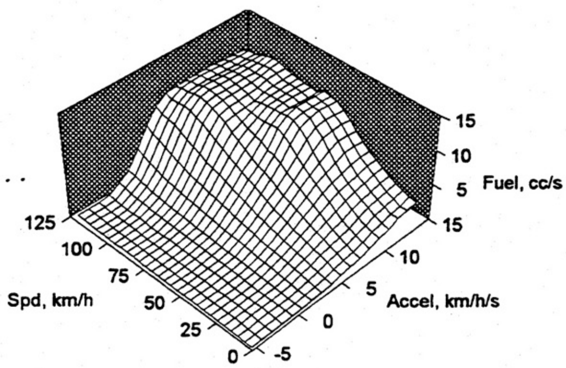

Figure 5. Composite vehicle fuel consumption

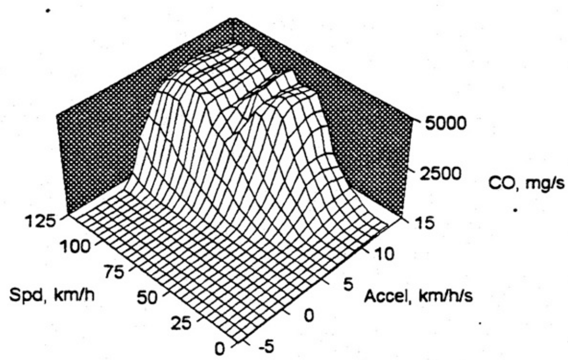

Figure 6. Composite vehicle CO emissions

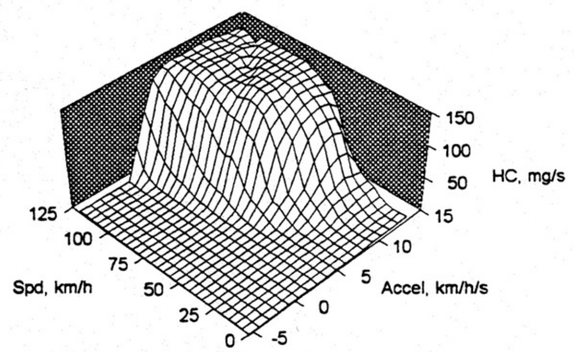

Figure 7. Composite vehicle HC emissions

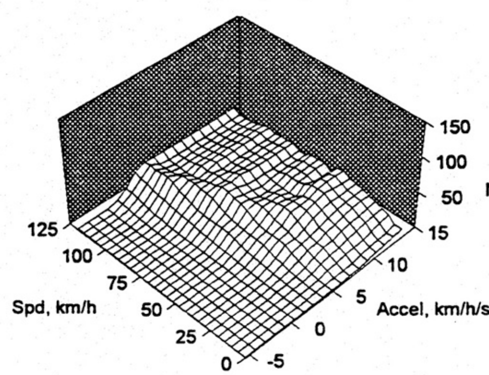

Figure 8. Composite vehicle NO_x emissions

(because the modal models were developed from 5 light cars and 3 light trucks). The four Heavy Light Trucks (>3850 kg (8500 lb) GVWR) in the FTPRP database were omitted from the averaging [8,9]. The resulting FTPRP average vehicle specifications are shown in Table 1.

Driving cycle emissions and fuel consumption were estimated for each of the "hot-stabilized" phases or "bags" of the FTPRP cycles. Cold start emissions were not predicted as the models currently have no cold-start algorithm. The emissions and fuel consumption of each phase were computed as follows: 1) compute the acceleration for each second of cycle,
2) lookup the instantaneous fuel consumption and emissions values in tables given the vehicle speed and acceleration,
3) integrate the speed, emissions, or fuel consumption over the specified number of seconds to obtain the distance traveled, the total grams of emissions, or the total volume of fuel consumed over each phase, or in each "bag."

Figure 9 shows the composite vehicle predicted fuel use for each phase of each driving cycle and the average measured fuel use for all light-duty vehicles tested in the FTPRP dynamometer runs. The individual phases (bags) are arranged from lowest to highest on the x-axis to elucidate the model's ability to predict changes in fuel consumption with changes in modal activity. Note also that despite the fact that a small number of completely different cars was used to develop the models, the modeled fuel consumption is generally within 10% of the measured values.

The CO, HC and NO_x, emissions for each bag are shown in Figures 10, 11, and 12, respectively. Like the fuel results shown in Figure 9, the emissions results are ranked from lowest to highest. While the absolute bag-to-bag comparisons can vary, the models generally show the proper trends. That is, when the different modal activity (represented by the different driving cycles) produces an increase in the emissions, the models generally predict the proper change. It is important to note that run-to-run variations for repeat tests *of the same car* at the same facility, can be significant. For all light duty passenger cars tested in the FTPRP, the average run-to-run variation for all phases was 10 to 60%, and the maximum variations ranged from 40 to 170% [9].

DISCUSSION

These models provide an easy-to-use tool for traffic engineers or other modelers to employ in traffic simulations to assess how changes in modal activity affect fuel consumption and emissions. As with any model, some detail is lost in the process of simplification. A vehicle's emissions are not a simple point function (as

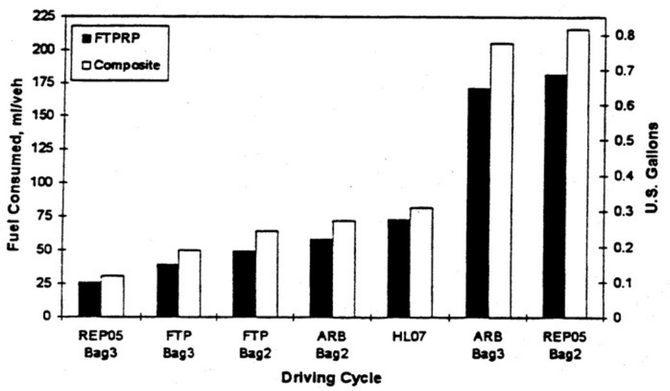

Figure 9. Modeled and measured per-vehicle fuel consumption

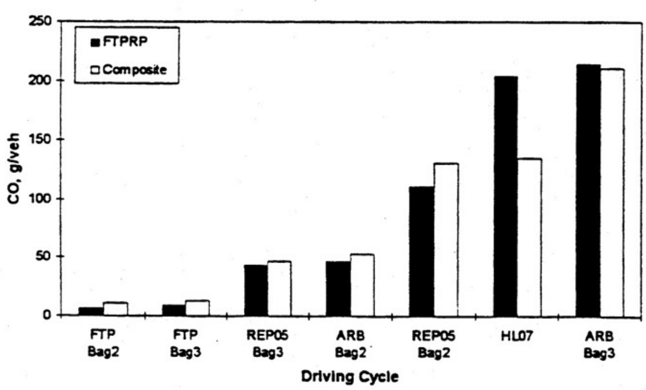

Figure 10. Modeled and measured per-vehicle CO emissions

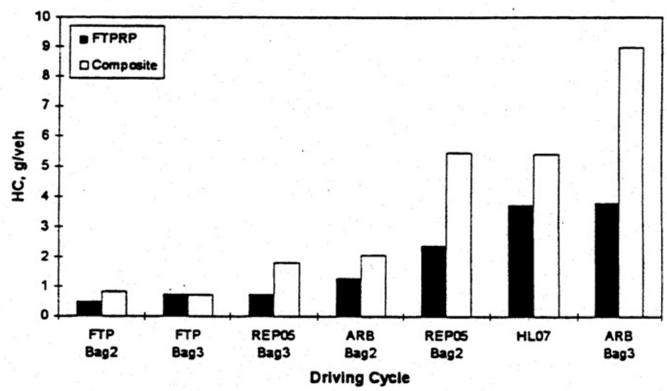

Figure 11. Modeled and measured per-vehicle HC emissions

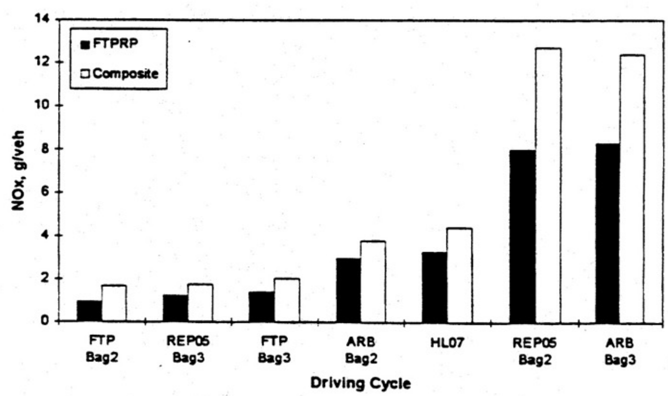

Figure 12. Modeled and measured per-vehicle NO_x emissions

represented) of speed and acceleration, but a function of many parameters, including engine and catalyst temperature, recent load and temperature history, etc. While it is understood that a more complex modeling approach might provide more accurate results, the framework of many traffic models does not readily accept added complexity.

One easy-to-change aspect of the models is weighting of each individual vehicle in the makeup of the composite vehicle. A simple numerical average of the eight vehicles was used to fill each cell of the composite lookup tables, due to the small number of vehicles available. Obviously, one high-emitter vehicle in the mix could drastically change the resulting model. For this first-pass verification exercise, no unusual weighting was applied, as the engine displacements, technologies, and vehicle weights were chosen to represent mainstream vehicles. All eight vehicles were late-model and well-functioning, like those in the FTPRP.

While the tailpipe emissions models presented have been shown to provide reasonable emissions estimates, there is some limit to how accurate a tailpipe model can be, given the confounding nature of the catalytic converter in predicting transient emissions. Engine-out emissions have been shown to be more predictable [13], but this approach to emissions prediction would then require a catalyst model to resolve tailpipe emissions.

CONCLUSIONS AND RECOMMENDATIONS

Data-based modal models developed for eight light-duty vehicles have been used to predict cycle fuel economy and emissions, and the results compared to those of a different fleet of vehicles actually tested on the same cycles. The resulting predictions are generally within the typical run-to-run variation in repeat dynamometer tests.

Future planned work includes adding more vehicles to the database, including high-emitter vehicles, pre-control vehicles, light and heavy-duty diesel vehicles, and alternative fuel vehicles. More work is planned with the existing engine-out emissions data, including development of engine-out lookup tables and a simple catalyst model that could be easily incorporated into traffic models. In addition, development of a cold-start algorithm that uses multipliers to correct hot-stabilized emissions and fuel consumption for a cold engine is also planned.

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