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Comparison of Emission Models with On-Road Heavy-Duty Diesel Modal Data

by

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INTRODUCTION

As progressively more states and local agencies develop State Implementation Plans (SIPs) to meet ambient air quality standards, mandated by the Federal Clean Air Act, it is clear that sources of ozone precursors and particulate matter (PM) will receive considerable attention. For those areas that are striving to meet ozone and fine particulate air quality goals, it is becoming increasingly apparent that mobile sources, primarily internal combustion engines, are contributing a substantial portion of the overall emission inventory. The diesel engine, already recognized as a major source of ozone precursor (volatile organic compound [VOC] and nitrogen oxide [NO_x]) and PM emissions, has become even more of a focus as reductions from gasoline engines become harder to obtain.

For the benefit of the emissions inventory community and regional air quality modelers, EPA's Office of Mobile Sources (OMS) has produced a model, the latest version of which is called MOBILE5b, that predicts mobile source emission factors for ozone precursors and carbon monoxide (PM exhaust emission factors are estimated with a similar, but separate, model: PART5). This model was developed using information on motor vehicle fleet characteristics, usage patterns, and the regulatory and economic forces that affect them. Among a vehicle's pertinent characteristics are its weight, fuel type, aerodynamic configuration, and emission control technology. Because many of these parameters vary by model year, the MOBILE model internally calculates emissions contributions separately by model year, vehicle class, and fuel type. The final outputs from the MOBILE model are composite emissions factors, usually expressed as grams/vehicle-mile of travel, in which all of these factors have been weighted together to produce average emission factors for each pollutant and each vehicle class and fuel type for a specific calendar year.

To develop the MOBILE model, it was necessary to incorporate emissions test data for each type of vehicle. Among the most readily available sources of emissions data for motor vehicles are the certification test results. Passenger car and light-duty truck models, prior to being sold in the United States, must be certified on a chassis dynamometer, using a test cycle that is meant to simulate the full range of "normal" vehicle operation. This type of test yields an emission measurement (grams/mile), which is used to calculate average emission factors for development of emission inventories.(1) Because off-road and heavy-duty vehicles often include engines from different manufacturers (bringing about an enormous number of potential vehicle/engine combinations), and because chassis dynamometers are limited in their load capacity, it is the engines that are certified for these classes of vehicles.

The engine dynamometer test results are expressed in grams per brake horsepower-hour (g/BHP-hr). In order to convert the results to grams per mile, a series of "conversion factors" (CFs), in units of BHP-hr/mile, was developed.(2) These CFs are calculated from fuel density, engine brake specific fuel consumption (BSFC), and fuel economy (FE). Although the CF development process performs separate calculations for each vehicle class and model year, the data that are actually incorporated into the MOBILE model is a single "Fleet-Average CF" for each model year. In response to EPA's desire that MOBILE use accurate CFs reflecting actual on-road emissions, its Air Pollution Prevention and Control Division (APPCD) has begun a validation program to confirm or modify those CFs using actual on-road-measured emissions data. (3)

BACKGROUND

Developers of emissions inventories require, and MOBILE calculates, emission rates in grams per vehicle-mile. This value is the product of two primary inputs and several "correction factors." The primary inputs are the base emission (BE) rates and the conversion factor (CF). The "correction factors" adjust for conditions that do not correspond to BE measurement conditions. For heavy-duty diesel vehicles (HDDVs), the only correction that is applied is a speed correction, which accounts for traffic speeds other than 20 MPH (which BE rates represent). The BE values that are incorporated into the model are meant to represent the nationwide fleet, and come from a combination of engine dynamometer testing and assumptions about regulatory compliance.

CFs are calculated, for each vehicle class and fuel type, using the formula

$$CF\left(\frac{bhp\cdot hour}{mile}\right) = \frac{\rho\ (lb/gallon)}{BSFC\ (lb/bhp\cdot hour) \times FE\ (miles/gallon)}$$

where ρ is fuel density. Table 1 shows the input parameters, along with the data sources for the most recent versions of the MOBILE model. A number of sources can provide fuel density values, with relatively little variation among them; the most recent versions of the MOBILE model use data from Motor Vehicle Manufacturers Association (MVMA)[1] fuel surveys.(4) BSFC values are interpolated from a combination of engine certification test results (pre-1979) and responses to direct inquiries of manufacturers. Truck fuel economy statistics come from the U.S. Department of Commerce's quintennial Truck Inventory and Use Survey (TIUS).

The APPCD validation program currently has on-road data available for two heavy-duty trucks. The first test tractor was a 1989 Ford CL9000 Cab-over with a 315 hp Cummins NTC-315 engine and approximately 105,000 miles of primarily short-trip, no-load use. The second test tractor

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[1] Current title: American Automobile Manufacturers Association (AAMA)

Table 1: Inputs to MOBILE Model Conversion Factor Calculation

Fuel Density	BSFC	Fuel Economy
Carbon content and mass fraction data published in 40CFR Part 600 - MOBILE3	Engine Manufacturers Association (EMA) - MOBILE3-5	1972 TIUS - MOBILE3-5
Motor Vehicle Manufacturers Association (MVMA) - MOBILE4&5	Individual Engine Manufacturer Contacts - MOBILE3-5	1982 TIUS - MOBILE4&5

was a 1990 Freightliner with a 325 hp Caterpillar 3176 engine, showing over 550,000 miles on its odometer; its history and maintenance condition are unknown.(5) The on-road emissions dataset consists of parametric test data (constant load, grade, and speed/acceleration conditions), representative urban route data (delivery, interstate bypass, and terminal entry/exit), and on-road simulations of dynamometer test cycles. This paper will analyze the MOBILE conversion factors, in the context of how well they represent the on-road test data.

CONVERSION FACTOR (CF) ANALYSIS

The CF methodology relies on several assumptions, many of which were made for lack of better or contradictory data. First, it was assumed that a single CF could represent all trucks of a given model year. This assumption is being abandoned, beginning with MOBILE6.(6) Second, it was assumed that brake-specific emissions can be used to effectively model emissions of all pollutants. The on-road data show that the approach of using a power-demand-based model may be feasible for accurately estimating NO_x emissions.(5) Third, it was assumed that the fuel statistics that serve as inputs to the CF calculations (fuel density, engine BSFC, and on-road fuel economy) are representative of suitably realistic and similar conditions, justifying their combination into a simplified CF. It is the third assumption that will be addressed here.

Fuel Density

There is little doubt that the fuel density values used in the MOBILE models are representative of the overall fuel supply. Figure 1 shows several values referenced in the CF technical reports (4,7), as well as several density measurements that have been made during the on-road emissions study. The MOBILE3 value is calculated from carbon mass fraction and carbon mass per unit fuel volume values published in the "Fuel Economy of Motor Vehicles" section of 40CFR,(8) but the 1983 MVMA fuel survey value is included in the EPA technical report for comparison.(7) MOBILE4 abandons the CFR values in favor of the average of the 1982-1985 MVMA fuel survey values (7.11 lb/gal). All of the values, including those measured from the on-road facility's fuel supply, are within ±1% Relative Standard Deviation (RSD).

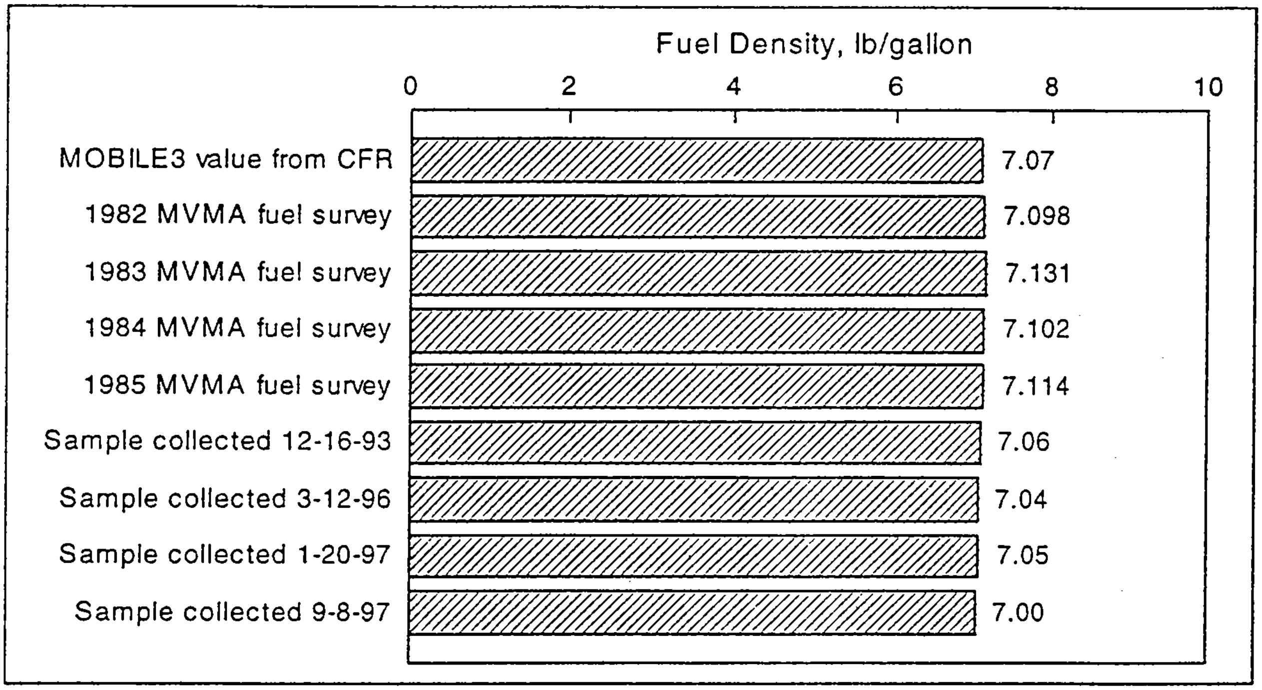

Figure 1: Comparison of Diesel Fuel Densities

Brake-Specific Fuel Consumption

Figures 2a and 2b show estimates, derived from on-road measurements, of BSFC for the first two test trucks, along with the most recent MOBILE BSFC of 0.39 lb/bhp•hr (which is applied to all model years 1987 and later). Other than the obvious upturn at low horsepower, there appear

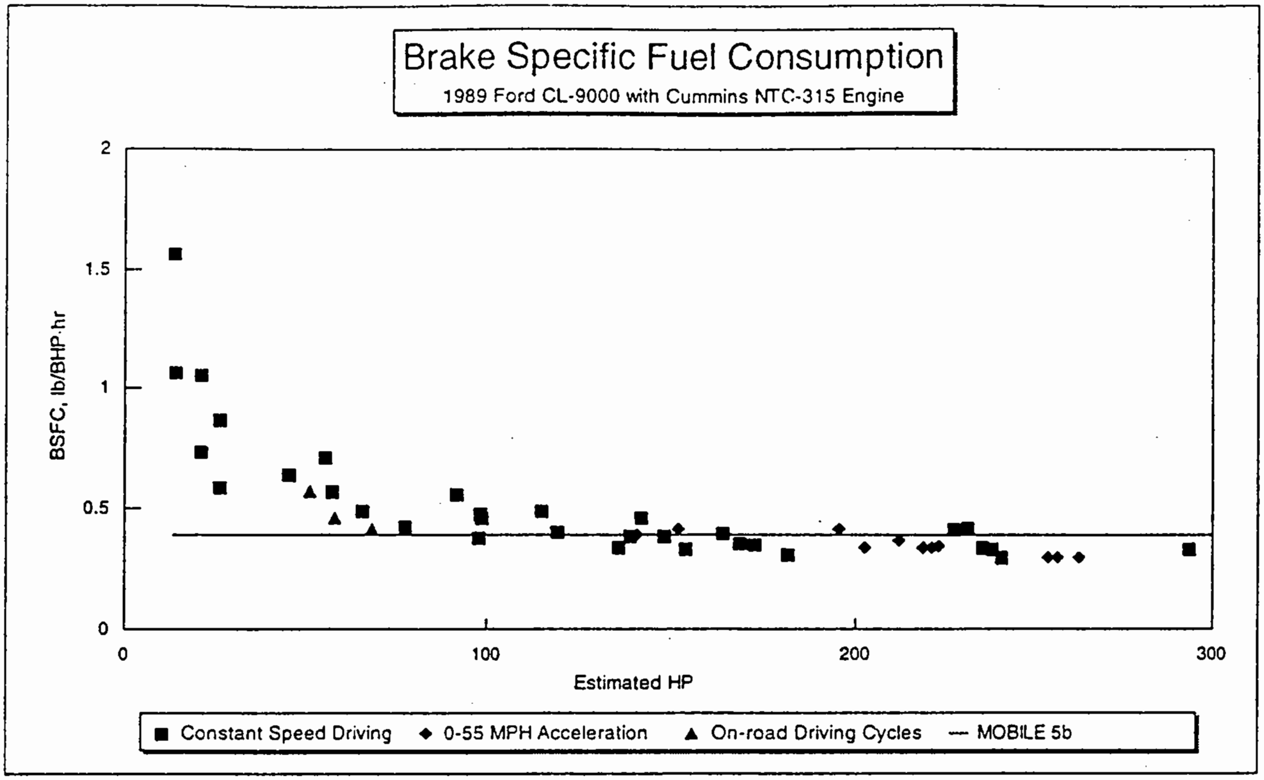

Figure 2a: Truck 1 Brake Specific Fuel Consumption

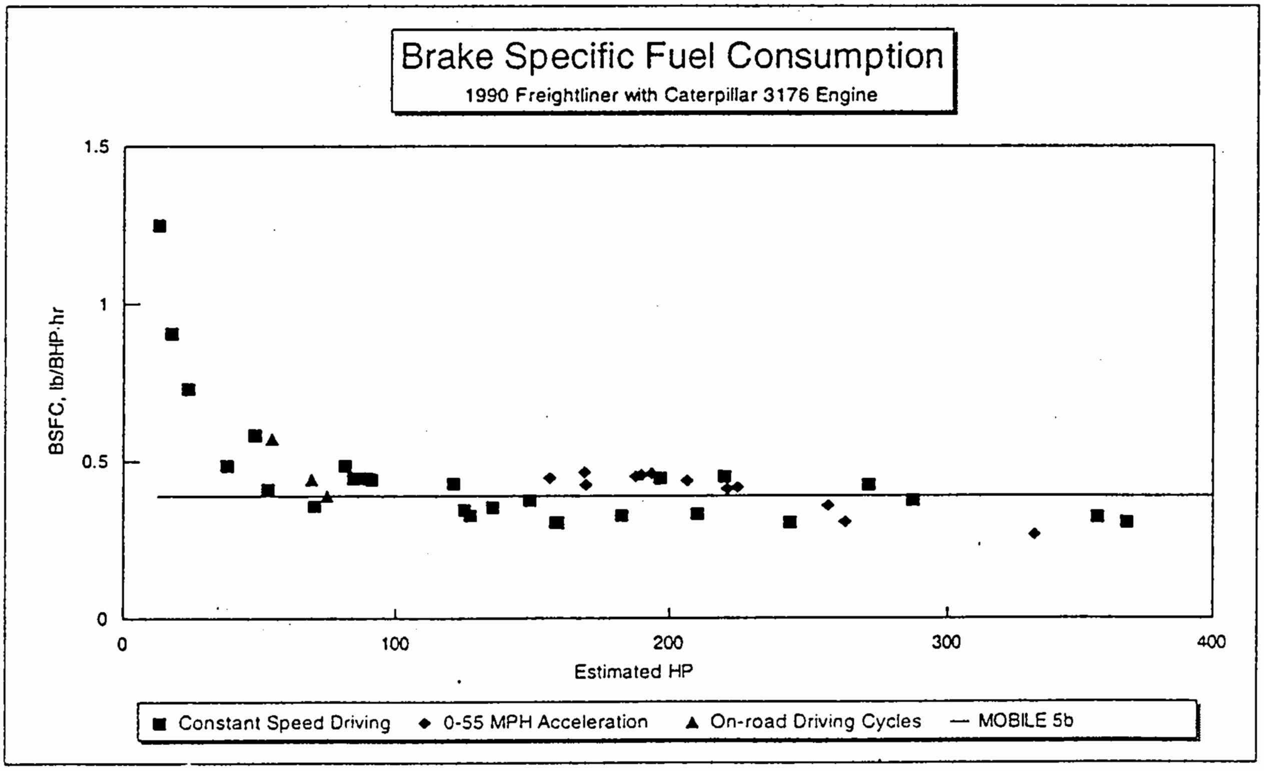

Figure 2b: Truck 2 Brake Specific Fuel Consumption

to be no statistically significant trends in the on-road BSFC data. The moderate-to-high-horsepower BSFC values correspond to the MOBILE line, within the precision of the data. The on-road driving cycles, by no means outlyers on the figures, do show a modest upturn in BSFC. The Freightliner data show elevated values under acceleration conditions, but the effect cannot be statistically quantified because of the overall scatter in that truck's data. It is likely that, under more controlled test conditions, it may be possible to quantify the effect of transient operation on BSFC in a statistically defensible manner. Nevertheless, the current BSFC values incorporated into the MOBILE conversion factors represent these two trucks reasonably well.

Fuel Economy

The engine certification cycle is generally accepted as "representative" of urban driving. Therefore the use of BSFC values from this test is seldom criticized, at least not for "urban" conversion factors. What has often been brought up as a "loose end" in the conversion factor methodology is the use of TIUS fuel economy values, which may not represent urban operation. (4,7) Fortunately, the on-road facility has furnished a large amount of fuel economy data under a variety of operating conditions. Figures 3a and 3b show some of the fuel economy measurements; each bar represents average fuel economy for the specified load (pounds Gross Combined Weight, GCW), and operating condition (test cycle, route, constant speed, or acceleration). Bars are pattern-coded to facilitate comparisons.

All but the "delivery route" measurements represent level grade; these measurements are included for comparison with the on-road transient driving cycles (the top three bars in each graph) that were run at the same load. These cycles, the West Virginia University (WVU) 5-Peak Driving Cycle (9), EPA's HDDV Schedule-D (10), and an on-road federal test procedure (FTP) simulation (9), were developed as in-chassis corollaries to the engine certification test. A fuel economy comparison shows that those cycles, all of which contain a considerable amount of transient operation, actually represent urban operation reasonably well.

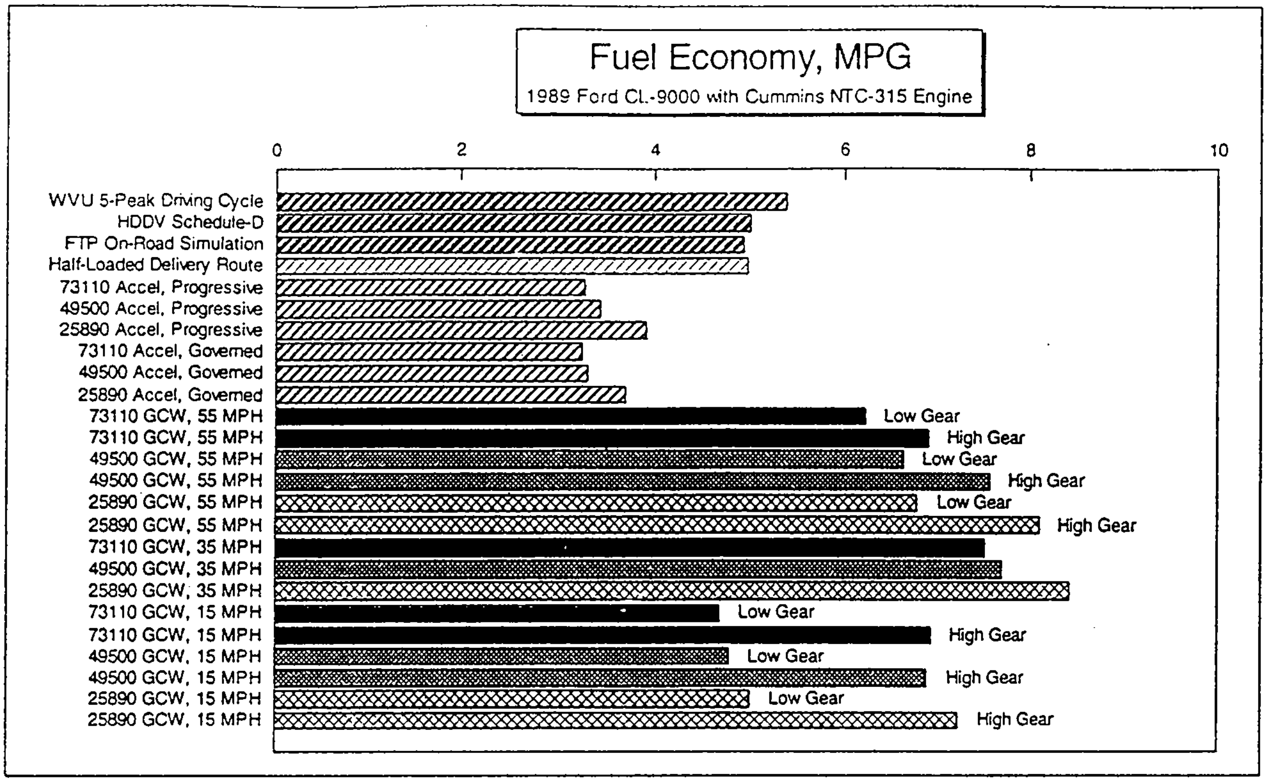

Figure 3a: Truck 1 Fuel Economy

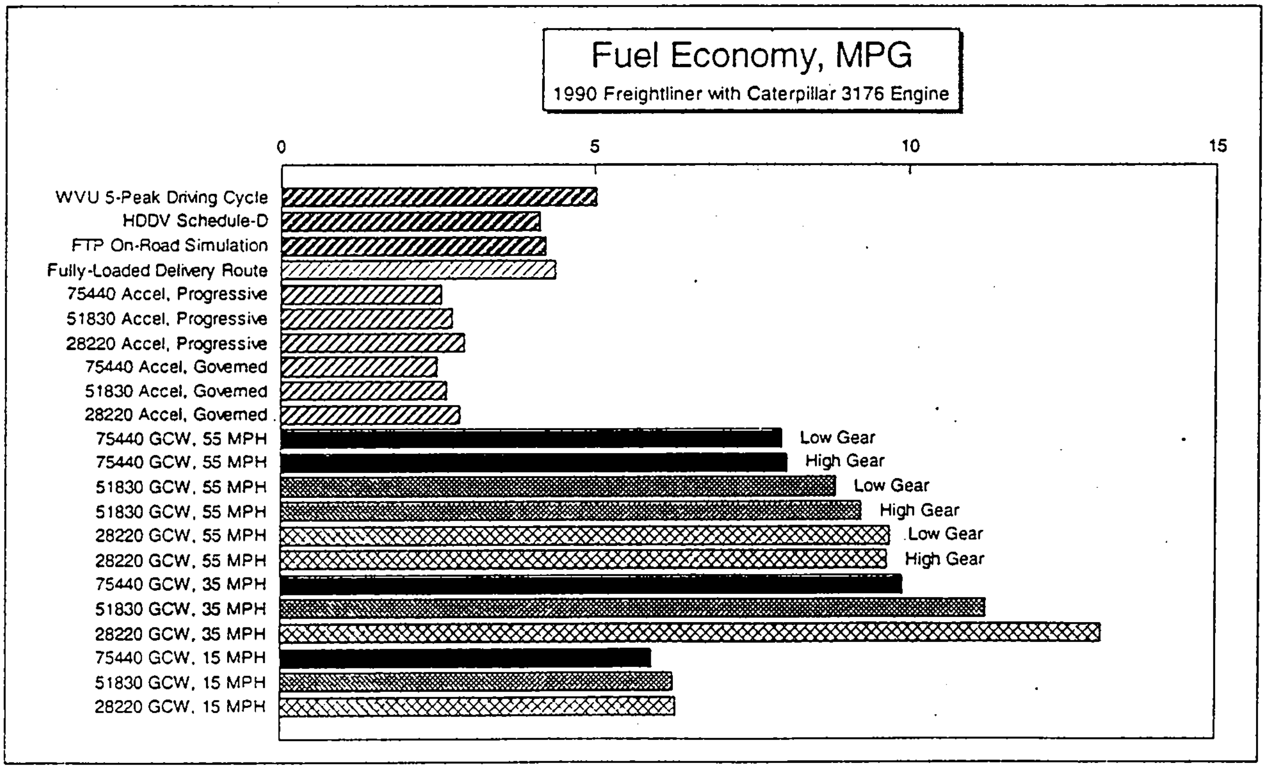

Figure 3b: Truck 2 Fuel Economy

The parametric data show that, for both trucks at all loads, the peak fuel economy was at the 35 MPH test condition. The drop in fuel economy at slow speeds is a result of the rapid rise in BSFC at near-minimal power demands (i.e., the engine uses proportionately more fuel to operate accessories and overcome internal friction as external power demands are decreased). As speeds increase above 35 MPH, the wind drag component of on-road power demand (nominally proportional to velocity squared) causes fuel economies to fall sharply. The MOBILE model incorporates this second-order variation of FE with speed in the form of a "speed correction factor," which reaches a minimum value at about 33.8 MPH for HDDVs. The model makes no attempt to distinguish between "urban" and "interstate" driving modes. In so doing, it neglects the effects of idle emissions and acceleration modes on urban emission inventories. Not surprisingly, both on-road test trucks see their lowest fuel economies of all during acceleration test conditions.

Some of the load/speed conditions are represented by more than one bar. In these cases, the prescribed condition was established with more than one gear ratio. The purpose of this duplication was to investigate RPM effects on emissions, but there was obviously an effect on fuel economy, as well. The effect was most pronounced on the Ford truck, with 15 MPH fuel economies suppressed by 30% during low-gear, high-RPM testing. Nonetheless, since this effect is likely to vary significantly from truck to truck, no attempt will be made to incorporate any type of "gearing" correction into the conversion factors.

For a more realistic comparison of fuel economies, we compare our "delivery" route to our "interstate" route, both of which represent multiple speeds and grades, as dictated by topography and traffic conditions. Figures 4a and 4b compare the fuel economy (FE) measurements for the two trucks. As expected, the "interstate" values are consistently higher than those for the "delivery" route, with load and overall grade (the eastbound interstate has more downhill driving than uphill) having predictable effects. Each bar represents three test runs of the same route; 90% confidence intervals are shown. A popular assumption in the modeling community is that long-haul (interstate)

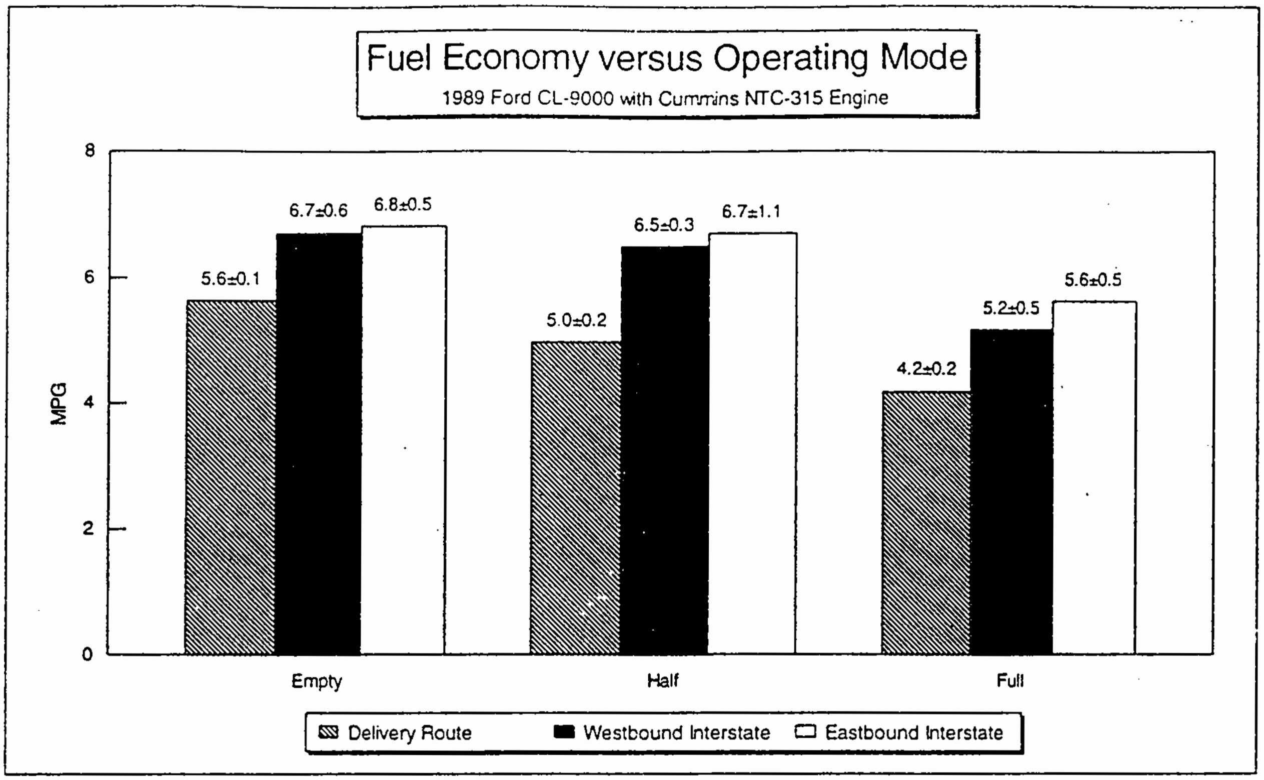

Figure 4a: Truck 1 Modal Fuel Economy Comparisons

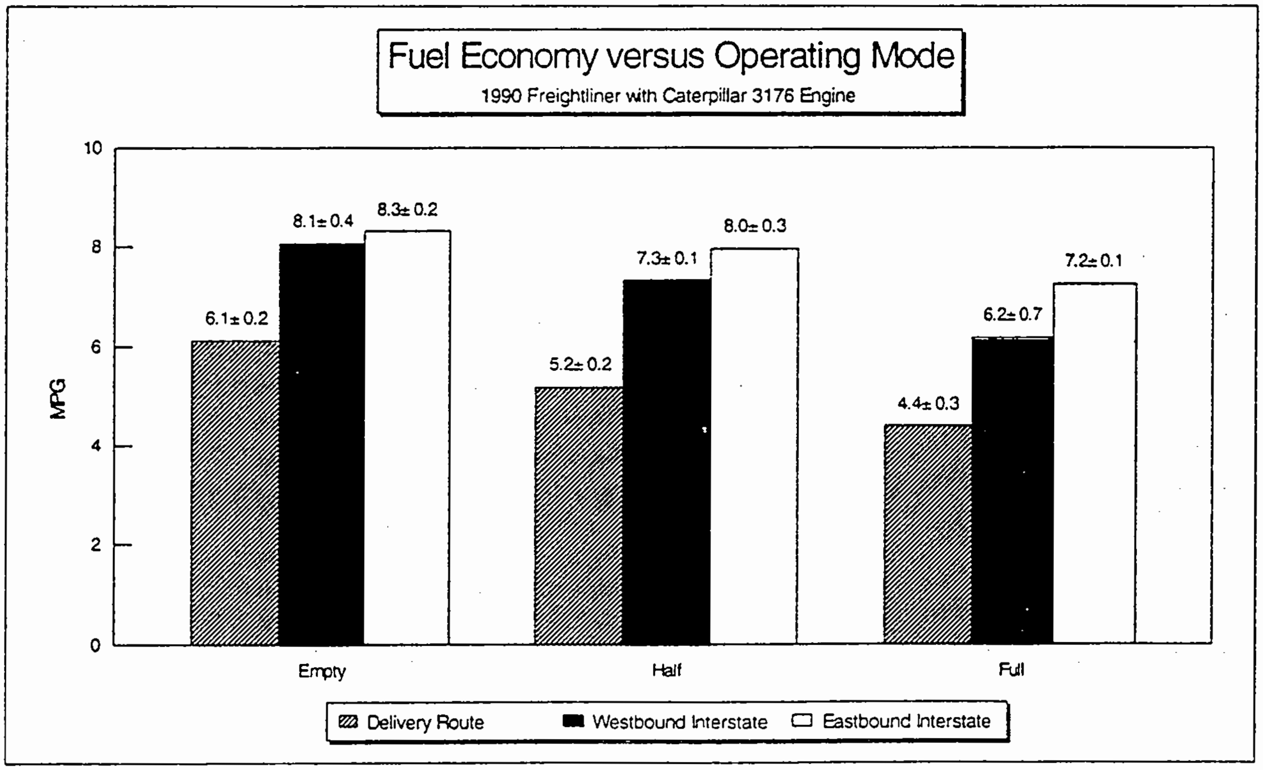

Figure 4b: Truck 2 Modal Fuel Economy Comparisons

trucks are half- to fully-loaded most of the time, while delivery trucks are most often empty to half-loaded. Tables 2a and 2b cross-compare all of the loads, with the statistical significance of the differences shown. The interstate fuel economy values are combined into a single, "round-trip" figure for this comparison. It appears that significant fuel economy differences exist between delivery and interstate driving for all but one comparison on one of the two trucks.

Table 2a: Significance of FE Differences

1989 Ford CL-9000 with Cummins NTC-315 Engine

	Delivery		
Interstate	Empty	Half	Full
Empty	98.76%	99.76%	99.94%
Half	98.62%	99.80%	99.96%
Full	Overlap	90.98%	99.47%

Table 2b: Significance of FE Differences

1990 Freightliner with Caterpillar 3176 Engine

	Delivery		
Interstate	Empty	Half	Full
Empty	99.99%	99.99%	100.00%
Half	99.97%	100.00%	99.97%
Full	95.37%	99.61%	99.96%

EMISSIONS MODEL COMPARISON

The MOBILE model calculates heavy-duty vehicle emissions as the product of the base emission (BE) rate, correction factors, and the conversion factor (CF). Within the MOBILE program, BE rates are specified as zero-mileage levels (ZMLs) and deterioration rates (DRs). The DR is a value that is added to ZML for each 10,000 miles accumulated on a vehicle or engine. ZML and DR are tabulated for each pollutant as a function of vehicle class, model year, and fuel type, but the MOBILE program also includes an option to accept user-supplied values. The speed correction factor (SCF) is a dimensionless value which is calculated as a function of vehicle speed. Parameters for calculating SCFs are tabulated as a function of vehicle class and pollutant. CF is tabulated as a function of model year and fuel type only.

Table 3 shows the ZML, DR, SCF equation, and CF values for HDDVs of the 1989 (Truck 1) and 1990 (Truck 2) model years. The zero DR values indicate that average BE rates are expected to remain the same (equal to ZML) throughout the life of that model year of trucks. The

SCF equation does not vary by model year. The CF that is used in MOBILE is a fleet average CF, intended to represent all classes of HDDVs.

Table 3: MOBILE5b Input Parameters for Tested Model Years (11)

Model Year	ZML g/mile	DR g/mile	SCF equation	CF bhp•hr/mile
1989	16.77	0	SCF = EXP(0.676 - 0.048*MPH + 0.00071*MPH^2)	2.1
1990	11.65	0	SCF = EXP(0.676 - 0.048*MPH + 0.00071*MPH^2)	2.07

Table 4 shows values that are substituted for MOBILE inputs in order to develop alternate versions of the MOBILE model. The Certification BE values are based on the actual reported engine certification test results for the engine family and model year of the trucks' engines.(12,13) Class CF is the class specific conversion factor which was developed during the most recent CF analysis, but was not actually incorporated into the model. Delivery CF and Interstate CF are the modal conversion factors that were calculated from on-road test data for each truck. The calculation follows the same general outline as the MOBILE CF calculation, except that the inputs are specific to the trucks. The BSFC input comes from an on-road simulation of the engine certification test. The FE inputs are specific to the actual routes (delivery or interstate) that they represent, which is what makes the resulting values "modal" CFs. MOBILE fuel density inputs were used for the modal CF calculations.

Table 4: Substitute Inputs for Alternative Models

Test Vehicle	Cert BE	Class CF	Delivery CF	Interstate CF
Truck 1	7.88	3.129	3.278	2.962
Truck 2	6.12	3.129	3.253	2.562

Figures 5a and 5b compare actual "delivery" and "interstate" emissions to various modeling approaches. The "delivery" route is a 57 mile loop, traversing downtown Raleigh, NC, that includes three stops at retail malls. The measurements in the figures represent an empty to half-loaded truck. The "interstate" route is a 75 mile section of I-40, passing through Raleigh and Durham, NC. The measurements in the figures represent a half- to fully-loaded truck.

Uncorrected BE rates are included among the built-in inputs to the MOBILE model. "MOBILE BE" represents those rates, with the speed correction factor (SCF) applied. These are the emissions that MOBILE would predict, given only the model year, fuel type, operating speeds, and the pollutant of interest. The "Cert BE & MOBILE CF" bars show the emissions that MOBILE would predict if, in addition, it were given the engine certification results for the test engines; MOBILE uses its built-in fleet-average conversion factors to convert engine certification results to grams/mile. . The "Cert BE & Class CF" bars substitute a class specific CF for the fleet average CF that is built into MOBILE. The "Cert BE & Modal CF" bars abandon MOBILE CFs and SCFs in favor of mode-specific CFs that are derived from trends observed in the on-road test data.

In comparing same-truck emissions between delivery and interstate operating modes, there are primarily two factors affecting the comparison. First is the difference in average speed, which would tend to increase interstate emissions relative to delivery emissions. This effect is incorporated into the MOBILE model through its SCF, which is a second order equation that reaches a minimum at about 33.8 MPH. It is because of this correction that the predicted interstate emissions are consistently higher that the corresponding predicted delivery emissions for each of the non-modal models. The second difference between delivery and interstate modes is due to idle time and acceleration. This effect is not incorporated into the MOBILE model, but shows up in the measured data as delivery emissions that meet or exceed interstate emissions for the same truck. The modal model arrives at its correction factors by direct comparison of fuel economy data between operating modes. Therefore, this model takes both speed and idle/acceleration effects into

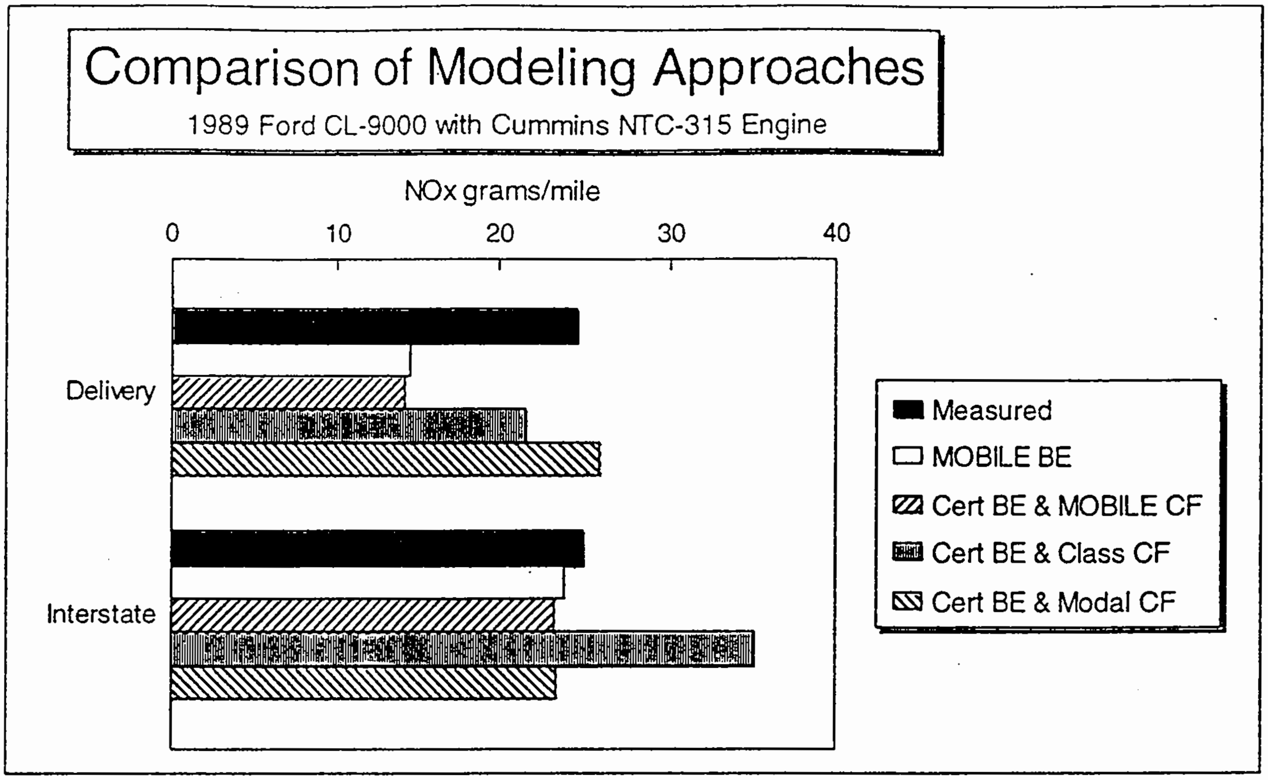

Figure 5a: Truck 1 Comparison of Modeling Approaches

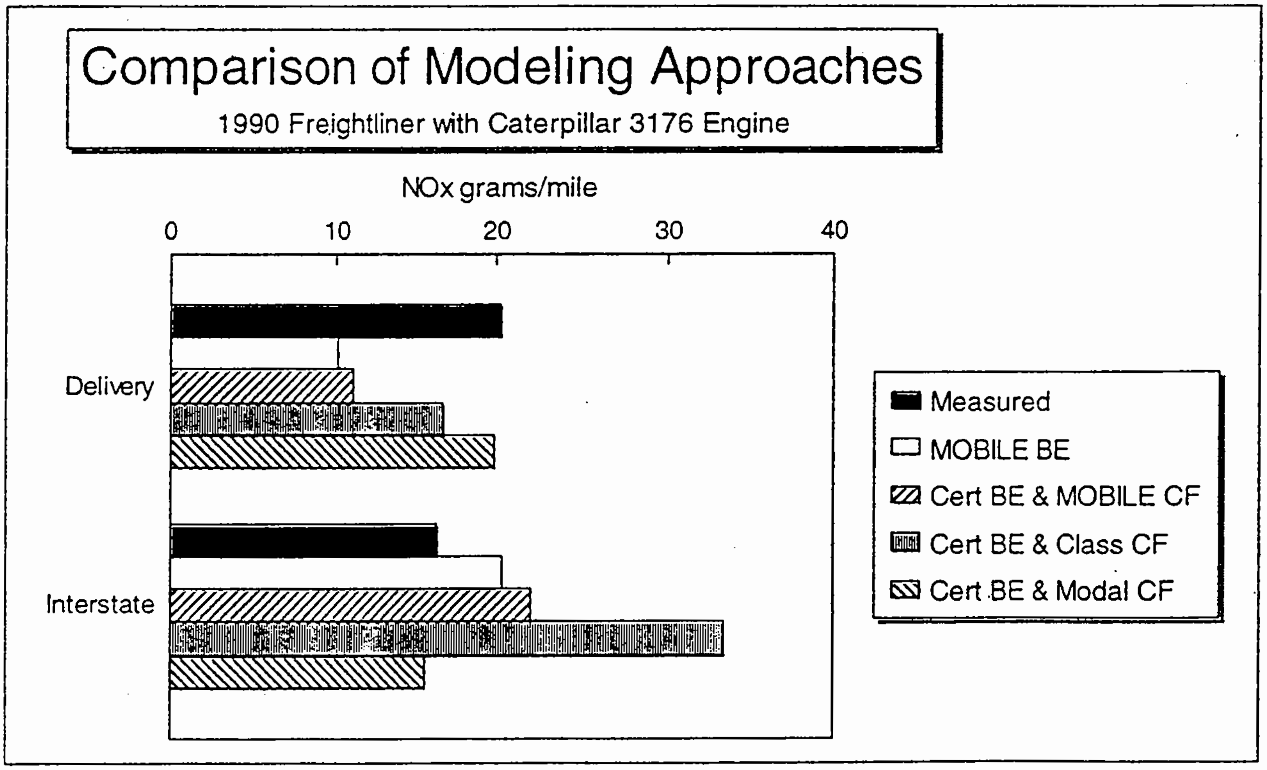

Figure 5b: Truck 2 Comparison of Modeling Approaches

consideration. This explains why it is the only model that consistently predicts emissions within ±10% of the measured value.

CONCLUSIONS AND RECOMMENDATIONS

Of the three inputs to the MOBILE conversion factor calculations, two of them represented real world data quite well. Fuel density varies very little between any of the references and measurements. Measured BSFC values for both test trucks are concentrated around the MOBILE value of 0.39 lb/bhp•hr. Some of MOBILE's assumptions regarding fuel economy, however, may need to be revised. The existence of significant FE differences between "delivery" and "interstate" operating modes would indicate that two sets of conversion factors are needed to accurately model emissions from those two modes.

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METRIC EQUIVALENTS

Readers more familiar with the metric system may use the following equivalents to convert to those units:

5/9(°F-32) = °C
1 ft = 0.3048 m
1 ft^3 = 0.0283 m^3
1 gal. = 3.785 l
1 hp = 745.7 W
1 lb = 0.4536 kg
1 mi = 1.609 km

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16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Particles	Pollution Control	13B
Mathematical Models		Mobile Sources	12A
Emission		Particulate	14G
Diesel Engines			21G
Ozone			07B
Carbon Monoxide			

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