DOCUMENTATION AND ANALYSIS OF HEAVY-DUTY DIESEL VEHICLE EMISSION TEST DATA

Final Report

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1. INTRODUCTION

This report is a task report documenting the emissions data obtained from testing a sample of heavy-duty diesel trucks that operate in the New York Metropolitan Area (NYMA). The overall work effort's objective is to investigate the nature and extent of heavy-duty diesel vehicle emissions in the NYMA. The procurement and testing of a representative sample of trucks was a central part of the overall effort, as well as the most resource intensive.

Our original work plan had estimated that we could test a sample of 50 trucks over a variety of different test cycles, with the majority being tested at the New York City Frost Street test facility. (Due to the availability of additional funding, the number was increased to 80.) However, the Frost Street facility was not operational for several years and appeared unlikely to be operational in the time frame after this effort. As a result, all testing was performed at West Virginia University (WVU) transportable chassis dynamometer emissions test facility. The costs for this facility per emission test are very high relative to the cost at the NYC facility, and the sample size had to be reduced to 37 vehicles. In addition, the number of test cycles also had to be reduced, which resulted in the elimination of some short test cycles that could be useful for vehicle emissions inspection.

Heavy-duty diesels operating in the NYMA span a wide variety of weight ranges and vintages, and a large number of engine models. A sample of just 37 trucks cannot possibly represent the breadth and diversity of the fleet, but can only provide a reasonable representation of the fleet in an average sense. The sample stratification and recruitment procedures, as well as a discussion of the 'representativeness' of the sample is provided in Section 2.

Section 3 provides a detailed documentation of the emissions test data received by EEA from WVU, and the data cleaning and aggregation procedures used. The analysis of the data is presented in Section 4 through 7. In an effort to normalize emissions from different weight

classes of trucks, EEA has developed a method to convert emissions to units of work, and the resulting emission rates in g/BHP-hr are more comparable to the emission standards and certification based emission measurements. All analyses of data are in units of g/BHP-hr.

While a number of topics of interest to New York State have been investigated, we caution the readers of this report that all these analyses are based on very limited data. The conclusions (or lack of conclusions) must be viewed in the context of the small sample size. Investigations of the effect of test weight are limited to data from a sample of two trucks tested at three test weights, for example. Differences between engines, test variability and repeatability create "noise" that makes it difficult or impossible to spot underlying trends with small samples. Nevertheless, there are a number of conclusions that are likely to be of great interest to the New York State Department of Environmental Conservation.

The reduction in sample size and in the number of short tests performed resulted in some changes to the original objectives. One objective was to evaluate alternative short tests and emission control programs for the NYMA. Available data from this test program does not permit a quantification of short test effectiveness and control program efficiency, so that this objective had to be attained with existing models and data. The extrapolation of the emission data from this small sample to the entire NYMA fleet may be inaccurate, so our results should be considered as preliminary. These results are provided in Section 8.

Conclusions of our study are presented in Section 9.

2. FLEET SEGMENTATION AND SAMPLE REPRESENTATIVENESS

2.1 HDT TYPES

Heavy-duty trucks span a very wide weight range from 8500 lbs gross vehicle weight (GVW) to 80,000 lbs GVW. The EPA has recognized three sub-categories of engine types among the heavy-duty fleet: light, medium, and heavy. Although all three types are required to meet the same emission standards, they have different durability requirements reflecting their substantial differences in application and annual travel rates. In each segment, three or four engine models have dominated sales. Due the introduction of stringent PM emission standards in 1991 and 1994, a large number of older engine models were replaced in the late-1980's and early-1990s.

The light-heavy category is dominated by three engine models: the Navistar 6.9/7.3L V-8, the Cummins 5.9L I-6 and the GM 6.2/6.5 L V-8. These engines were introduced in the mid- to late-1980s and were technologically updated in the 1994 time frame to meet more stringent emission standards. Typically, these engines are used in the heavier pickup trucks and panel vans that range from 8500 lbs to 16,000 lbs GVW. In some less demanding applications (e.g., school buses), these engines are used in vehicles of 16,000 to 26,000 lbs GVW.

The medium-heavy category is dominated by four engine models. Two V-8 models, the Caterpillar 3208 and the GM 8.2L were discontinued in the early 1990s and have been replaced by the six-cylinder Caterpillar 3116 and four-cylinder Detroit Diesel (DDC) Series 50 engines. The Navistar DT 466 and Cummins C Series 8.3L I-6 engines have continued to be offered over the last 20 years. These engines are typically used in vehicles with a GVW range from 20,000 to 50,000 lbs. Some imported engines from Volvo, Renault and Ford of Brazil have achieved modest market share in the East Coast in this category.

In the heavy-heavy category, there traditionally have been two horsepower ranges: one from 270 to 350 HP, and the second from 330 to 450 HP. The latter category of engines is generally used

in the heaviest end of trucks or in applications that demand high performance. Again, four models of engines have dominated the two HP subcategories. Historically, the Cummins L-10 and N-14, the Caterpillar 3306 and 3406, the Mack E-5 and E-7 and the Detroit 6-71 and 6-92 engines have dominated the two horsepower ranges respectively. The L10 engines has been replaced by the M11, while the Caterpillar 3306 has been replaced by the 3176. Detroit Diesel was unique in offering two stroke engines, but both two-stroke models have been replaced by the Series 60 engine available in two displacements (11.1L and 12.6L). Table 2-1 summaries the popular engine types sold by class and category. Historically, Cummins has had the dominant market share in this class. The higher horsepower range of engines is less common in the East Coast and in trucks operating in urban areas.

In the last few years, improvements to diesel engine technology has resulted in continued increases in specific output, so that all engines are moving up to heavier applications. However, since our testing was limited to 1998 and earlier trucks, this factor had only limited effect on our sampling plan.

Engine and vehicle emissions also vary by the emission regulations in force at the time that the engine was sold. Emission standards for heavy-duty trucks are shown in Table 2-2. Emission standards have increased in stringency in 1984, 1990, 1991, 1994, and 1998 respectively. The 1984 standards had little effect since they were relatively lax and most pre-1984 engines would have meet the 1984 standards. The standards for 1990 were originally proposed for 1988 but delayed due to litigation. Since the standards changed again in 1991, and banking of emission credits was allowed, the fleet differences in emission between 1990, 1991, and 1992 model years were not large, so that 1990 need not be treated as a unique model year.

2.2 SAMPLING PLAN

The original sampling plan was based on the expectation of testing of a total of 50 trucks, 40 at the New York City Frost Street Laboratory, and ten at West Virginia University's mobile test laboratory. The sample of 50 was to be split by weight category and model year group as follows:

TABLE 2-1
LIST OF POPULAR ENGINE MODELS BY WEIGHT CATEGORY

Category	**Older Models**	**Newer Models**
Light-Heavy	GM 6.2L V-8 Navistar 6.9L V-8 Cummins 5.9L I-6	GM 6.5L V-8 Navistar 7.3L V-8 Cummins 5.9L I-6
Medium-Heavy*	Caterpillar 3208 V-8 Navistar DT466 I-6 GM 8.2L V-8 Cummins C 8.3L I-6	Caterpillar 3116 I-6 Navistar DT466 I-6 DDC Series 50 I-4 Cummins C 8.3L I-4
Heavy-Heavy (<350 HP)	Caterpillar 3306 I-6 Cummins L-10 I-6 DDC 6V-71 V-6 Mack E-5 I-6	Caterpillar 3176 I-6 Cummins M-11 I-6 DDC Series 60 (11.1L) I-6 Mack E-5
Heavy-Heavy (>330 HP)	Caterpillar 3406 I-6 Cummins N-14 I-6 DDC 6V-92 V-6 Mack E-7 I-6	Caterpillar 3406 I-6 Cummins N-14 I-6 DDC Series 60 (12.6L) I-6 Mack E-7 I-6

* Brazilian built Ford engines were relatively popular during the late-1980s/early-1990s but were discontinued.

TABLE 2-2
FEDERAL EXHAUST EMISSION STANDARDS FOR HEAVY-DUTY DIESEL ENGINES
(grams per brake horsepower-hour)

Model Year[1]	Hydrocarbons	Carbon Monoxide	Oxides of Nitrogen	HC +NO_x	Particulates	Smoke Opacity	
1970-1973	--	--	--	--	--	Accel. Lug	40% 20%
1974-1978	--	40	--	16	--	Accel. Lug Peak	20% 15% 50%
1979-1983	1.5 --	25 25	-- --	10 5	-- --	Same	
1984[2]	1.3 0.5	15.5 15.5	10.7 9.0	-- --	-- --	Same	
1985-1987	1.3	15.5	10.7	--	--	Same	
1988-1990	1.3	15.5	6.0	--	--	Same	
1991-1993	1.3	15.5	5.0	--	0.25[3]	Same	
1994-1997	1.3	15.5	5.0	--	0.10[3]	Same	
1998-2003	1.3	15.5	4.0	--	0.10[3]	Same	
2004 and Subsequent	0.5	15.5	2.0	2.4	0.10[3]	Same	

[1] The steady-state procedures were used through 1984 and the transient procedure has been used since 1985.
[2] Manufacturers had the option of using the 1983 procedure and standards, or standards of 1.3 HC, 15.5 CO and 10.7 NO_x on the transient procedure or standards of 0.5 HC, 15.5 CO and 9.0 NO_x on the steady-state procedures.
[3] See text for discussion of urban bus emission standards.

Model Year	Light-Heavy	Medium-Heavy	Heavy-Heavy
1979-1984	6	6	2
1985-1989	7	7	4
1990-1994	7	7	4
Total	20	20	10

Due to maximum test weight limitations at the NYC Frost Street laboratory, all ten heavy-heavy-duty vehicles were to be tested by West Virginia University (WVU). The intent of the plan was to obtain a broad representation of all engine model types and model year combinations that are significant in New York City Metropolitan Area truck population.

Unfortunately, the Frost Street laboratory was not operational and all testing had to be conducted at the West Virginia University laboratory. Due to the significantly higher costs of testing at the WVU faculty, the total number of tests had to be cut back to 37 vehicles. Two of the 37 vehicles were also tested at multiple inertia weight settings, to obtain information on how vehicle payload affects emissions.

The WVU laboratory also had restrictions on the lightest weight vehicles that could be tested, which effectively eliminated light-heavy duty trucks from consideration. Hence, the sample was restricted to only medium-heavy and heavy-heavy duty trucks. Analysis by JFA (Task A2) revealed that the medium-heavy diesel population was about twice as large as the heavy-heavy diesel population in the NYMA. Hence, it was decided to split the sample into 25 medium-duty trucks and 12 heavy-heavy duty trucks. In addition, it was planned to obtain a representation of most or all of the makes and models listed in Table 2-1, and to recruit vehicles within the 1984-1998 model year range, which constitute close to 85 percent of the current population in the NYMA.

The overall sampling plan also had the objective of sampling across a variety of owners such as large government fleets, private fleets, truck rental/lease organizations, and small independents with one to three trucks in their fleets.

2.3 ACTUAL SAMPLE PROCURED

The multiple requirements of the sampling plan made it difficult to achieve all goals completely. This was recognized at the outset, and the plan was considered as a 'target" from which real world compromises were made. One significant factor that limited our ability to reach the target was the requirement to have a truck awaiting testing as soon as the previous truck was released from testing. Since the testing schedule was somewhat variable due to equipment failures and invalid tests, trucks had to be recruited on an "as available" basis from organizations that were contacted prior to testing.

EEA analysis of ownership of trucks revealed several large government and private diesel fleets with over 500 trucks in the fleet in the NYMA. Due to the total sample being limited to 37 vehicles, we established contacts with the three largest public and four largest private fleets. The largest public fleets are these with the NYC Department of Transportation, Department of Sanitation and Department of Environmental Protection. Four large private fleets we contacted included those with Bell Atlantic, Con Edison, Federal Express and United Parcel Service (UPS). (There are other large private fleets such as Coca-Cola Bottling, Brooklyn Gas, etc, which were not contacted). The seven fleets contacted represent over 20 percent of the NYMA registered diesel fleet of 54,230 medium and heavy vehicles.

We also found that a large number of independents lease or rent their trucks from rental agencies. We contacted four large agencies, three of which had over 500 trucks in their fleet. The largest, Mendon, has about 2000 diesel trucks operating in the NYMA. Salem has about 1250 vehicles, while 4G has a little over 500 vehicles. Even Kreger Leasing, the smallest, had about 250 vehicles in the fleet.

Contacting small independent truckers and obtaining their trucks for testing was difficult since they cannot afford the downtime and disruption to their business. Nevertheless, we procured trucks from two small food distribution companies, Avanti and MJLK.

The seven large fleets and four rental companies have a total fleet size that accounts for almost 25 percent of the NYMA medium and heavy diesel fleet. Hence, the composition of the fleets sampled is very representative of the NYMA fleet.

Since testing was delayed by almost two years relative to the original proposal a significant number of 1994 and later vehicles were sampled. Due to the stringent PM standards that were enacted for 1994 and later model years, these newer trucks were grouped into one category. Also, no trucks older than model year 1984 were obtained. Hence, the sample was segregated into three model year groups: pre-1990, 1990-1993, and 1994+.

The resulting sample of trucks procured by weight category and model year group is shown in Table 2-3. Very good representation was obtained across the three model year groups and across engine models within each model year group for the 25 medium-duty trucks. The sample distribution for the 12 heavy-duty trucks is not as good, with nine of the 12 in the 1994 and newer model year group. The representation of models is also not as good with eight of 12 engines manufactured by Cummins. To some degree, the sample represents the dominant market share of Cummins in the heavy-heavy segment (over 50 percent until recently) and their strength in the East Coast market. However, inclusion of one or two Caterpillar and DDC engines in the sample would have been preferable, but these engines were not represented in the fleets sampled.

All trucks procured were direct from operations and <u>no</u> servicing or special maintenance was performed immediately before testing. To the best of our knowledge, trucks were randomly withdrawn from the fleet on an “as available” basis, and no sampling bias towards cleaner or better-maintained trucks is likely.

TABLE 2-3
SAMPLE DISTRIBUTION BY
WEIGHT CLASS AND MODEL YEAR GROUP

Model Year Group	Medium Heavy Duty Trucks	Heavy Heavy Duty Trucks
Pre-1990	7 Vehicles	2 Vehicles
	EEA-10: 1985 Caterpillar 3208 - 210 hp (10.4L) EEA-18: 1988 GM 8.2L - 225 hp (8.2L) EEA-25: 1986 International 9.0L - 165 hp (9L) EEA-26: 1988 Caterpillar 3208 - 215 hp (10.4L) EEA-31: 1987 Navistar DT466 - 210 hp (7.6L) EEA-34: 1985 Volvo FVT0334 - 174 hp (5.5L) EEA-36: 1988 Ford 6.6L - 170 hp (6.6L)	EEA-7: 1986 Cummins L10 - 270 hp (10L) EEA-16: 1984 Cummins NTC - 300 hp (14L)
1990-1993	9 Vehicles	1 Vehicle
	EEA-2: 1992 Navistar DT466 - 195 hp (7.6L) EEA-3: 1990 Navistar DT360 - 170 hp (5.9L) EEA-5: 1993 Cummins C8.3 - 210 hp (8.3L) EEA-6: 1990 Ford 7.8L - 240 hp (7.8L) EEA-11: 1991 Caterpillar 3116 - 185 hp (6.6L) EEA-12: 1993 Navistar DT466 - 270 hp (7.6L) EEA-13: 1990 Ford 6.6L - 165 hp (6.6L) EEA-21: 1992 Navistar DT360 - 190 hp (5.9L) EEA-22: 1992 Renault 6.2L - 210 hp (6.2L)	EEA-23: 1991 Mack EM7 - 250 hp (11.9L)
1994+	9 Vehicles	9 Vehicles
	EEA-1: 1994 Cummins B5.9 - 190 hp (5.9L) EEA-4: 1994 Renault 6.2L - 190 hp (6.2L) EEA-19: 1995 Cummins B5.9 - 190 hp (5.9L) EEA-20: 1996 Navistar 7.3L - 175 hp (7.3L) EEA-28: 1999 Mitsubishi 6D34 - 175 hp (5.9L) EEA-29: 1995 Cummins C8.3 - 225 hp (8.3L) EEA-30: 1995 Cummins C8.3 - 225 hp (8.3L) EEA-32: 1996 Caterpillar 3116 - 275 hp (6.6L) EEA-33: 1995 Navistar DT466 - 230 hp (7.6L)	EEA-8: 1996 Cummins L10 - 280 hp (10L) EEA-9: 1994 Cummins L10 - 300 hp (10L) EEA-14: 1995 Cummins M11 - 330 hp (10.8L) EEA-15: 1998 Cummins M11 - 280 hp (10.8L) EEA-17: 1997 Cummins M11 - 280 hp (10.8L) EEA-24: 1997 Cummins M11 - 330 hp (10.8L) EEA-27: 1998 Mack EM7 - 275 hp (11.9L) EEA-35: 1997 Mack E7 - 250 hp (11.9L) EEA-37: 1995 DDC Series 60 - 365 hp (11.1L)
All	25 Vehicles	12 Vehicles

3. EMISSIONS ANALYSIS DATASET

3.1 INTRODUCTION

Basic emissions and descriptive data for all test vehicles were provided to EEA by West Virginia University (WVU) in Microsoft Word format. A single data sheet was provided for each test vehicle/test cycle combination. Figure 3-1 presents a sample data sheet illustrating test data for a New York City Department of Transportation truck, equipped with a Cummins B5.9 engine, and tested over the Routized Test D cycle. These WVU data sheets comprised the bulk of the data available to EEA for review. Second-by-second test data was not provided by WVU despite numerous requests. As a result, all emissions analysis presented in this report was performed on a cycle average basis. Smoke measurement data (peak smoke) was provided to EEA by the New York State Department of Environmental Conservation (DEC), and these data were appended to the WVU test data as appropriate to provide for investigation of vehicle peak smoke versus mass emissions relationships. This section presents the procedures implemented by EEA to construct the overall emissions analysis dataset from these various data sources.

3.2 DATASET CONSTRUCTION AND VALIDATION

To develop a dataset suitable for statistical analysis, EEA first converted the WVU data sheets into Microsoft Excel spreadsheet format. Each WVU datasheet was converted into one or more spreadsheet records in accordance with the number of individual emission tests summarized on the source datasheet. For example, if four component tests were summarized on a WVU datasheet (as in Figure 3-1), four spreadsheet records (one per test) were created. All of the data included on the WVU data sheet was retained on the spreadsheet record, with the exception of: (1) the “fleet owner” name and address (which was coded as EEA on all data sheets), (2) the test engineer and vehicle driver, and (3) the emissions averages, standard deviations, and coefficients of variation. These omitted data items either provided no information useful to the emissions analysis or, as in the case of the aggregate emissions statistics, could be replicated through analysis of the component emissions data. In addition, the WVU Test Reference Number was

FIGURE 3-1
SAMPLE WVU DATA SHEET

Test Sequence Number: 3231
WVU Test Reference Number: EEA-NYDOT-199C-D1-D-RT

Fleet Owner Full Name	EEA
Fleet Address	75 Frost Street
Fleet Address (City, State, Zip)	Brooklyn, NY 11211
Vehicle Type	Flatbed Truck
Vehicle ID Number (VIN)	1FDPK74CXRVA23853
Vehicle Manufacturer	Ford
Vehicle Model Year	1994
Gross Vehicle Weight (GVW) (lb.)	31000
Vehicle Total Curb Weight (lb.)	Not Available
Vehicle Tested Weight (lb.)	21000
Odometer Reading (mile)	8900
Transmission Type	Automatic
Transmission Configuration	4-Speed
Number of Axles	2
Engine Type	Cummins B5.9-190
Engine ID Number	44924174
Engine Displacement (Liter)	5.9
Number of Cylinders	6
Engine Rated Power (hp)	190
Primary Fuel	D1
Test Cycle	D-RT
Test Date	5/20/99
Engineer	J. Kopasko
Driver	J. England

Emissions Results (g/mile) **Fuel Economy**

Run Seq. No.	CO	NO_x	FIDHC	PM	CO_2	mile/gal	BTU/mile	Miles
3231-1	1.65	14.1	0.25	c	1561	6.16	20451	5.56
3231-2	1.56	14.0	0.25	0.41	1537	6.26	20131	5.55
3231-3	1.54	13.8	0.28	0.33	1559	6.17	20418	5.55
3231-4	1.47	13.9	0.27	0.29	1520	6.33	19908	5.55
3231 Average	1.55	14.0	0.26	0.34	1544	6.23	20227	5.55
Std. Dev.	0.07	0.1	0.01	0.06	20	0.08	257	0.01
CV%	4.6	1.0	5.6	18.1	1.3	1.3	1.3	0.1

shortened to include only the vehicle identification portion of the data entry, since the remaining elements of the WVU encoded "number" were replicated in individual data fields.

Each data record extracted from the WVU data sheets was subjected to both visual and automated error screening to the extent possible. Emissions test data was excluded from this review since there is no alternative source of information for comparison. All descriptive test data were compared to information on EEA's data collection worksheets completed during the actual vehicle testing process. Through this comparison, a substantial number of data entry errors were identified and corrected in key emissions analysis fields (e.g., vehicle odometer reading, the test engine model, and the gross vehicle weight rating). Correction of these errors is critical to the proper analysis of emissions test data since errors can result in the improper aggregation of emissions test data and the resulting skewing of analysis results. No listing of data sheet corrections is provided, but the extent of implemented corrections can be observed by comparing the data sheets provided by WVU to the final analysis dataset employed by EEA.

Since engine model year is one of the most critical data items supporting the proper aggregation of emissions test data, EEA decoded test vehicle identification numbers (VINs) to isolate the manufacturer's indicated vehicle model year. To facilitate this decoding, EEA first checked the basic reliability of the indicated VINs by ensuring that each was properly configured in terms of the number of overall characters and the validity of the model year identifier (the 10th of 17 VIN characters). In several cases, the data sheet VIN was found to be incomplete or incorrect and was revised through comparison to raw data collection worksheets or follow-up conversations with vehicle owners. The VIN-indicated model year was then compared to the model year indicated on the WVU data sheets. In several cases, a single model year differential was noted indicating that the chassis model year was actually one year newer than the year indicated on the data sheet. This is not unexpected given that virtually all model year information collected at the time of testing is based on data extracted from the vehicle engine label, and heavy duty vehicles are often constructed using engines produced well in advance of the final assembly. Since the engine label must be presumed correct in all instances where the VIN-indicated model year is equal to or one year newer than the engine label-indicated model year, no revisions were made to

the *engine* model year in such cases. The *vehicle* model year was, however, updated to match that indicated on the VIN. In effect, EEA expanded the WVU data sheet information to include both a vehicle and engine model year. All statistics presented in this report are based on the latter.

In compiling the WVU data sheets, a serious problem was noted in the proper designation of the two program steady state cycles (i.e., 20 and 40 miles per hour (mph)). Many of the data sheets labeled with a WVU Test Reference Number that included the suffix "20mph" and indicated a "value" of "20MPH" in the test cycle field actually presented emissions measurements for both the 20 and 40 mph cycles. Such data sheets indicate very large coefficients of variation and the 40 mph test results can generally be distinguished from the 20 mph results by the substantially larger accumulated test mileage. This problem affects about 50 percent of the steady state data sheets and can seriously influence analysis results if not corrected. The appropriate corrections were implemented prior to the analyses presented in this report.

One additional problem was encountered in compiling data from the WVU data sheets. In tracking and reporting program test data, WVU used a test sequence numbering system that ran consecutively from 3229 through 3419. Unfortunately, in the data delivered to EEA, data for test sequence numbers 3256 through 3264 was not included. Data for test sequence numbers 3356 through 3364 was included in both its expected numerical location and in the numerical location for tests 3256 through 3264 as well. In effect, data for tests 3356 through 3364 was reported in duplicate, while data for tests 3256 through 3264 was not reported at all. This deficiency was resolved by obtaining a corresponding copy of the WVU data sheets from the DEC. The DEC copy did not include this data substitution problem and the data sheets for tests 3256 through 3264 were extracted from the DEC copy and inserted into EEA's copy in the proper location, displacing the first set of data for tests 3356 through 3364.

EEA also added several important data analysis fields to the basic data compiled by WVU. A weight class designator of either MHDT (medium heavy duty truck) or HHDT (heavy heavy duty truck) was added based on engine certification data. Estimated values for typical brake

specific fuel consumption (BSFC) were derived from data previously provided to EEA by engine manufacturers and are based on a linear decline from 182 grams of fuel per brake horsepower hour (g/BHP-hr) in 1990 to 176 g/BHP-hr in 1995 for medium heavy duty vehicles and from 159 g/BHP-hr in 1990 to 154 g/BHP-hr in 1995 for heavy heavy duty vehicles. Years prior to 1990 and after 1995 assume no change from the 1990 and 1995 values respectively. Fuel mass consumed per mile was estimated using reported emission rates and carbon mass balance. Finally, brake horsepower hours expended per mile (BHP-hr/mile) during the test were estimated using the results of the BSFC and fuel mass calculations, and emission rates in g/BHP-hr were estimated using the WVU-reported grams per mile (g/mile) emissions data in conjunction with the calculated BHP-hr/mile estimates. More detailed discussion of the conversion of reported g/mile emissions data to equivalent g/BHP-hr data is presented in Section 5 of this report, where each of the specific elements of this conversion are documented.

The vehicle frontal area assumed by WVU in setting their dynamometer power absorption equipment was encoded in the emissions analysis database to provide a means of quality control for the EEA-derived g/BHP-hr emissions estimates. Section 5 includes the results of the quality control analysis in the detailed discussion of the methodology used to derive the g/BHP-hr estimates. An indicator of whether or not the vehicle was catalyst equipped was added to allow the independent examination of catalyst equipped and non-catalyst vehicles.

An indicator of whether or not the reported test data was valid was added to allow exclusion of invalid test results from analysis statistics. In total 10 of 408 test cycles were declared invalid. Test sequence 3247 (three WVU 5 Mile Route cycles on vehicle NYDOT-15SC) was invalidated on the basis of inconsistent emission measurements across tests due to a failure to key off reset between test cycles. These cycles were repeated as test sequence 3248 (with the key off reset) so that no net data was lost. Test sequence 3261 (three Routized Test D cycles for vehicle 4G's-661) was invalidated due to particulate filter clogging. These cycles were repeated as test sequence 3263, so that no net data was lost. The last snap cycle of two cycle test sequences 3281 and 3331 (vehicles NYDOT-890Q and Mendon-83608 respectively) were invalidated as corresponding opacity data was only provided for the first snap cycle. Test sequence 3302 (one

WVU 5 Mile Route cycle on vehicle FedEx-3105028) was invalidated on the basis of incorrect tire diameter assumptions. The cycle was repeated as part of test sequence 3303 so that no net data was lost. Lastly, the first snap cycle of two cycle test sequence 3373 (vehicle Bell Atlantic-4260616) was invalidated due to improper snap performance during the cycle.

An indicator of whether or not the reported test data was for replicate testing over an alternative inertia weight was added to the analysis database to eliminate the potential biasing of analysis results due to the inclusion of multiple test results for single vehicles. Including multiple results for inertia weight vehicles would effectively increase the statistical weighting of such vehicles relative to non-inertia weight test vehicles. Through this indicator, test sequences 3255 and 3257 (two sets of three Routized Test D cycles for vehicle ConEd-C60309) were excluded from all analyses but those focused on inertia weight effects. Test sequence 3251, the corresponding test sequence for the same vehicle at the standard WVU inertia weight, was included in all analyses for the Routized Test D cycle. Similarly, test sequences 3271 and 3272 (two sets of three Routized Test D cycles for vehicle Mendon-14713) were excluded from all analyses but those focused on inertia weight effects. Test sequence 3268, the corresponding test sequence for the same vehicle at the standard WVU inertia weight, was included in all analyses for the Routized Test D cycle. Test sequence 3256 (one 40 mph steady state cycle for vehicle ConEd-C60309) was excluded from all 40 mph analyses in favor of corresponding test sequence 3254, which reflects the same cycle performed at an alternative inertia weight setting. Finally, test sequence 3270 (one 20 mph and one 40 mph steady state cycle for vehicle Mendon-14713) was also excluded from all 20 and 40 mph analyses (as applicable) in favor of corresponding test sequence 3266, which reflects the same cycles performed at the standard WVU inertia weight setting.

Standardized descriptive data for the applicable test cycle was added to each dataset record. This data consisted of the time, mileage, and travel speed of the standard test cycle. Ratios of actual cycle time and mileage to standard cycle time and mileage were calculated for both cycle validation and cycle load factor estimation purposes. Actual cycle mileage was reported by WVU. Estimated cycle time is based on actual reported mileage and standard cycle speed. The

maximum brake horsepower hours for the cycle as driven are estimated by multiplying the rated engine horsepower by the estimated cycle time. This value is then used to calculate an estimated cycle load factor equal to the ratio of the WVU-reported mileage multiplied by the estimated brake horsepower hours per mile over the estimated maximum brake horsepower hours for the cycle.

Finally, EEA augmented the resulting dataset constructed from the WVU data sheets with opacity data collected and provided to EEA by the DEC. These DEC data were merged with the criteria pollutant emission data using appropriate vehicle and criteria emission rate keys. These opacity data were used to support all opacity emissions analysis results presented in this report.

Table 3-1 presents an overview of the resulting EEA analysis dataset, including an example data record. Table 3-2 describes the source of the various data fields.

3.3 DATASET PROCESSING

All dataset analysis was performed using the SAS statistical processing system. Analyses investigating a diverse range of relationships were performed, from a review of basic emission rates by test cycle and vehicle model year group, to more complex analyses of inter-pollutant and inter-cycle relations. The premise behind each of these analyses as well as analysis results are presented in the sections of the report that follow. This section describes the steps taken to facilitate the presented analyses.

Section 3.2 discussed the construction of the basic EEA analysis dataset. That dataset consists of a rectangular database file (stored in Microsoft Excel spreadsheet format) with each record representing a single test cycle. For example, a vehicle tested three times over the Routized Test D cycle, three times over the WVU 5 Mile Route cycle, and once each over the 20 mph steady state cycle, the 40 mph steady state cycle, and the lugdown cycle would be represented by 9 records in the basic analysis dataset. While this dataset provides a comprehensive representation of individual test performance and results for all 408 test cycles conducted under the project, it does not lend itself to direct analysis of emissions performance across individual test trucks, test

Field Number	Field Name	Field Type	Field Length	Sample Record
1	TRKNUM	Numeric	8.0	3231
2	EEA_ID	Numeric	8.0	1
3	REF_ID	Character	25	NYDOT-199C
4	VEHMAKE	Character	15	Ford
5	VEHMY	Numeric	8.0	1994
6	VEHTYPE	Character	20	Flatbed Truck
7	VIN	Character	20	1FDPK74CXRVA23853
8	VIN_LEN	Numeric	9.0	17
9	VIN_ERR	Character	8	Okay
10	VIN_MYC	Character	8	R
11	VIN_MYN	Numeric	8.0	1994
12	MY_ERR	Character	8	Okay
13	GVW	Numeric	8.0	31000
14	CURBWT	Numeric	8.0	
15	TESTWT	Numeric	8.0	21000
16	ODOM	Numeric	8.0	8900
17	ENGMAKE	Character	15	Cummins
18	ENGMODEL	Character	10	B5.9
19	ENGMY	Numeric	8.0	1994
20	MY_DELTA	Numeric	8.0	0
21	ENGID	Character	20	44924174
22	DISP	Numeric	8.1	5.9
23	NUMCYL	Numeric	8.0	6
24	RATHP	Numeric	8.0	190
25	WTCLASS	Character	8	MHDT
26	BSFC	Numeric	8.0	177.5
27	TRANTYPE	Character	9	Automatic
28	NUMSPDS	Character	8	4-Speed
29	NUMAXL	Numeric	8.0	2
30	FRAREA	Numeric	8.2	52.50
31	CATEQUIP	Character	8	No
32	TESTFUEL	Character	8	D1
33	TESTCYCL	Character	8	D-RT
34	TESTMO	Numeric	8.0	5
35	TESTDAY	Numeric	8.0	20
36	SEQNUM	Numeric	8.0	2
37	BADTEST	Character	8	No
38	IWTEST	Character	8	No
39	CO_MI	Numeric	8.2	1.56
40	NOX_MI	Numeric	8.2	14.00
41	HC_MI	Numeric	8.2	0.25
42	PM_MI	Numeric	8.2	0.41
43	CO2_MI	Numeric	8.0	1537
44	MPG	Numeric	8.2	6.26
45	BTU_MI	Numeric	8.0	20131
46	MILES	Numeric	8.2	5.55
47	O_CEL_ON	Numeric	8.2	
48	O_BOS_ON	Numeric	8.2	
49	O_W67_OF	Numeric	8.2	
50	O_W65_OF	Numeric	8.2	
51	O_BOS_OF	Numeric	8.2	
52	O_RED_OF	Numeric	8.2	
53	FUEL_MI	Numeric	8.1	484.0
54	BHPHRS	Numeric	8.2	2.73
55	CO_HPHR	Numeric	8.2	0.57
56	NOX_HPHR	Numeric	8.2	5.13
57	HC_HPHR	Numeric	8.2	0.09
58	PM_HPHR	Numeric	8.2	0.15
59	CO2_HPHR	Numeric	8.1	563.6
60	STD_MILE	Numeric	8.4	5.5520
61	STD_TIME	Numeric	8.0	1060
62	STD_SPD	Numeric	8.2	18.86
63	MILE_RAT	Numeric	8.4	0.9996
64	EST_TIME	Numeric	8.0	1059
65	TIME_RAT	Numeric	8.4	0.9994
66	MAX_HPHR	Numeric	8.2	55.91
67	LOAD_FAC	Numeric	8.3	0.271

TABLE 3-1. EEA'S BASIC ANALYSIS DATSET FORMAT

TABLE 3-2
SOURCE OF BASIC ANALYSIS DATSET FIELDS

Field Name	Data Source (prior to any quality control correction)
TRKNUM	WVU data sheet - Test Sequence Number
EEA_ID	Arbitrary EEA-assigned vehicle tracking number, 1 through 37 based on test date.
REF_ID	WVU data sheet - vehicle portion of WVU Test Reference Number
VEHMAKE	WVU data sheet - Vehicle Manufacturer
VEHMY	WVU data sheet - Vehicle Model Year
VEHTYPE	WVU data sheet - Vehicle Type
VIN	WVU data sheet - Vehicle ID Number (VIN)
VIN_LEN	Calculated length of VIN (used to validate, should be 17)
VIN_ERR	VIN error indicator (set to “Okay” if VIN length is 17, “ERROR” otherwise)
VIN_MYC	Model year code of VIN (10th digit)
VIN_MYN	Numeric translation of VIN model year code (as defined in standard VIN references)
MY_ERR	Model year error indicator (set to “Okay” if VIN_MYN = VEHMY, “ERROR” otherwise)
GVW	WVU data sheet - Gross Vehicle Weight (GVW) (lb.)
CURBWT	WVU data sheet - Vehicle Total Curb Weight (lb.)
TESTWT	WVU data sheet - Vehicle Tested Weight (lb.)
ODOM	WVU data sheet - Vehicle Odometer Reading (mile)
ENGMAKE	WVU data sheet - manufacturer portion of Engine Type
ENGMODEL	WVU data sheet - model portion of Engine Type
ENGMY	Handwritten test data collection sheets
MY_DELTA	Difference between vehicle and engine model years (VEHMY minus ENGMY)
ENGID	WVU data sheet - Engine ID Number
DISP	WVU data sheet - Engine Displacement (Liter)
NUMCYL	WVU data sheet - Number of Cylinders
RATHP	WVU data sheet - Engine Rated Power (hp)
WTCLASS	Vehicle/engine weight class based on certification durability testing
BSFC	EEA estimated brake specific fuel consumption (grams/brake-horsepower hour)
TRANTYPE	WVU data sheet - Transmission Type
NUMSPDS	WVU data sheet - Transmission Configuration
NUMAXL	WVU data sheet - Number of Axles
FRAREA	Handwritten test data collection sheets and WVU follow-up data submittal
CATEQUIP	Handwritten test data collection sheets
TESTFUEL	WVU data sheet - Primary Fuel
TESTCYCL	WVU data sheet - Test Cycle
TESTMO	WVU data sheet - month portion of Test Date
TESTDAY	WVU data sheet - day portion of Test Date
SEQNUM	WVU data sheet - last digit of Run Seq. No.
BADTEST	EEA assigned bad test indicator (set to “Yes” if invalid test, “No” otherwise)
IWTEST	EEA assigned inertia weight test indicator (set to “IWTx” if inertia weight test, “No” otherwise)
CO_MI	WVU data sheet - CO (g/mile)
NOX_MI	WVU data sheet - NO_x (g/mile)
HC_MI	WVU data sheet - FIDHC (g/mile)
PM_MI	WVU data sheet - PM (g/mile)
CO2_MI	WVU data sheet - CO_2 (g/mile)
MPG	WVU data sheet - mile/gal
BTU_MI	WVU data sheet - BTU/mile
MILES	WVU data sheet – miles

TABLE 3-2

SOURCE OF BASIC ANALYSIS DATSET FIELDS

(Continuted)

Field Name	Data Source (prior to any quality control correction)
O_CEL_ON	DEC opacity data - Celesco on-dynamometer opacity reading
O_BOS_ON	DEC opacity data - Bosch on-dynamometer opacity reading
O_W67_OF	DEC opacity data - Wager 6700 off-dynamometer opacity reading
O_W65_OF	DEC opacity data - Wager 6500 off-dynamometer opacity reading
O_BOS_OF	DEC opacity data - Bosch off-dynamometer opacity reading
O_RED_OF	DEC opacity data - Red Mountain off-dynamometer opacity reading
FUEL_MI	EEA calculated fuel per mile (grams, equals *(13.8/12)*(PM_MI+0.273CO2_MI+0.429CO_MI+0.886HC_MI)*)
BHPHRS	EEA calculated BHP-hr/mile (equals FUEL_MI/BSFC)
CO_HPHR	EEA calculated CO in g/BHP-hr (equals CO_MI/BHPHRS)
NOX_HPHR	EEA calculated NO_x in g/BHP-hr (equals NOX_MI/BHPHRS)
HC_HPHR	EEA calculated HC in g/BHP-hr (equals HC_MI/BHPHRS)
PM_HPHR	EEA calculated PM in g/BHP-hr (equals PM_MI/BHPHRS)
CO2_HPHR	EEA calculated CO_2 in g/BHP-hr (equals CO2_MI/BHPHRS)
STD_MILE	Standard mileage for test cycle
STD_TIME	Standard time (seconds) for test cycle
STD_SPD	Standard speed (miles per hour) for test cycle
MILE_RAT	Ratio of actual cycle mileage to standard cycle mileage (equals MILES/STD_MILE)
EST_TIME	Estimated cycle time (seconds, equals MILES/STD_SPD×3600)
TIME_RAT	Ratio of estimated cycle time to standard cycle mileage (equals EST_TIME/STD_TIME)
MAX_HPHR	Estimated maximum BHP-hr over cycle (equals RATHP×EST_TIME/3600)
LOAD_FAC	Estimated load factor over cycle (equals BHPHRS×MILES/MAX_HPHR)

cycles, etc., for the simple reason that not all trucks were subjected to same universe of test cycles or the same number of component test cycles within that universe.

For example, vehicle Mendon-10250 was tested only over four repetitions of the WVU 5 Mile Route before testing was aborted due to tire overheating, whereas vehicle Mendon-12280 was tested over three repetitions of the WVU 5 Mile Route, three repetitions of the Routized Test D cycle, and one repetition each of the 40 mph steady state, lugdown, and snap acceleration test cycles. Treating the WVU 5 Mile Route cycles on an individual basis would weight resulting statistics toward vehicle Mendon-10250 by a factor of 4:3. To surmount this potential bias, the individual test cycle repetitions for each vehicle were aggregated using SAS so that each test cycle is represented a maximum of one time. These aggregated results reflect the simple arithmetic average of all measured data fields, and all records with one or more missing *emissions measurement* fields are excluded. For example, several individual test cycle records do not report particulate emissions. These records are not included in the aggregation process. Calculated data fields as defined in Table 3-2 are subsequently recalculated from the aggregated measured data as opposed to being averaged themselves. Through this process, a collapsed dataset consisting of 37 records, one per test vehicle, was developed so that each truck carries equal weight through the subsequent analysis process. It is this collapsed dataset that was used to generate all statistics presented throughout the remainder of this report.

Two additional nuances should also be a recognized part of the record aggregation process. First, all records flagged as invalid (i.e., BADTEST equals “Yes”) are ignored. Second, for the two test vehicles tested at three separate inertia weights, only one set of inertia weight tests, (those performed at the standard WVU test weight conditions) are included in the aggregated 37 truck analysis data set. To investigate inertia weight effects, a second analysis dataset was constructed following the same basic data aggregation process, but including only three aggregate test records (one aggregate record for each inertia test weight) for each of the two inertia weight test vehicles. All inertia weight analysis is based on this smaller 6 record dataset.

3.4 BASIC DATASET STATISTICS

Table 3-3 presents a summary of the aggregated analysis dataset. As indicated, 37 total test vehicles tested over 184 individual test cycles are represented. Although there are nine distinct test cycles represented, five (the Routized Test D, the 20 mph steady state, the 40 mph steady state, the snap acceleration, and the WVU 5 Mile Route cycles) account for all but 14 of the test cycles performed. These five cycles, in conjunction with the lugdown cycle, were the primary focus of this project. However, the lugdown test was only performed on 8 vehicles due to WVU's hesitancy to perform the cycle and contractual constraints that prohibited EEA from requiring universal performance of the cycle. The remaining six cycles were performed for miscellaneous reasons, none of which have any bearing on the test project and, therefore, all such cycles are ignored in the EEA emissions analysis documented in this report. The standard (i.e., non-routized) Test D cycle was accidentally performed on four vehicles following a shift change where the new dynamometer operator did not realize that the routized version of the cycle was being performed. The CBD cycle was performed as the first test cycle in the project to allow WVU testers to check the test system over a cycle with which they were intimately familiar. The Kern cycle was run a single time for internal purposes by WVU staff.

As indicated above, the Routized Test D and the WVU 5 Mile Route were the standard transient emissions test cycles utilized in this project. Routized Test D data was collected for 32 vehicles, while WVU 5 Mile Route data was collected for all 37 trucks tested. The "short" test cycles investigated consisted of the snap acceleration and lugdown cycles, the former being performed for 34 test vehicles while the latter was limited to 8 test vehicles (for reasons cited above). Steady state testing at 20 and 40 mph was also performed at the request of DEC. Data for 32 trucks tested at 20 mph and 35 trucks tested at 40 mph was provided to EEA by WVU. Data collected under the Routized Test D, the WVU 5 Mile, the 20 and 40 mph steady state, and the lugdown test cycles form the basis of the statistics presented throughout the remainder of this report.

TABLE 3-3

AGGREGATED ANALYSIS DATASET

		Test Cycle Represented?								
EEA ID	Vehicle Reference ID	Routized Test D	Standard Test D	CBD	20 mph Steady State	40 mph Steady State	Kern Cycle	Snap Accel	Lug-down	WVU 5 Mile Route
1	NYDOT-199C	Yes		Yes		Yes		Yes		Yes
2	Mendon-12280	Yes				Yes		Yes	Yes	Yes
3	Mendon-10250									Yes
4	4G's-513	Yes			Yes	Yes		Yes		Yes
5	NYDOT-15SC	Yes			Yes	Yes		Yes		Yes
6	ConEd-C60309	Yes[1]			Yes[2]	Yes[3]		Yes[4]		Yes[4]
7	NYDOT-186FF				Yes	Yes				Yes
8	4G's-661	Yes			Yes	Yes		Yes	Yes	Yes
9	Mendon-14713	Yes[5]			Yes[6]	Yes[6]		Yes[7]	Yes[8]	Yes[7]
10	ConEd-C60124	Yes			Yes	Yes		Yes		Yes
11	NYDOT-890Q	Yes			Yes	Yes		Yes		Yes
12	FedEx-300474	Yes				Yes	Yes	Yes	Yes	Yes
13	ConEd-C50351	Yes			Yes	Yes		Yes		Yes
14	FedEx-301208	Yes			Yes	Yes		Yes	Yes	Yes
15	NYDEP-785	Yes			Yes	Yes		Yes		Yes
16	FedEx-3105028	Yes						Yes		Yes
17	NYDOS-25CF264	Yes			Yes	Yes		Yes		Yes
18	NYDEP-831012	Yes			Yes	Yes		Yes		Yes
19	UPS-176391	Yes			Yes	Yes		Yes	Yes	Yes
20	UPS-655579	Yes			Yes	Yes		Yes		Yes
21	Kreger-2040	Yes			Yes	Yes		Yes		Yes
22	Mendon-83608	Yes			Yes	Yes		Yes		Yes
23	Kreger-117232	Yes			Yes	Yes		Yes		Yes
24	UPS-263026	Yes			Yes	Yes		Yes	Yes	Yes
25	NYDEP-8742WS		Yes		Yes	Yes		Yes		Yes
26	Perrier-0189438		Yes		Yes	Yes		Yes		Yes
27	NYDOS-38W301		Yes		Yes	Yes		Yes		Yes
28	Avanti-79631	Yes			Yes	Yes		Yes		Yes
29	Bell Atlantic-7060605	Yes			Yes	Yes				Yes
30	Bell Atlantic-4260616	Yes	Yes		Yes	Yes		Yes		Yes
31	FedEx-437015MSS	Yes			Yes	Yes		Yes		Yes
32	Bell Atlantic-7070252	Yes			Yes	Yes		Yes		Yes
33	Bell Atlantic-7066614	Yes			Yes	Yes		Yes		Yes
34	MJLK-11669AN	Yes			Yes	Yes		Yes		Yes
35	NYDOS-26AM203	Yes			Yes	Yes		Yes		Yes
36	Perrier-297080	Yes			Yes	Yes		Yes		Yes
37	Salem-1622	Yes			Yes	Yes		Yes	Yes	Yes

1. Inertia weight vehicle. Routized Test D cycles performed at 36,400, 26,000, and 52,000 pounds. Only the 36,400 pound test is included in the 37 vehicle dataset. All test weights are included in the 2 vehicle inertia weight dataset.
2. Cycle was not performed at 36,400 pound "standard" inertia weight. Data is from 52,000 pound testing.
3. Cycle was not performed at 36,400 pound "standard" inertia weight. Data is from 52,000 pound testing, although cycle also run at 26,000.
4. Data is from 36,400 pound "standard" inertia weight testing. Cycle was not run at other inertia weights.
5. Inertia weight vehicle. Routized Test D cycles performed at 27,000, 42,000, and 50,000 pounds. Only the 42,000 pound test is included in the 37 vehicle dataset. All test weights are included in the 2 vehicle inertia weight dataset.
6. Data is from 42,000 pound "standard" inertia weight testing. Cycle was also run during 50,000 pound testing, but data is excluded.
7. Data is from 42,000 pound "standard" inertia weight testing. Cycle was not run at other inertia weights.
8. Cycle was not performed at 42,000 pound inertia weight. Data is from 26,000 pound testing.

4. BASIC MEASURED EMISSIONS

All mass emission measurements were reported by WVU in units of grams per vehicle mile traveled (g/mile). This is a convenient unit of emissions measurement for light duty vehicles, but of limited significance in the heavy-duty vehicle sector due to the broad range of power to weight ratios encountered. Emissions mass per unit work performed is a more robust measure of heavy duty vehicle emissions, allowing for a more equitable comparison of emission rates across the diverse heavy duty vehicle fleet as well as allowing for a direct comparison with work-specific engine certification standards. Therefore, all of the emissions analysis results presented in this report rely on work-specific emission rates, calculated using the g/mile emission rates provided by WVU in accordance with the methodology presented in Section 5. Nevertheless, Figures 4-1 through 4-8 present a summary of the WVU-provided g/mile emission rate data by emission species, engine size, model year group, and test cycle.

Several basic observations are apparent from the data presented in the figures. As indicated, the range of measured g/mile emission rates is quite broad for vehicles with engines certified to similar emission standards. Again, this is not unexpected given both expected truck-to-truck emissions variability and the differential in effective load factors across test vehicles and test cycles. While Section 6.3 presents a detailed discussion of the load factor calculations used in this study, the average observed load factors for the test fleet are approximately 0.27 for the Routized Test D cycle, 0.23 for the WVU 5 Mile Route cycle, 0.18 for the 20 mph steady state cycle, and 0.38 for the 40 mph steady state cycle. No specific load factor for the lug down cycle could be estimated since there is no standard test time available to estimate maximum expended power (under the load factor calculation approach defined in Section 6.3), but by design the load factor for the lugdown cycle approaches unity. Specific load factors for individual test trucks show a degree of variation at least as wide as the differential between cycle average load factors, while instantaneous load factors over during the two transient test cycles (the Routized Test D and WVU 5 Mile Route cycles) vary similarly. Each of these variations affects the indicated

g/mile emission rates, and the net result is the substantial overlap between the minimum and maximum observed emission rates across test cycles, despite the differential cycle average load factors.

Although the emission rate variability is substantial, a general decline in per mile emission rates can be observed in accordance with declining emission standards as vehicles become newer. For example, the particulate emission standard declined between 1993 and 1994 and a corresponding decline in average g/mile emission rates is evident. For HHDT engines, the decline is less obvious. However, since there are only two pre-1994 vehicles in the dataset, this is not unexpected. If emissions for those two vehicles are averaged, the expected decline becomes more evident. Similarly, a drop in the NO_x standard between 1989 and 1990 is equally apparent in the observed emission rates. CO and HC also exhibit emission rate declines, despite the fact that the applicable emission standards for neither have changed in over 15 years.

With limited exception, the differentials between the average observed emission rates for the various test cycles are typically less than the range of observed emissions for the transient test cycles. The variability in observed vehicle load factors, as described above, certainly contributes to this phenomena, but the net effect is that average steady state g/mile emission rates are generally not unreasonable indicators of transient cycle g/mile emission rates.

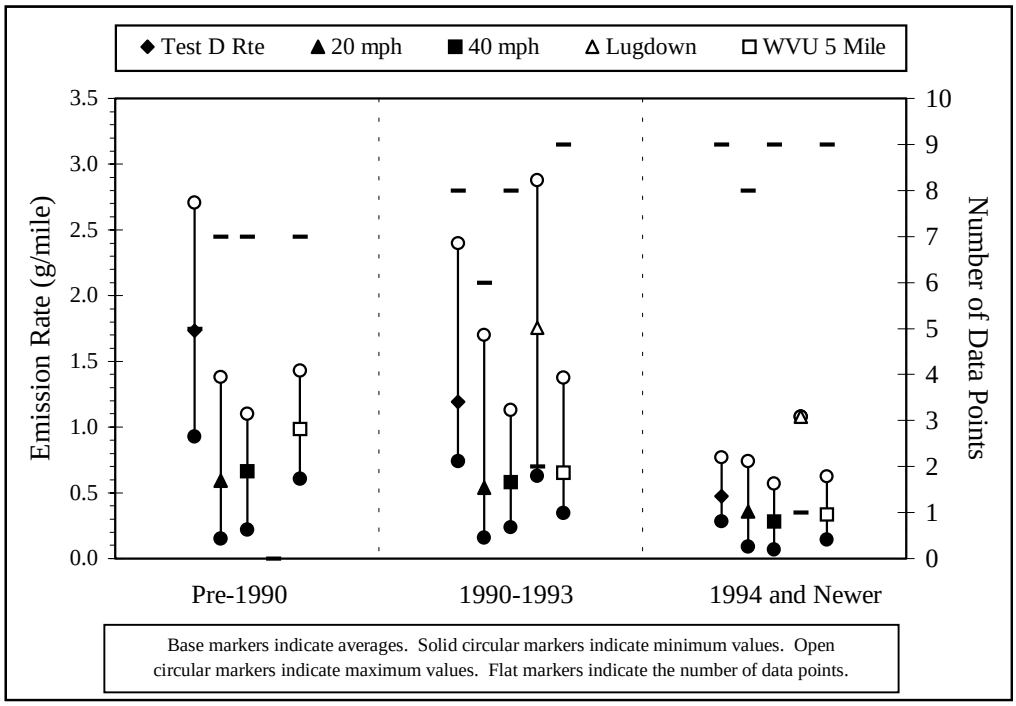

FIGURE 4-1. MHDT PARTICULATE EMISSION RATES (GRAMS/MILE)

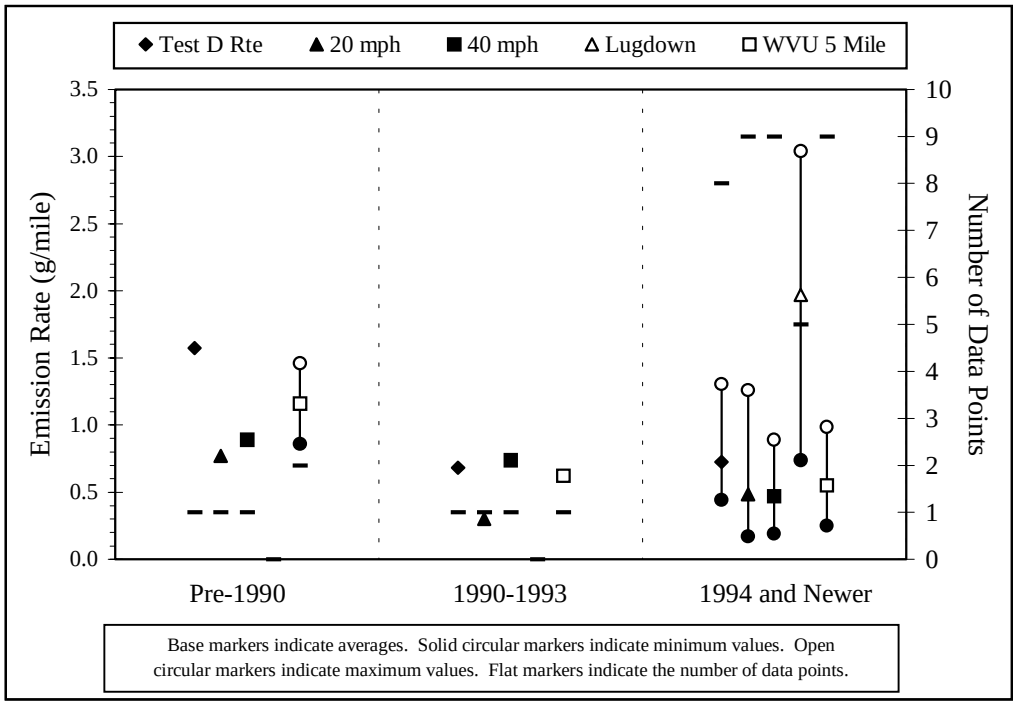

FIGURE 4-2. HHDT PARTICULATE EMISSION RATES (GRAMS/MILE)

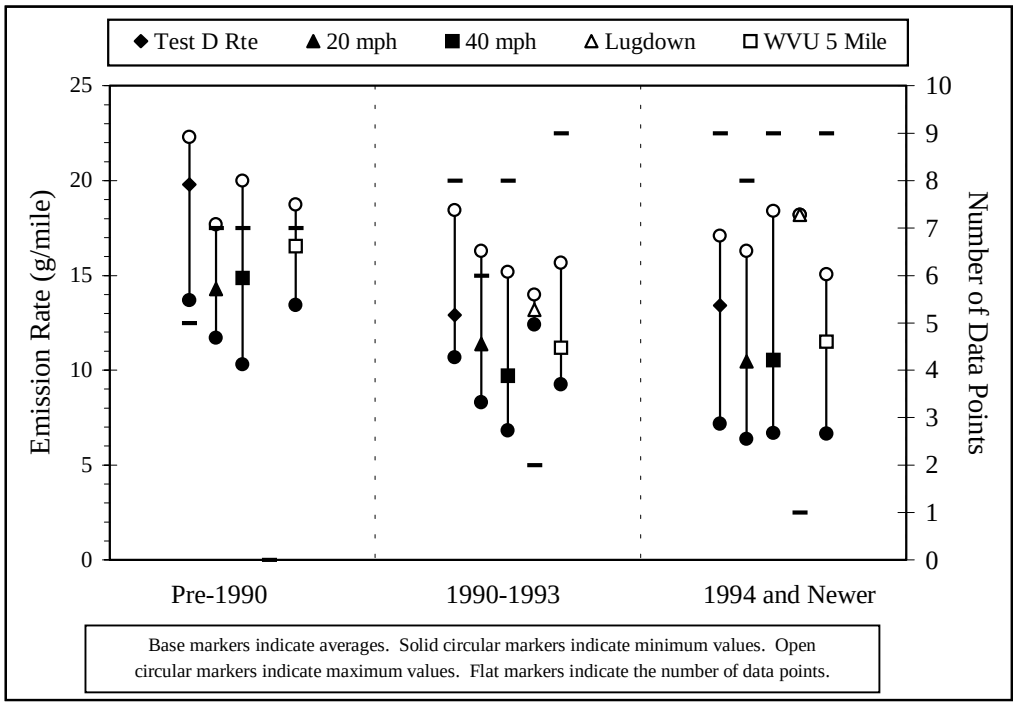

FIGURE 4-3. MHDT NO_x EMISSION RATES (GRAMS/MILE)

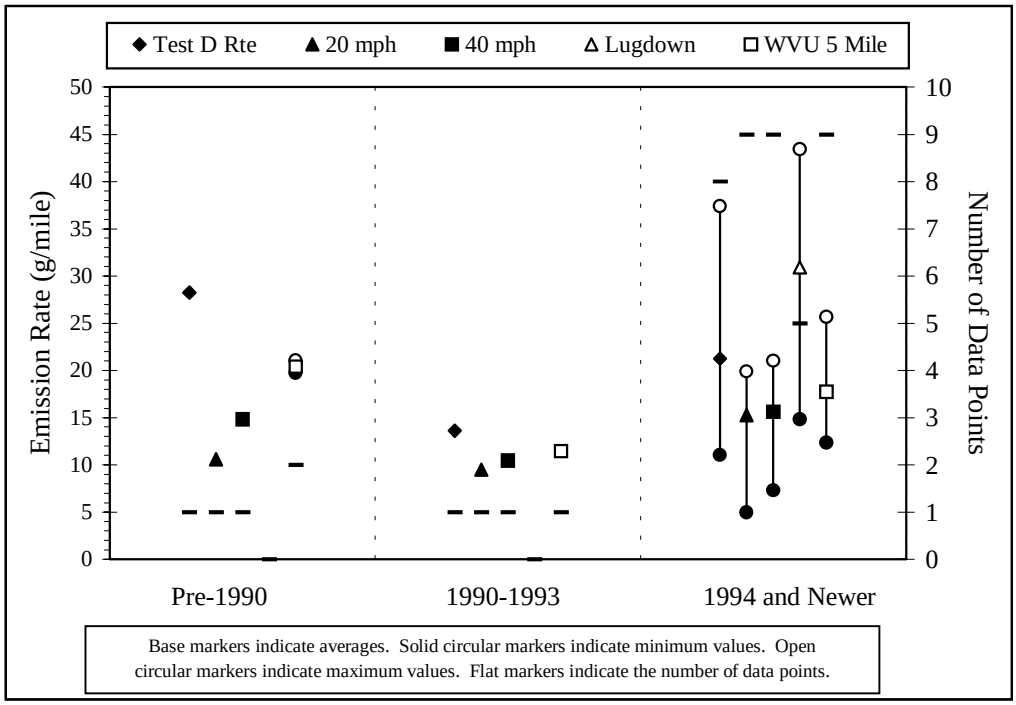

FIGURE 4-4. HHDT NO_x EMISSION RATES (GRAMS/MILE)

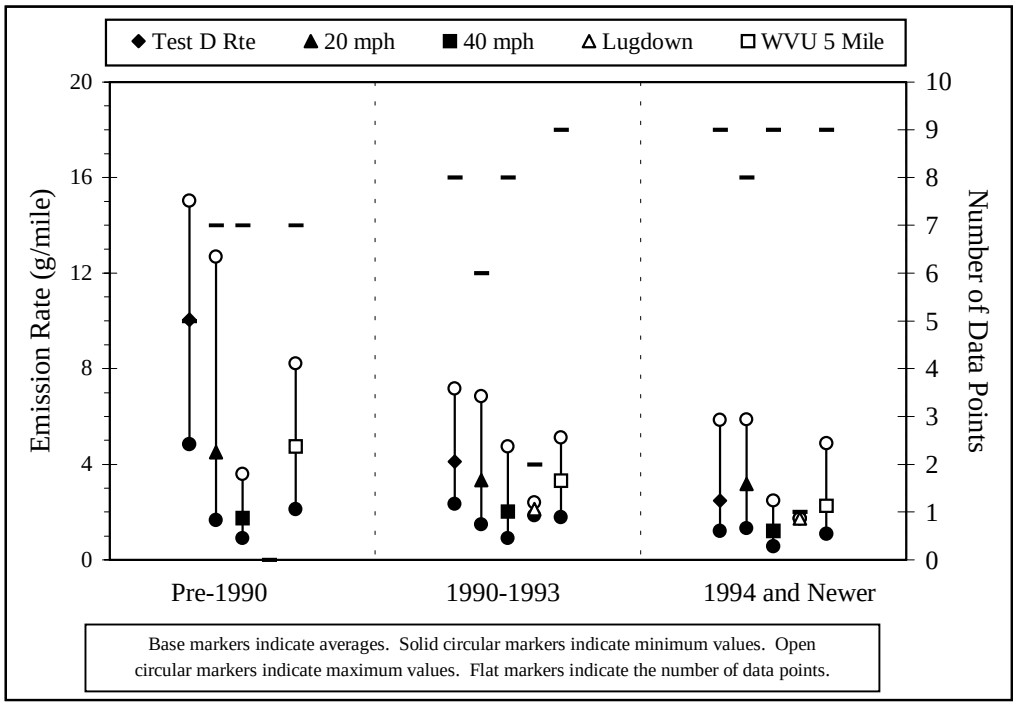

FIGURE 4-5. MHDT CO EMISSION RATES (GRAMS/MILE)

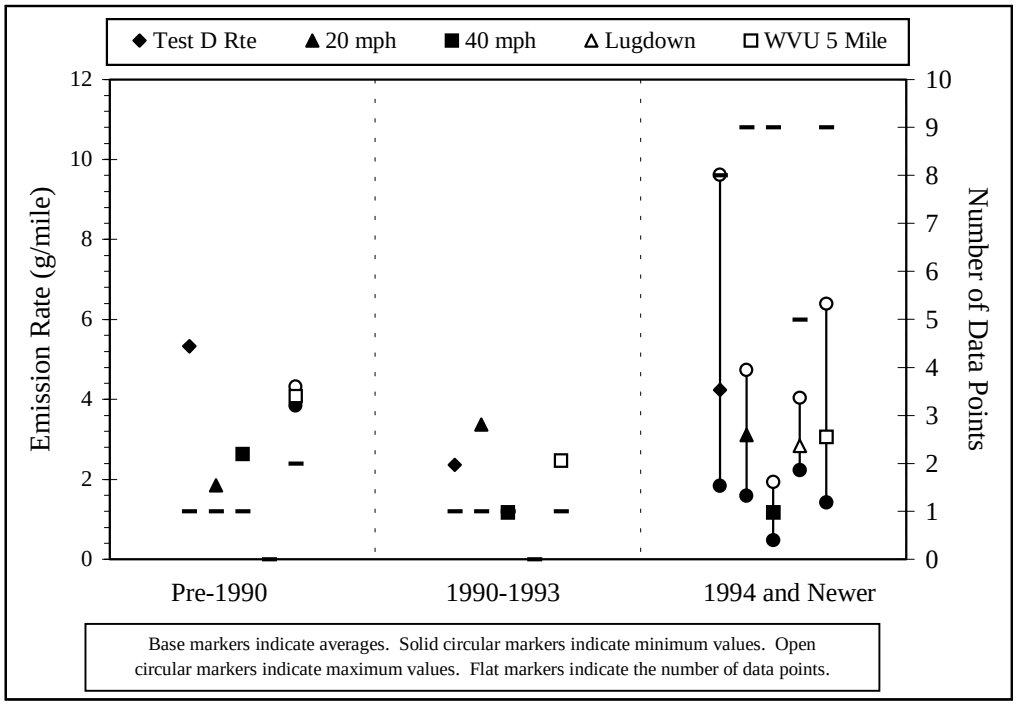

FIGURE 4-6. HHDT CO EMISSION RATES (GRAMS/MILE)

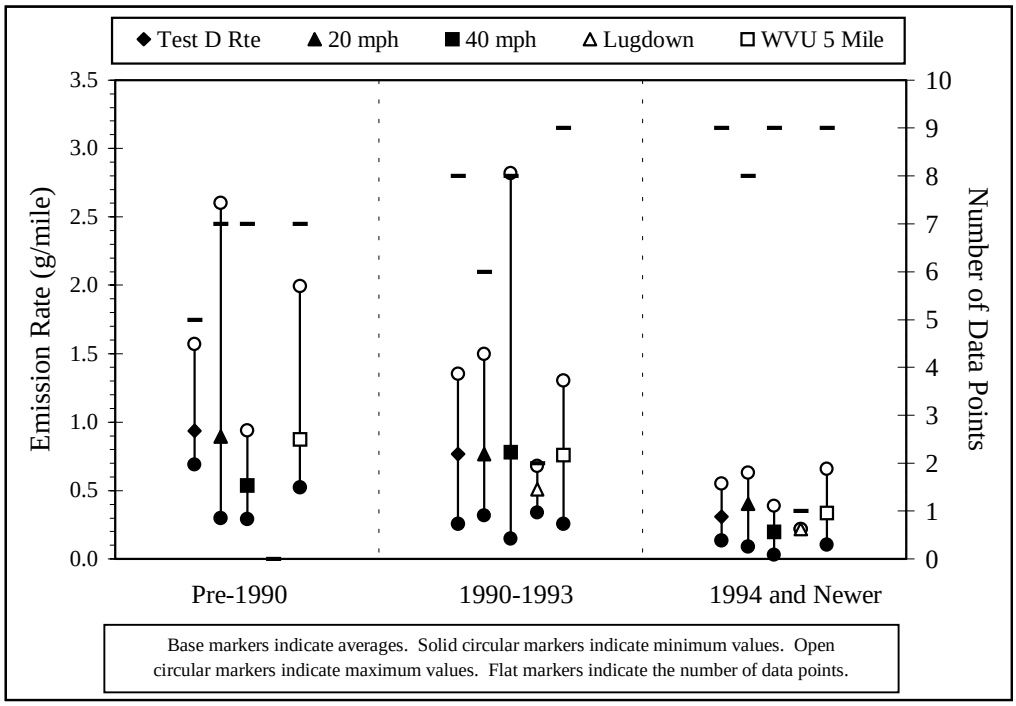

FIGURE 4-7. MHDT HC EMISSION RATES (GRAMS/MILE)

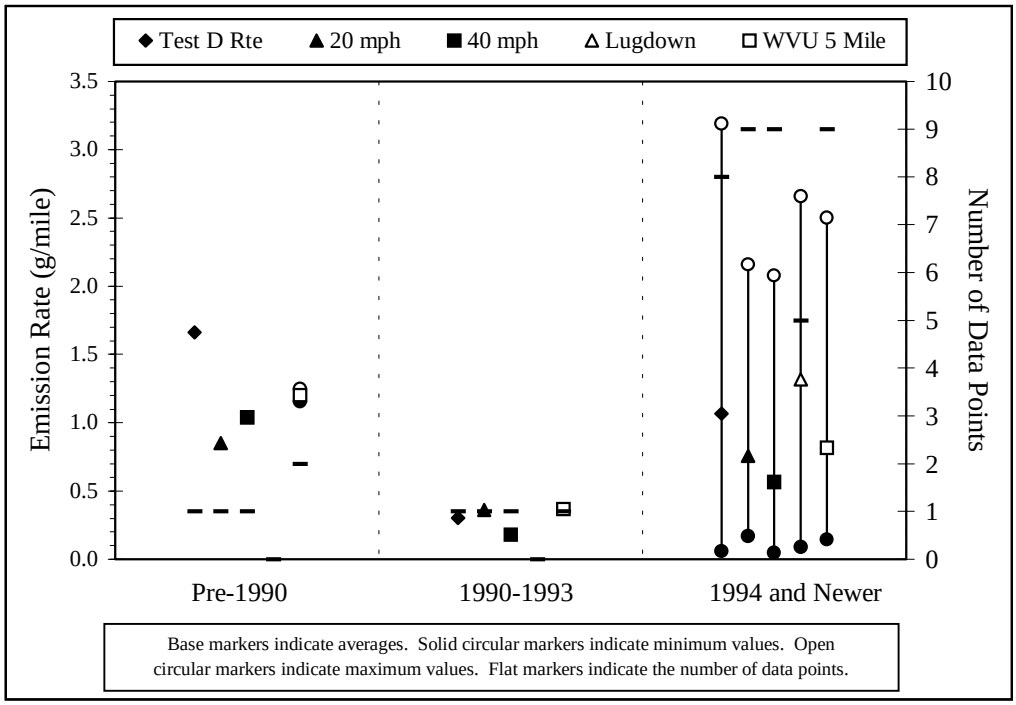

FIGURE 4-8. HHDT HC EMISSION RATES (GRAMS/MILE)

5. ANALYSIS OF EMISSIONS IN UNITS OF WORK

5.1 CONVERSION TO UNITS OF WORK

Since heavy-duty trucks span such a wide range of weights, emissions in grams per unit distance of travel are generally not comparable across trucks. In addition, EPA emission standards for engines are based on emission per unit of work, g/BHP-hr. The term "BHP-hr" is the work done by the engine in overcoming the inertia force, aerodynamic drag, tire rolling resistance and drivetrain friction when being tested over a cycle. The work done per unit of distance, BHP-hr/mile, is cycle dependent, with higher average speed cycles requiring more work per unit of travel.

In a typical chassis dynamometer, the inertia weight and aerodynamic drag are simulated by the dynamometer rotating inertia weights and the power absorption unit. The tire rolling resistance is the actual rolling resistance of the tires against the rollers, while drivetrain friction is unchanged from that experienced in actual driving.

There are two methods to convert emissions per unit distance to emission per unit of work. In the first method, the conversion of vehicle emissions in grams per mile to engine emissions in units of work, grams per BHP-hr, utilizes the identity:

$$\text{grams/mile} = \frac{\text{grams}}{\text{BHP-hr}} \times \frac{\text{BHP-hr}}{\text{grams-fuel}} \times \frac{\text{grams-fuel}}{\text{mile}}$$

The term grams-fuel/BHP-hr is referred to as the engine 'bsfc' or brake specific fuel consumption, and the bsfc for "well-maintained" engines over the engine transient cycle is available from the manufacturers, as measured from the certification test. In general, the presence or absence of malperformances does not alter the bsfc value significantly (less than ±5 percent) unless the malperformance is very severe.

Based on data obtained by EEA from manufacturers, medium duty engines such as the Caterpillar 3208 and Navistar DT466 has typical bsfc values of 182 g/BHP-hr in the 1985-1990 time frame, declining to about 176 g/BHP-hr by the mid-1990s due to the advent of electronic control. Heavy-heavy-duty engines, like the Cummins NTC-315, have significantly lower consumption at 159 g/BHP-hr for pre-electronic control 1985-1991 engines. This has declined to about 154 g/BHP-hr by 1994.

Fuel consumption was estimated using the carbon balance equation that accounts for the carbon fraction of all pollutants, and is given by:

$$\text{C-fuel/mi} = 0.273\ x\ CO_2 + 0.429\ x\ CO + 0.886\ x\ HC + PM$$

where CO_2, CO, etc represent their emissions in grams per mile. The carbon in fuel is converted to total fuel weight by assuming that the diesel fuel carbon-to-hydrogen ratio is 1:1.8. The conversion factor to BHP-hr/mile is simply the weight of fuel divided by the bsfc. This represents the work done by the truck to move one mile on the test cycle.

The work done is to oppose the force on the tires imposed by the dynamometer, the vehicle forces are given by:

$$\text{Total Force} = \text{Tire Rolling Resistance} + \text{Inertia Force} + \text{Aerodynamic Drag Force}$$

The inertia force and the aerodynamic drag force are imposed by the dynamometer and are proportional to the inertia weight setting and dynamometer power absorption unit (PAU) setting. Tire rolling resistance is based on the actual tires rolling resistance co-efficient on the dyno rollers, which was not available. However, the variation among tire rolling resistance co-efficients is not large, and a regression of the BHP-hr/mi calculated using bsfc versus the inertia weight and dynamometer PAU setting was performed with the model of the form:

$$\text{BHP-hr/mi} = A + B \times IWT + C \times PAU$$

where A, B, and C are regression constants, and A represents the tire rolling resistance loss.

Data was obtained from truck emission tests conducted on a conventional chassis dynamometer located at the Colorado School of Mines, with test results from 16 trucks spanning the 20,000 to 50,000 lb vehicle weight range. All trucks were repaired to manufacturer specifications.

A regression* using post-repair data showed:

BHP-hr/mi	=	0.7175	+	0.0301 (IWT/1000)	+	0.0237 x PAU
		(0.2485)		(0.0048)		(0.0126)

This regression had a r^2 of 0.907, consistent with expectations, and all co-efficients are significant at the 95 percent confidence level. Hence, the calculations of work done are reasonably consistent with the dynamometer settings, and likely to be a good estimate of the actual BHP-hr/mile for all vehicles.

The West Virginia University dynamometer, however is not a usual chassis dynamometer, but one where the engine loads are transmitted directly though the hub by means of hub adapters. Hence, tire loads could be smaller or minimal under this system. In addition, we did not obtain the dynamometer PAU setting directly but used frontal area (FA) as a surrogate, since the WVU laboratory calculates the PAU setting from truck frontal area using a standard drag co-efficient for all trucks.

The West Virginia test data was available for 33 trucks on the test D (route) cycle and 37 trucks on the 5 mile route test. BHP-hrs/mile derived from assumed bsfc values were regressed against the dynamometer settings. The results from the D cycle were as follows

BHP-hr/mi	=	0.09538 (IWT/1000)	+	0.0104 (FA)
		(0.0081)		(0.0030)

As expected, the intercept term was not significant, and the regression r^2 was 0.97. All co-efficients were significant at the 95 percent confidence level.

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* Number in parentheses are standard errors of the co-efficients.

For the 5 mile cycle, the resulting regression was:

$$\text{BHP-hr/mi} = \underset{(0.0069)}{0.08279\,(\text{IWT}/1000)} + \underset{(0.0016)}{0.0463\,(\text{FA})}$$

The r^2 was even higher at 0.97 and all co-efficients are significant at the 95 percent confidence level. Note that for a given inertia weight, the 5 mile cycle requires about 15 percent less work than the D-cycle, and the effect of aerodynamic drag is much lower, consistent with the lower speed of the 5 mile cycle.

Figure 5-1 and 5-2 show the scatter plot of the BHP-hr/mile predicted by the two methods. On the D-cycle (Figure 5-1) two "outliers" are evident. Both these outliers were Department of Sanitation trucks fitted with special accessories; it is possible that the accessory drives absorb some power, leading to the higher fuel based estimate of BHP-hr/mile, relative to the dynamometer setting. In addition, there may be some potential test errors in recording the PAU/inertia weight data. Nevertheless, for the vast majority of trucks, the two methods produced BHP-hrs estimates that are in close agreement, and only small errors are likely in the conversion.

5.2 EMISSION RESULTS IN G/BHP-HR

Emissions in units of g/BHP-hr can be directly compared to emission standards if (1) the calculation of work estimates work done by the engine as opposed to work done by the vehicle (the two differ by the power absorbed in overcoming drivetrain friction) and (2) the test cycles used for the engine test and vehicle test are comparable. The Task A(1) report showed that chassis cycles specified as a speed versus time trace are not necessarily comparable to engine cycles since the engine load factor can differ on the chassis cycle from the load factor on the engine cycle. However, previous work by EEA has shown that if the load factors fall within a certain range (±10 percent) of the 40 percent load factor in the engine cycle, emissions are approximately comparable.

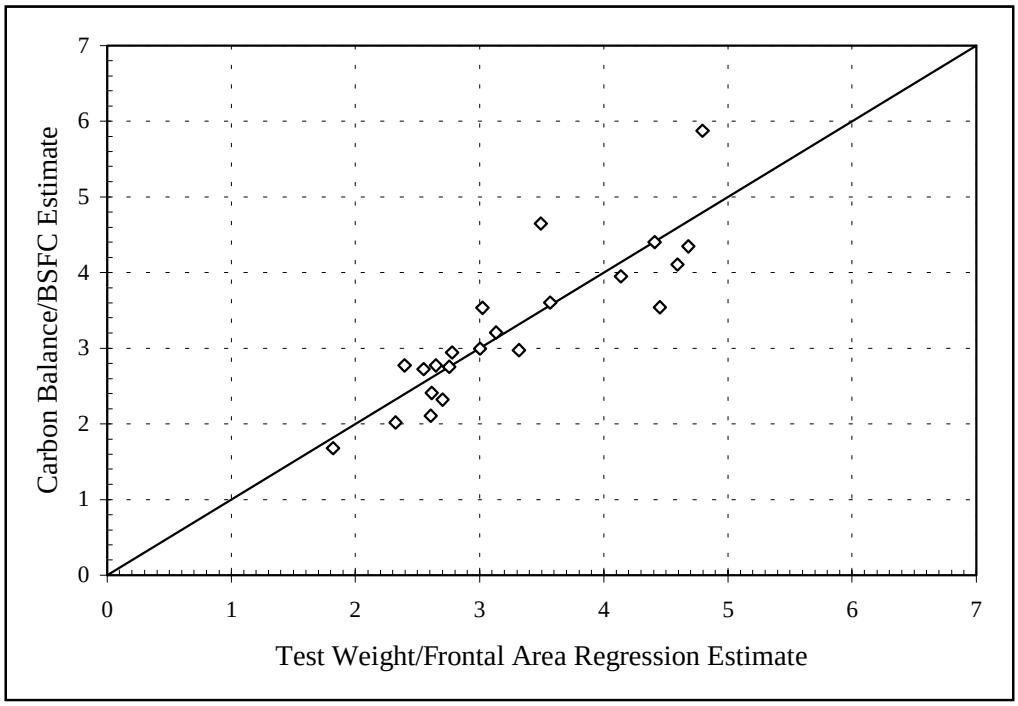


FIGURE 5-1. BHP-HRS CONSISTENCY, ROUTIZED TEST D CYCLE

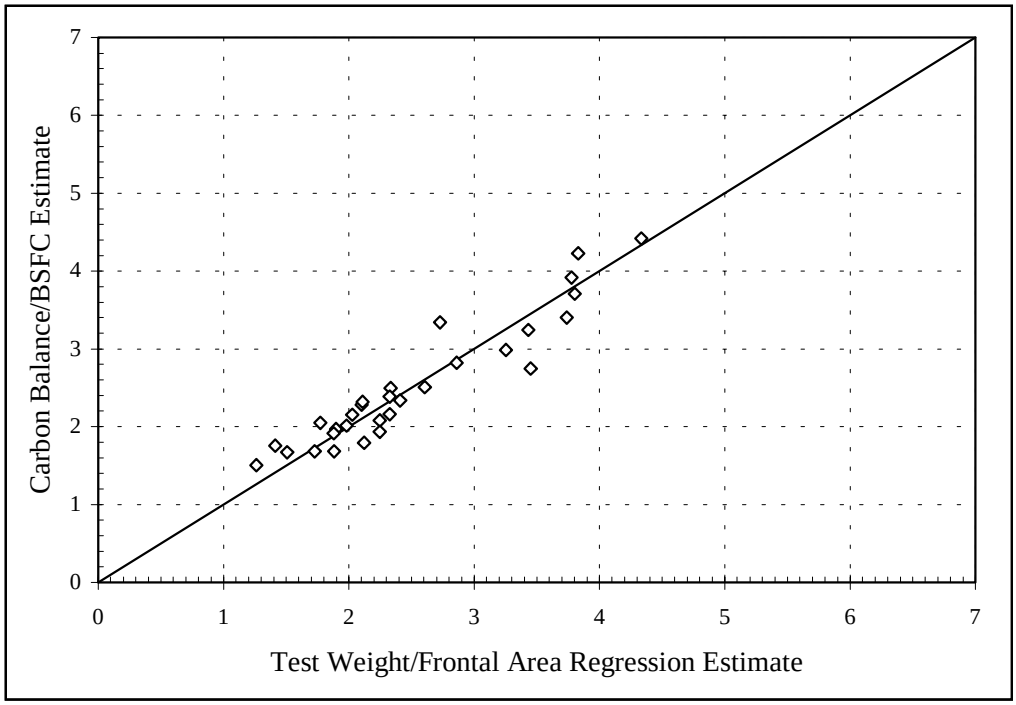


FIGURE 5-2. BHP-HRS CONSISTENCY, WVU 5 MILE ROUTE CYCLE

Analysis of emissions on the 'D-cycle' is most appropriate since this cycle is closely related to the engine cycle (although they are not identical). In addition, the bsfc based conversion methodology estimates engine work rather than vehicle work. Hence, EEA believes it is appropriate to compare D-cycle emissions in g/BHP-hr to certification standards, recognizing that the chassis based test procedure and work estimation process lead to only approximate comparisons, and can not be used to gauge compliance with standards in the strict sense. Emissions of HC, CO, NO_x, and PM are compared to standards for the three model year groups analyzed.

5.2.1 Pre-1990 Model Year Engines

Five MHDTs and only one HHDT were tested in the D-cycle in this effort. Data for the five MHDT's emissions of HC, CO, NO_x, and PM are shown in Figures 5-3 to 5-6. As noted, the pre-1990 standards were not very stringent and most engines were certified to levels well below HC, CO, NO_x standards. No PM standard was in force but engine tests indicated a typical range of 0.4 to 0.6 g/BHP-hr. Three of the five MHDTs exhibited CO emissions of about 2 g/BHP-hr while the other two exceeded 5 g/BHP-hr. Interestingly, the HC emissions of these vehicles were not as variable, falling between 0.22 and 0.39 g/BHP-hr. HC emissions were not correlated with CO emissions. Four out of five trucks had NO_x emissions well below applicable NO_x standards, but one truck marginally exceeded the 10.7 g/BHP-hr standard. PM emissions for three trucks were at or below the anticipated range of emissions from engine tests, although two trucks had relatively high PM emission, as high as 0.9 g/BHP-hr, or about twice the expected value. No direct or inverse correlations were observed between any of the pollutant emission levels.

Data on all emissions from the one HHDT tested are shown in Figure 5-7. All emissions rates were very low, with NO_x emissions at less than 6.5 g/BHP-hr and PM emissions at 0.4 g/BHP-hr.

5.2.2 1990-1993 Model Year Engines

Six MHDTs and one HHDT were tested in this model year group on the D-cycle. Emissions data for the MHDTs are shown in Figure 5-8 to 5-11. CO emissions are around 1 to 1.5 g/BHP-

FIGURE 5-3

TEST ROUTE D: PRE 1990 - MDT CO

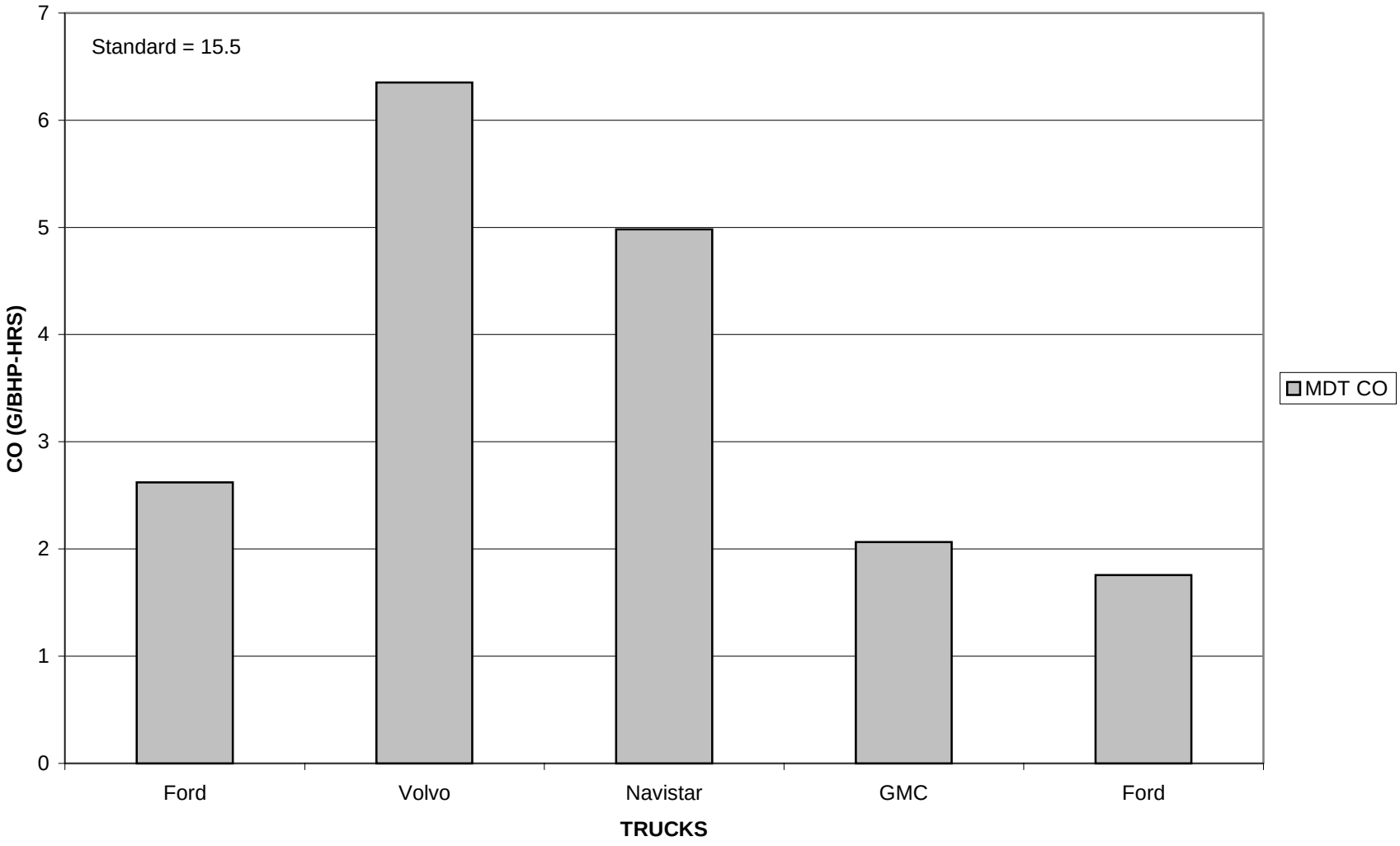


FIGURE 5-4

TEST ROUTE D: PRE 1990-MDT HC

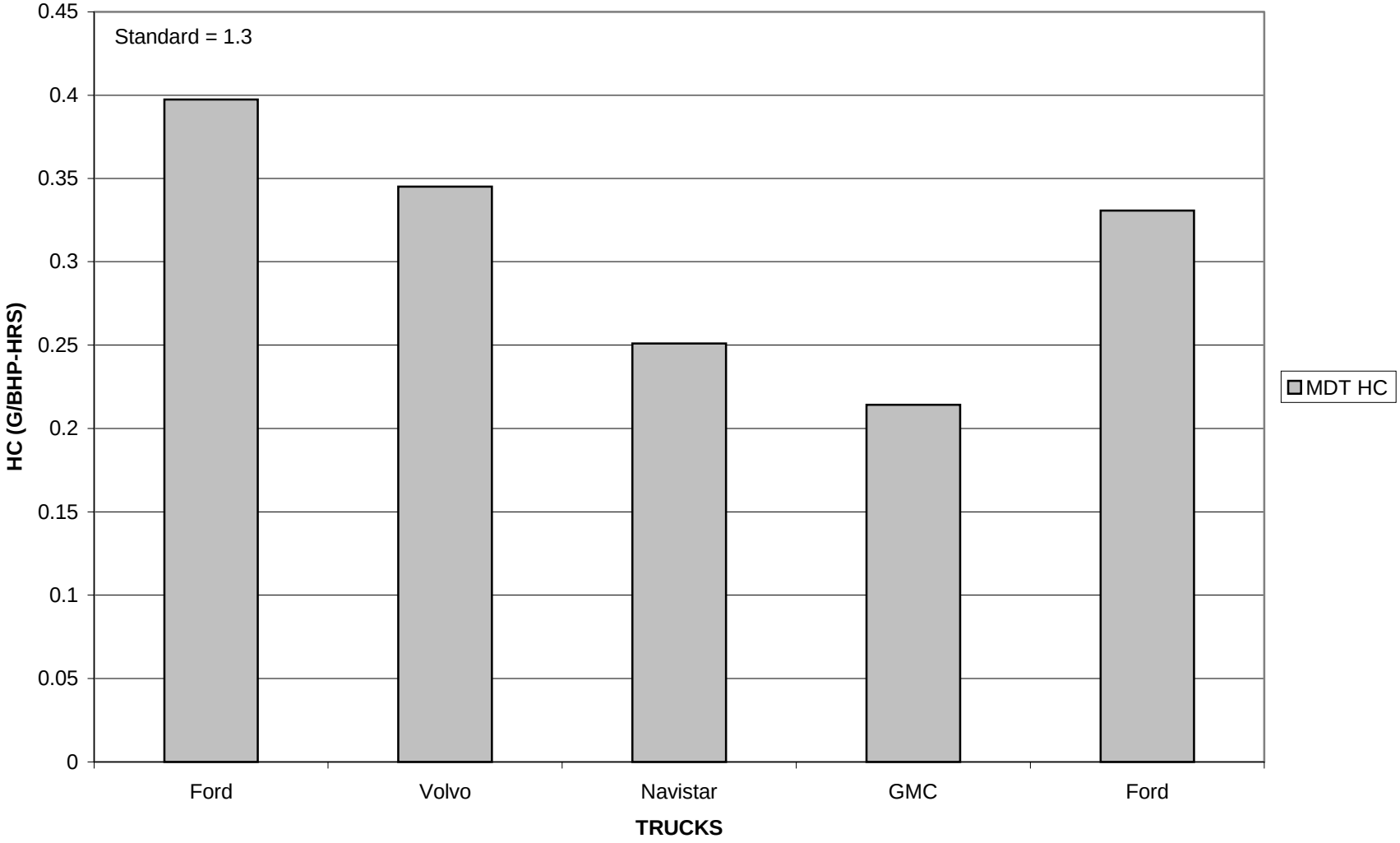


FIGURE 5-5

TEST ROUTE D: PRE 1990-MDT NOX

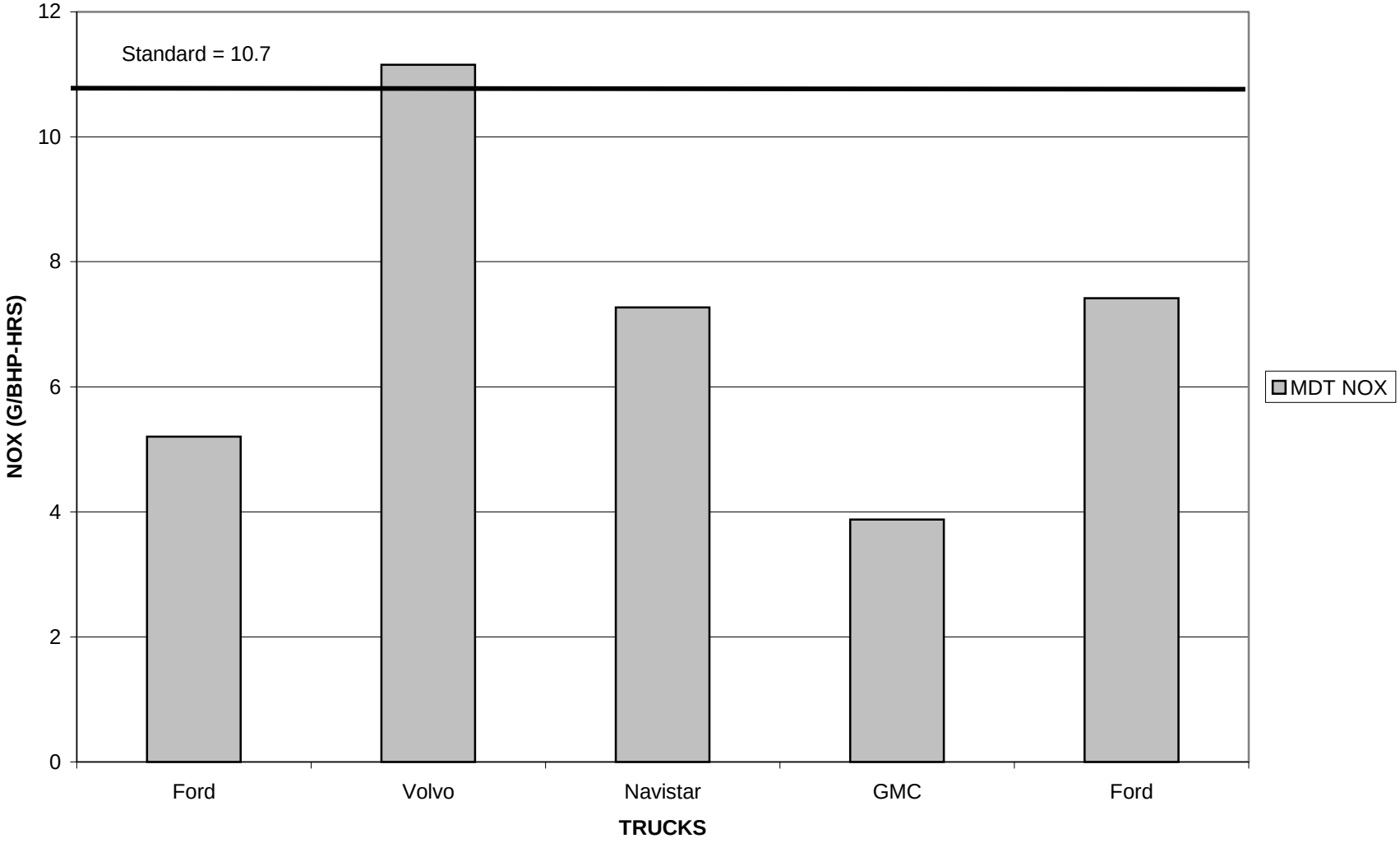


FIGURE 5-6

TEST ROUTE D: PRE 1990-MDT PM

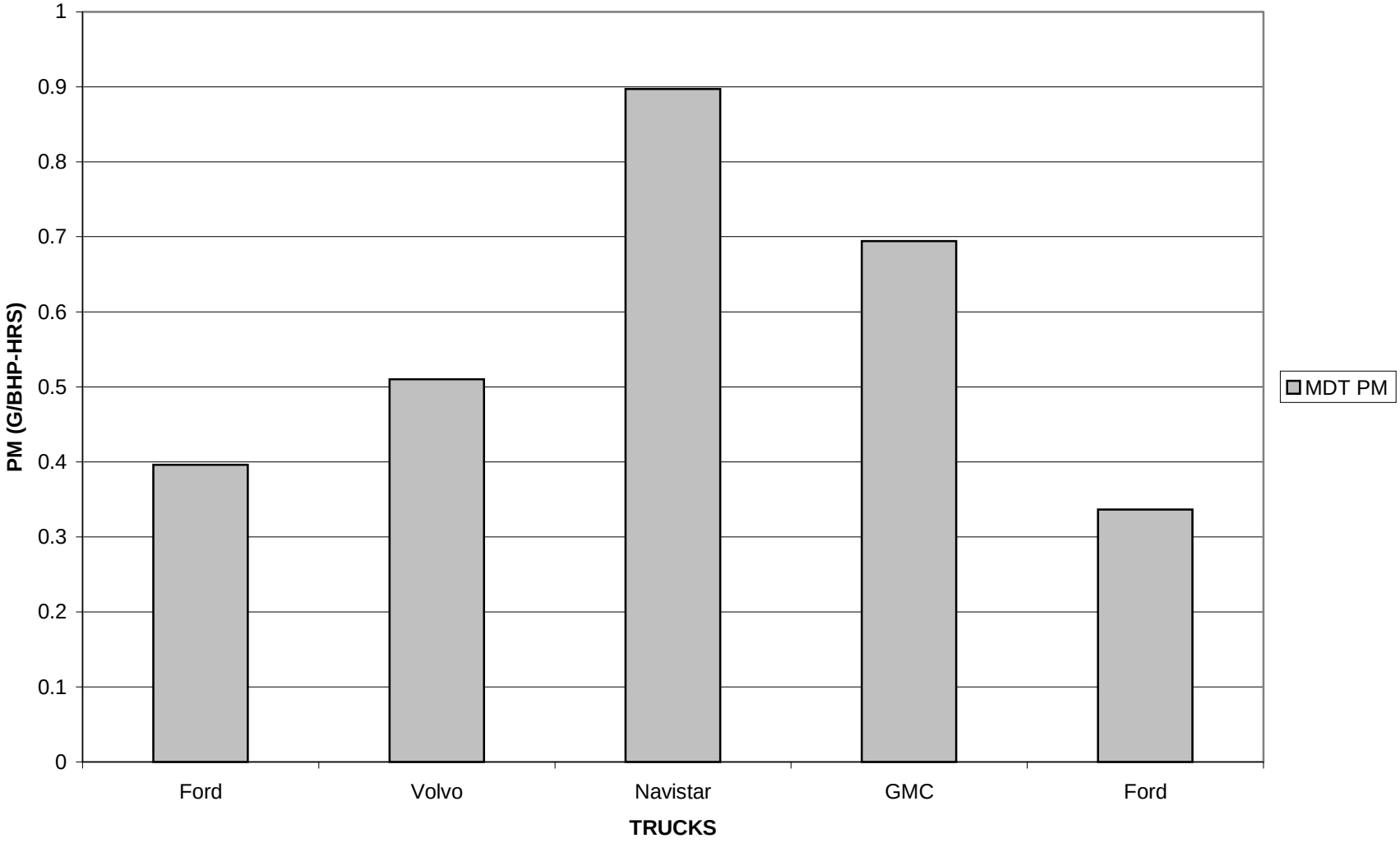


FIGURE 5-7

TEST ROUTE D: PRE 1990 HDT

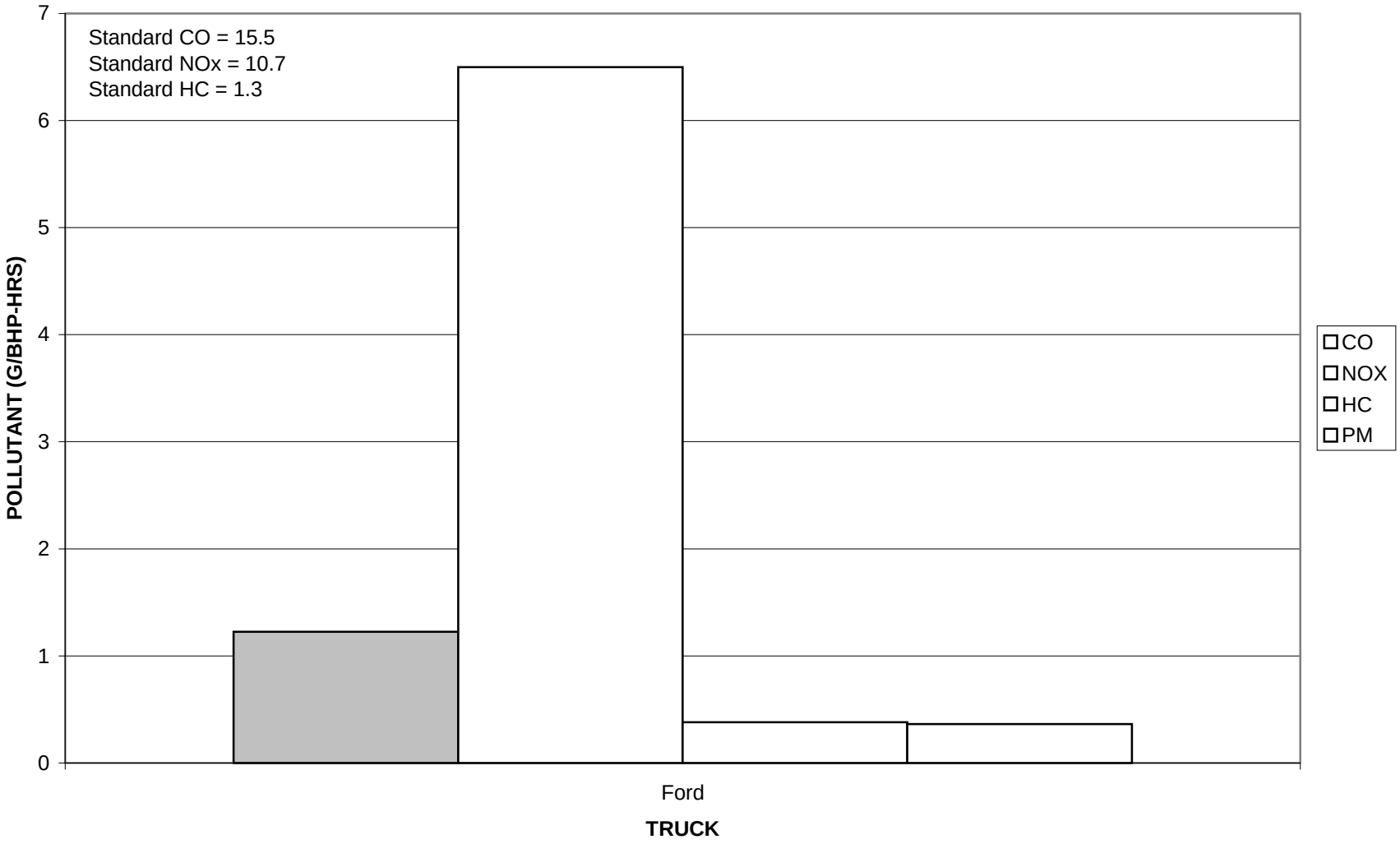


FIGURE 5-8

TEST ROUTE D: 1990-1993 - MDT CO

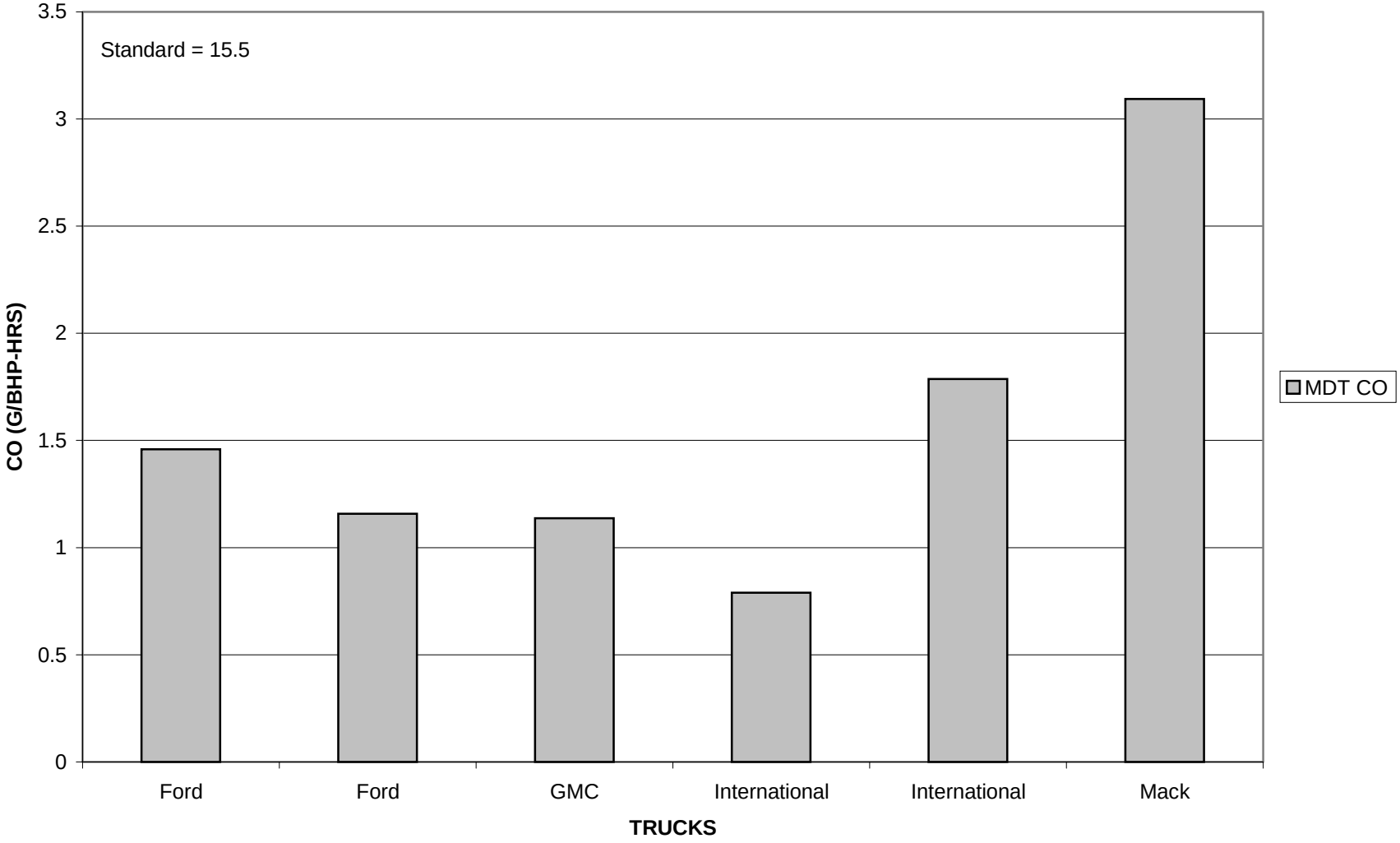


FIGURE 5-9

TEST ROUTE D: 1990-1993-MDT HC

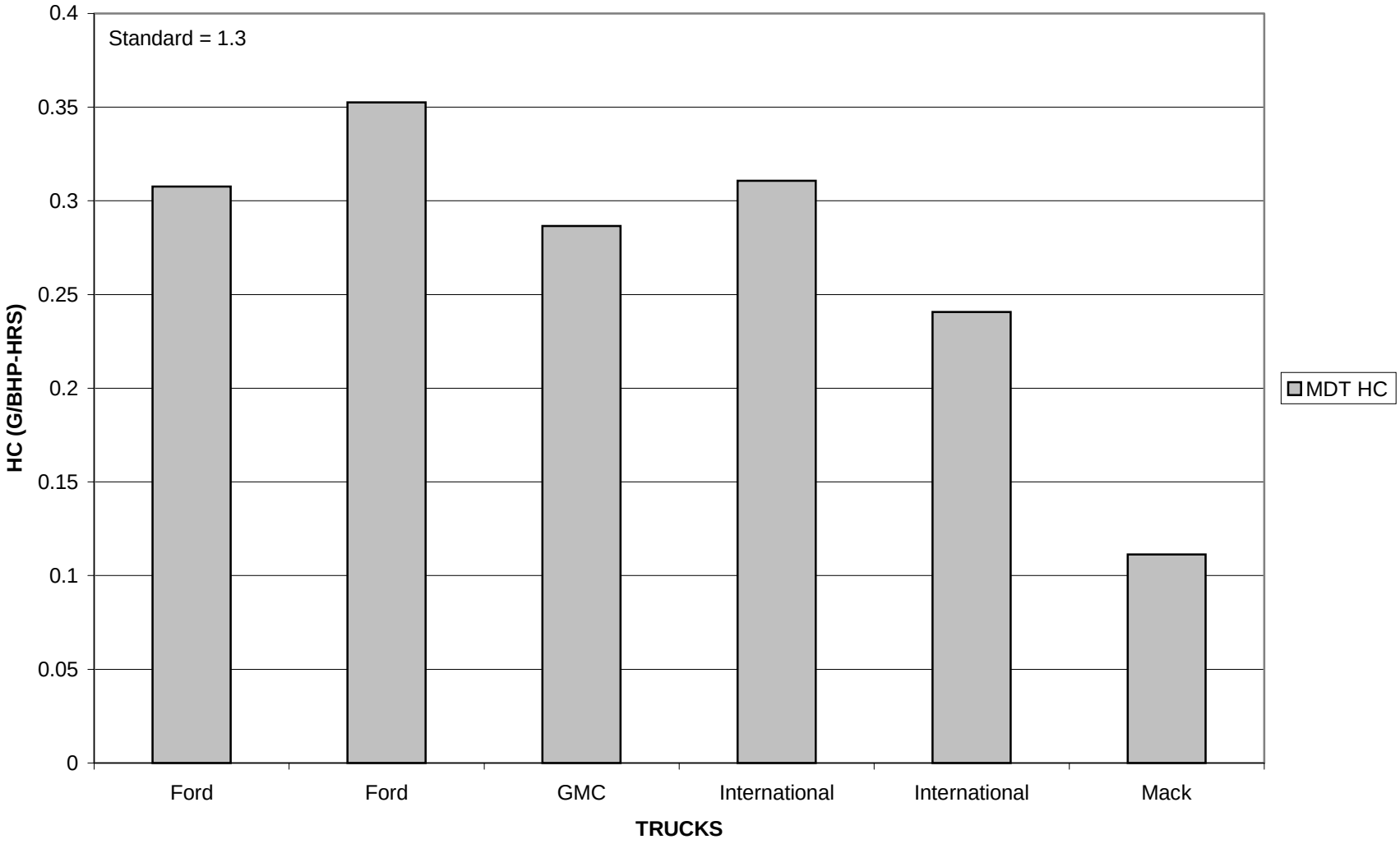


FIGURE 5-10

TEST ROUTE D: 1990-1993-MDT NOX

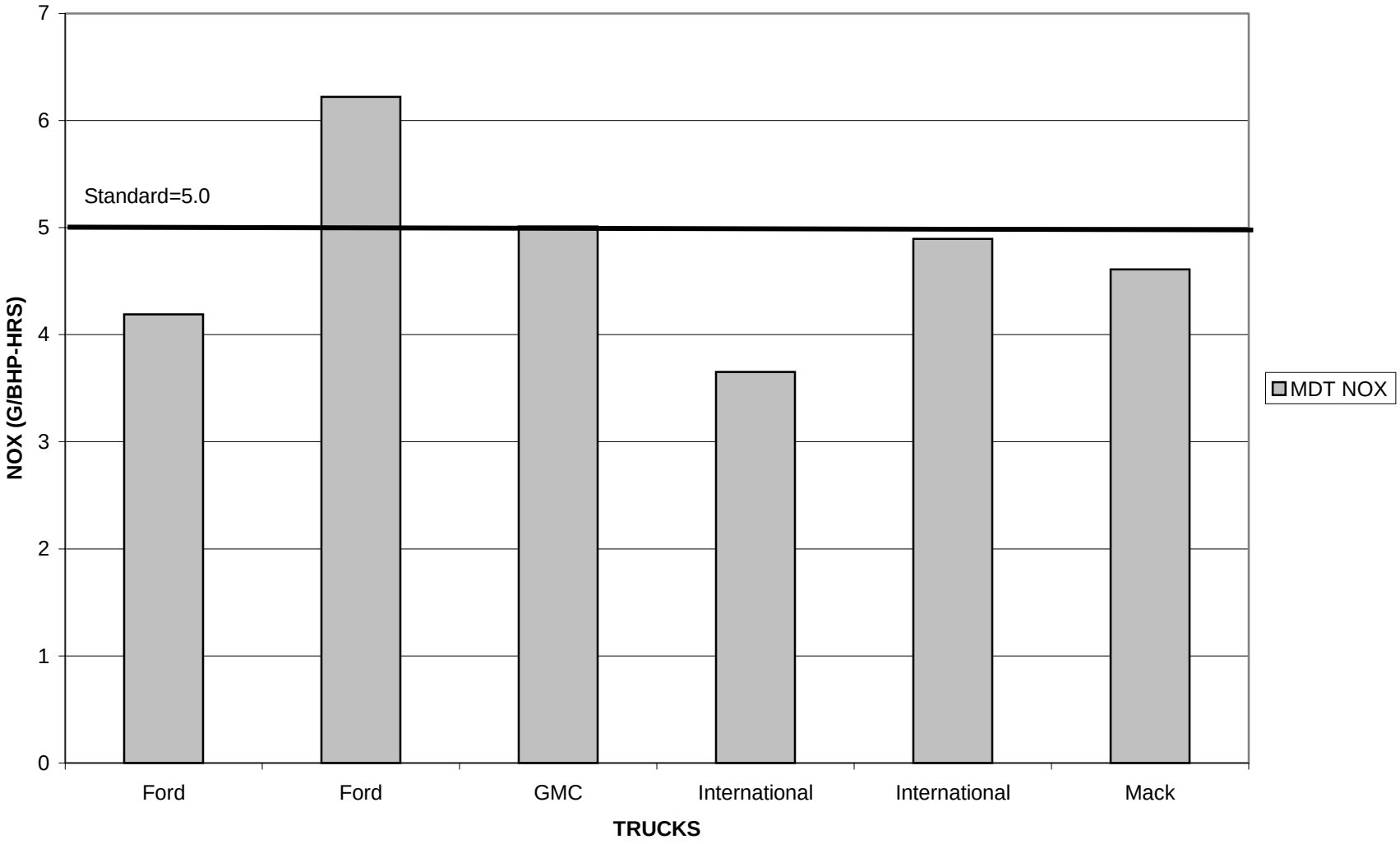
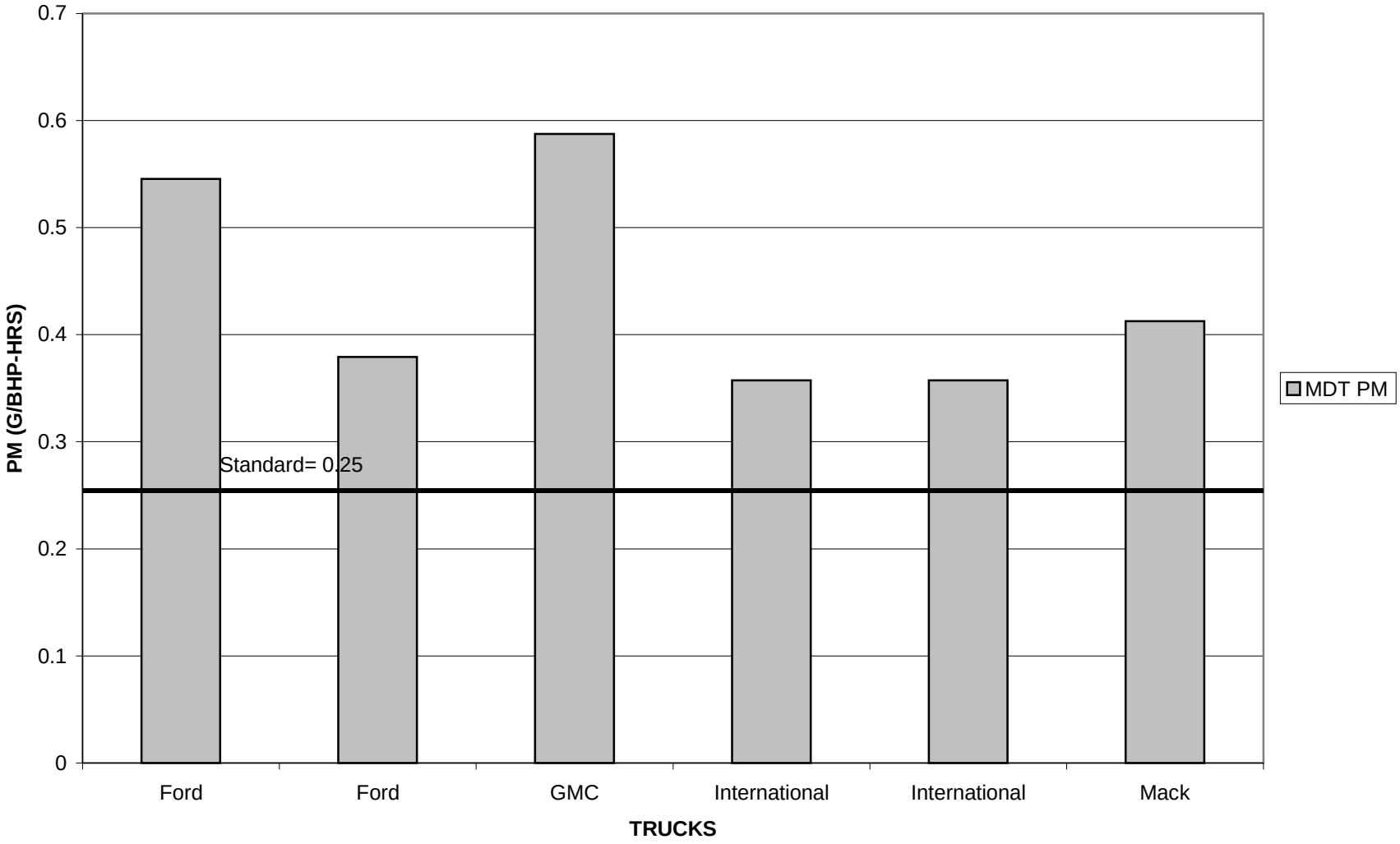


FIGURE 5-11

TEST ROUTE D: 1990-1993-MDT PM



hr for five of six vehicles, with one relatively high emitter at 3 g/BHP-hr. HC emissions are in a narrow range of 0.3±0.06 g/BHP-hr for five of six trucks, with only one at a low 0.12 g/BHP-hr. The low HC emitter was the high CO emitter. NO_x emissions for all vehicles were only slightly below the 5.0 g/BHP-hr standard, with only vehicle at 6.2 g/BHP-hr. On the other hand, all of the vehicles tested had PM emissions higher than applicable standards of 0.25 g/BHP-hr, with two of six engines exceeding twice the PM standard.

The one HHDT tested had extremely low emissions of HC and CO, but NO_x emissions and PM emissions were comparable to the average emissions of the MHDTs tested. These data are shown in Figure 5-12.

5.2.3 1994 and Later Model Year Engines

Eleven MHDTs and eight HHDTs were tested, making it the largest group for sample representation. Data for the MHDTs are shown in Figure 5-13 to 5-16. CO emissions are very low, with average levels of less than 0.8 g/BHP-hr and the highest value at about 1.6 g/BHP-hr. HC emissions are also very low, with all except one truck having emissions below 0.2 g/BHP-hr. Once again, the lowest HC emitter (at 0.04 g/BHP-hr) had the highest CO emissions. NO_x emissions for most trucks were within 1 g/BHP/hr of the 5.0 standard, with one 1999 vehicle (certified to a 4.0 standard) at less than 3.0 g/BHP-hr. As with the 1990-1993 trucks, all vehicles exceeded the 0.1 g/BHP-hr standard for PM, with five of 11 exceeding 0.2 g/BHP-hr and one at 0.35 g/BHP-hr.

Data on the eight HHDTs tested are shown in Figure 5-17 to 5-20. The CO and HC emissions are consistent with these emissions observed for MHDTs, although there are two of eight trucks with abnormally high HC emissions. The highest HC emitter in this group, at 1.1 g/BHP-hr, was the highest emitter across all model year groups. The same vehicle also exhibited very high PM and CO emissions, but low NO_x emissions, indicating some type of 'rich' malperformance. As with NO_x emissions from the MHDTs, NO_x emissions were within ±1.2 g/BHP-hr of the 5.0 standard for all trucks, and three of the eight trucks exceed the NO_x standard by small amounts. PM emission results were also similar to the results for MHDTs, if the one vehicle with obvious

FIGURE 5-12

TEST ROUTE D: 1990-1993 HDT

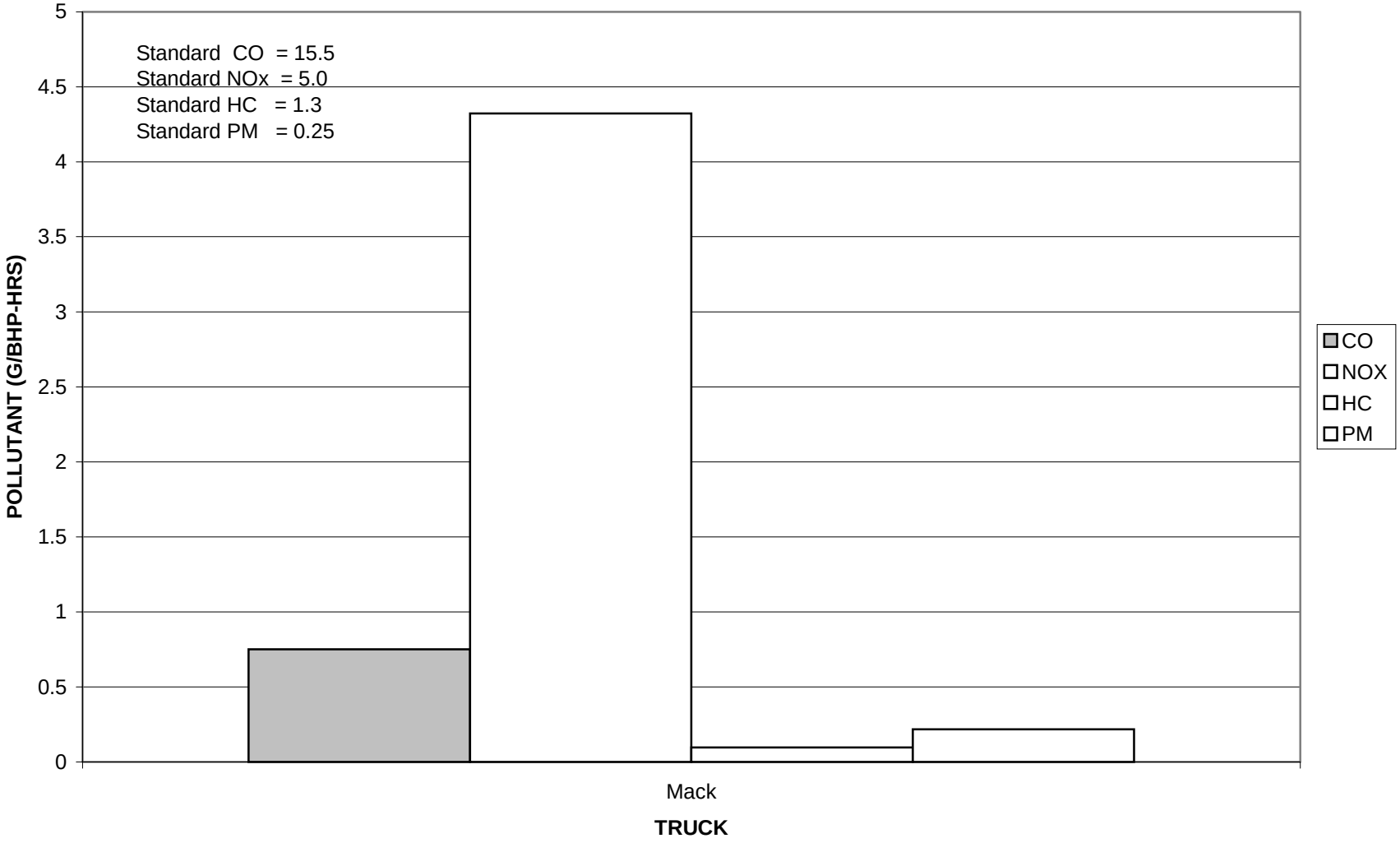


FIGURE 5-13

TEST ROUTE D: 1994-1999-MDT CO

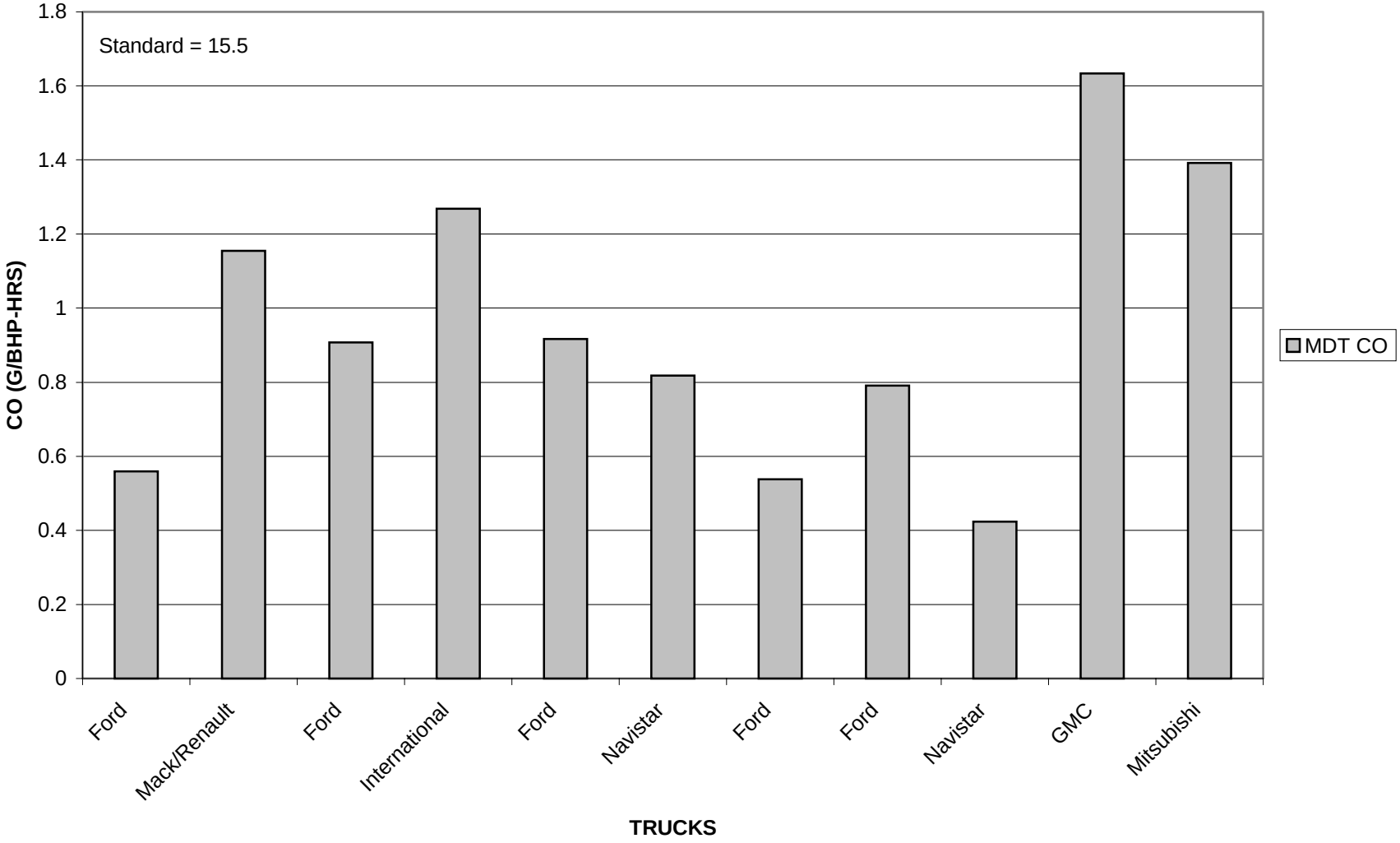


FIGURE 5-14

TEST ROUTE D: 1994-1999-MDT HC

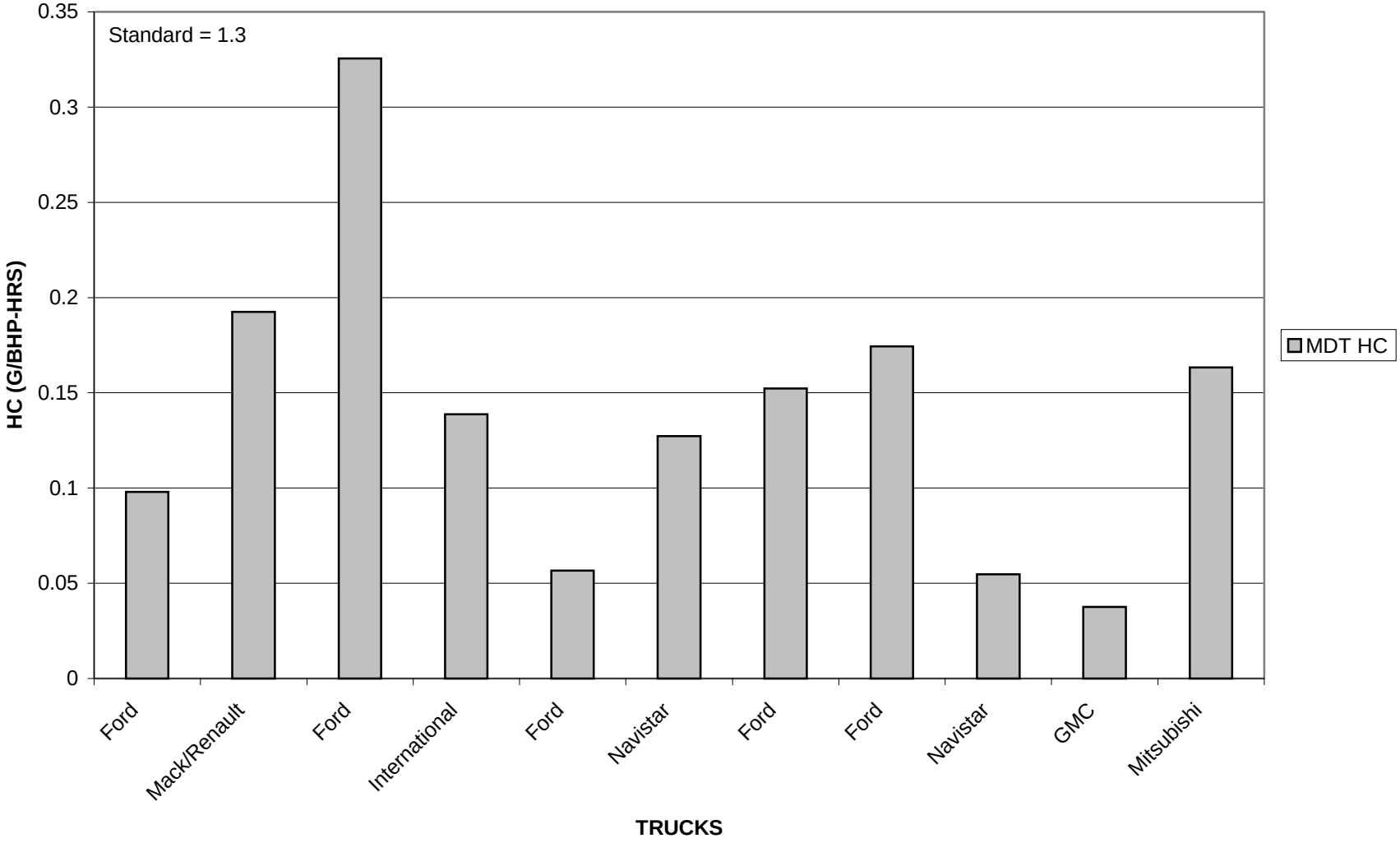


FIGURE 5-15

TEST ROUTE D: 1994-1999-MDT NOX

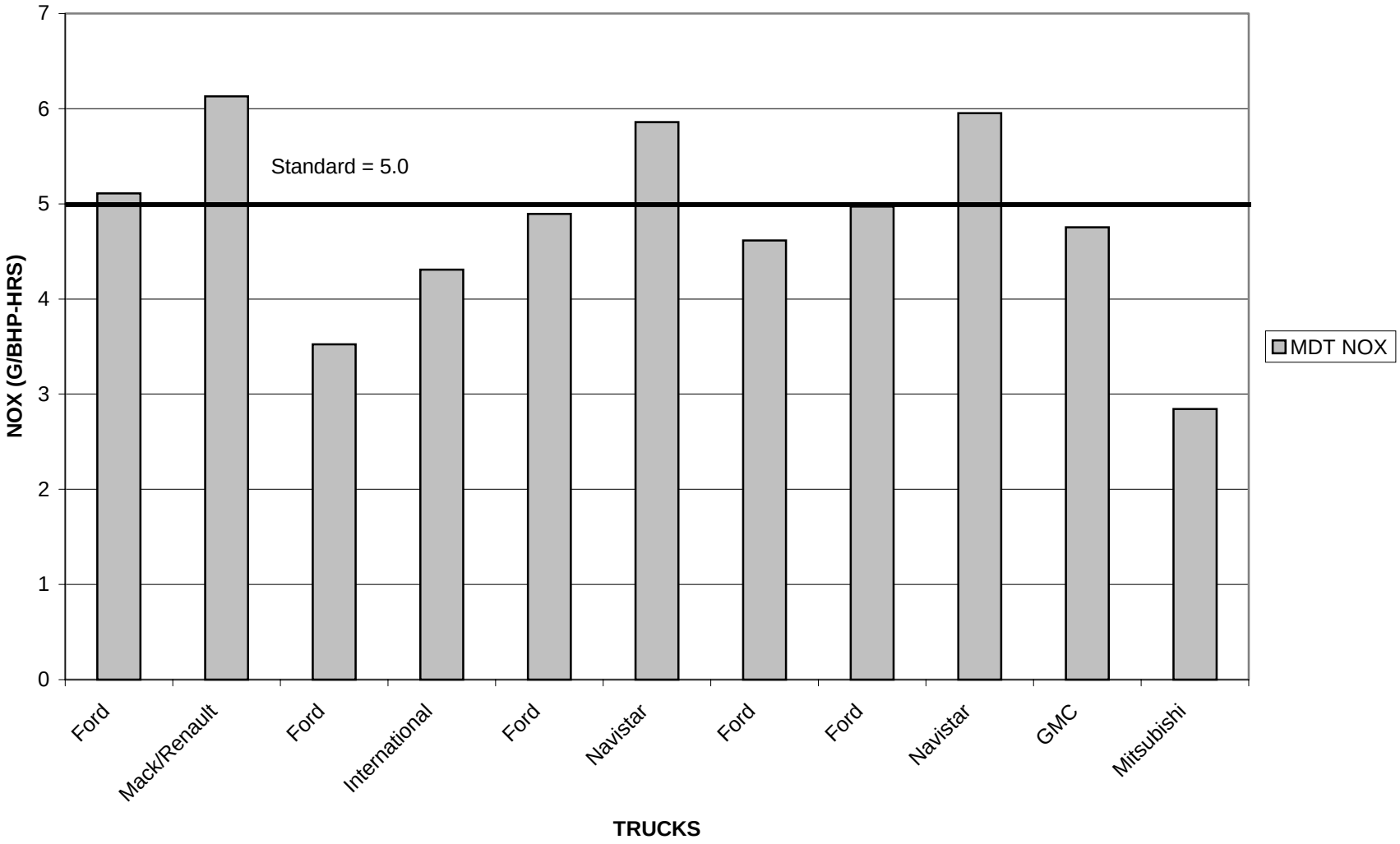


FIGURE 5-16

TEST ROUTE D: 1994-1999- MDT PM

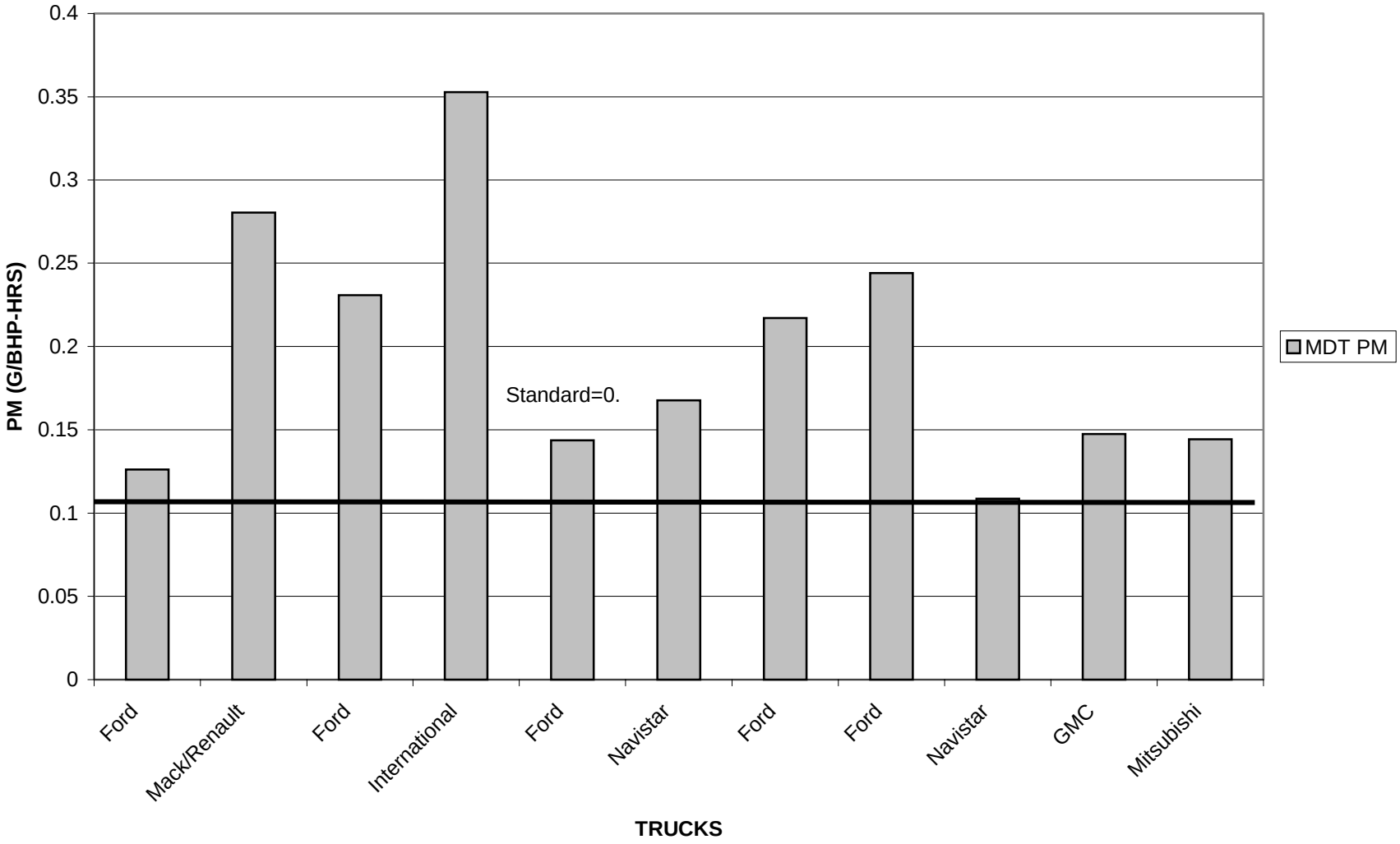


FIGURE 5-17

TEST ROUTE D: 1994-1999-HDT CO

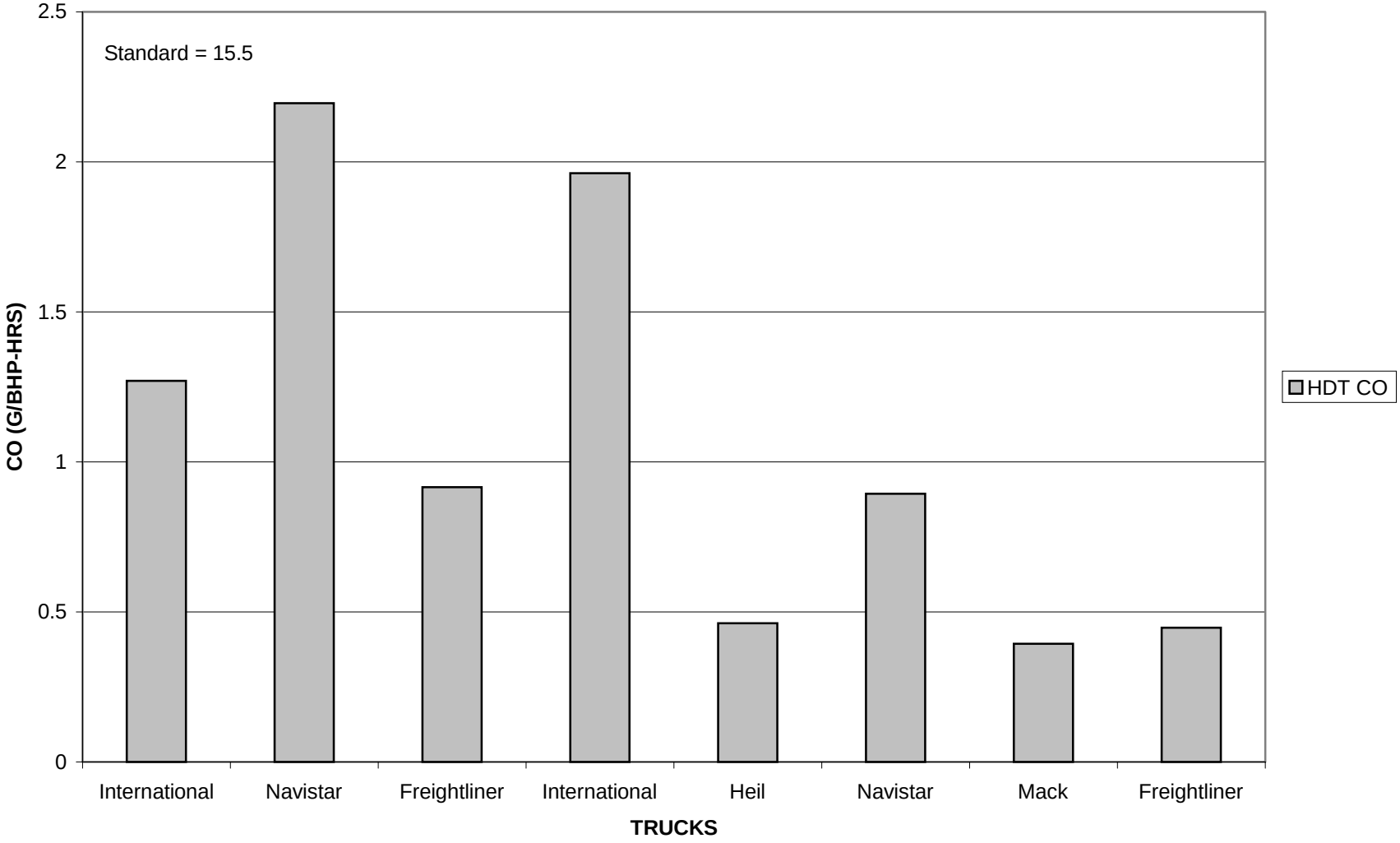


FIGURE 5-18

TEST ROUTE D: 1994-1999-HDT HC

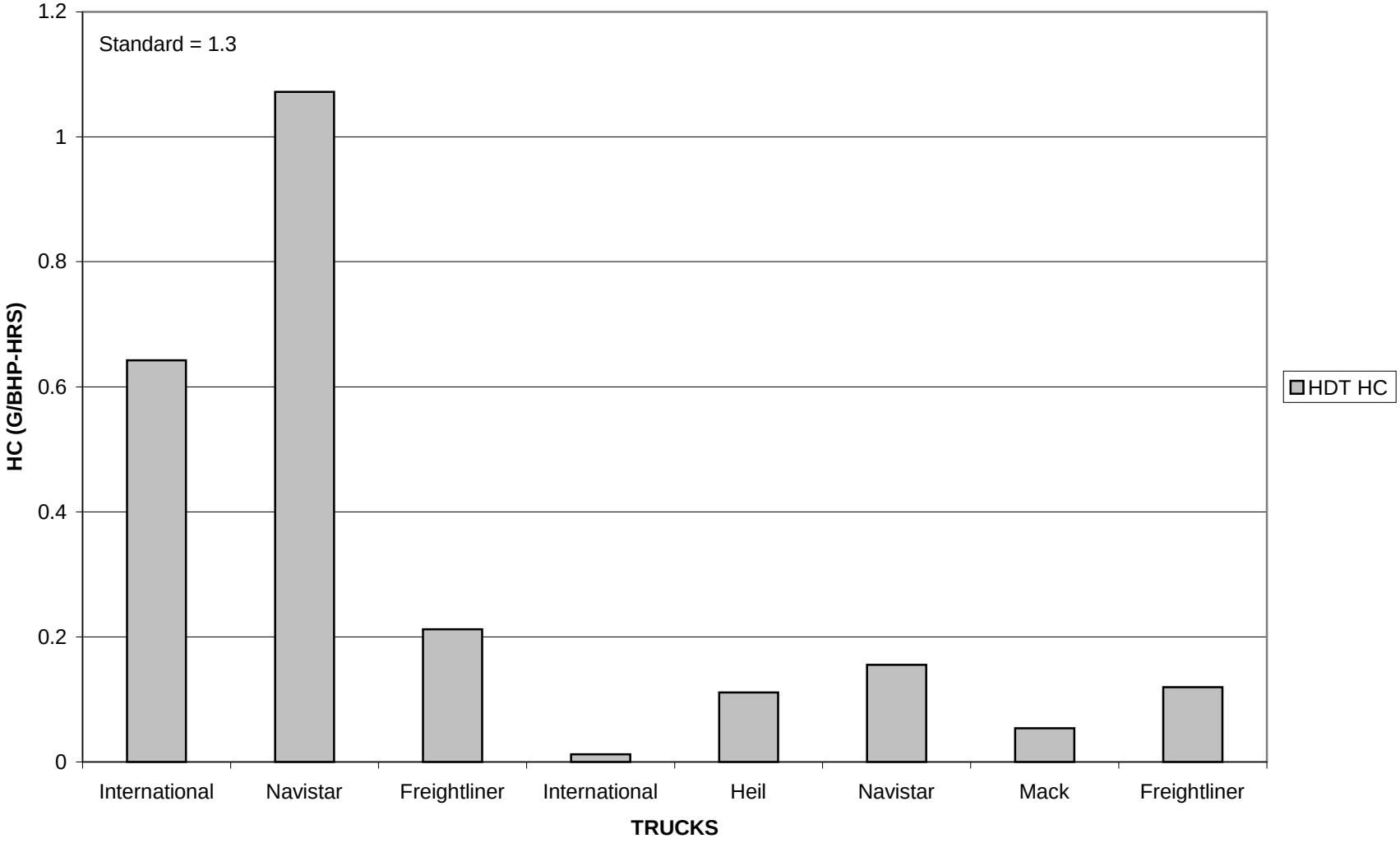


FIGURE 5-19

TEST ROUTE D: 1994-1999-HDT NOX

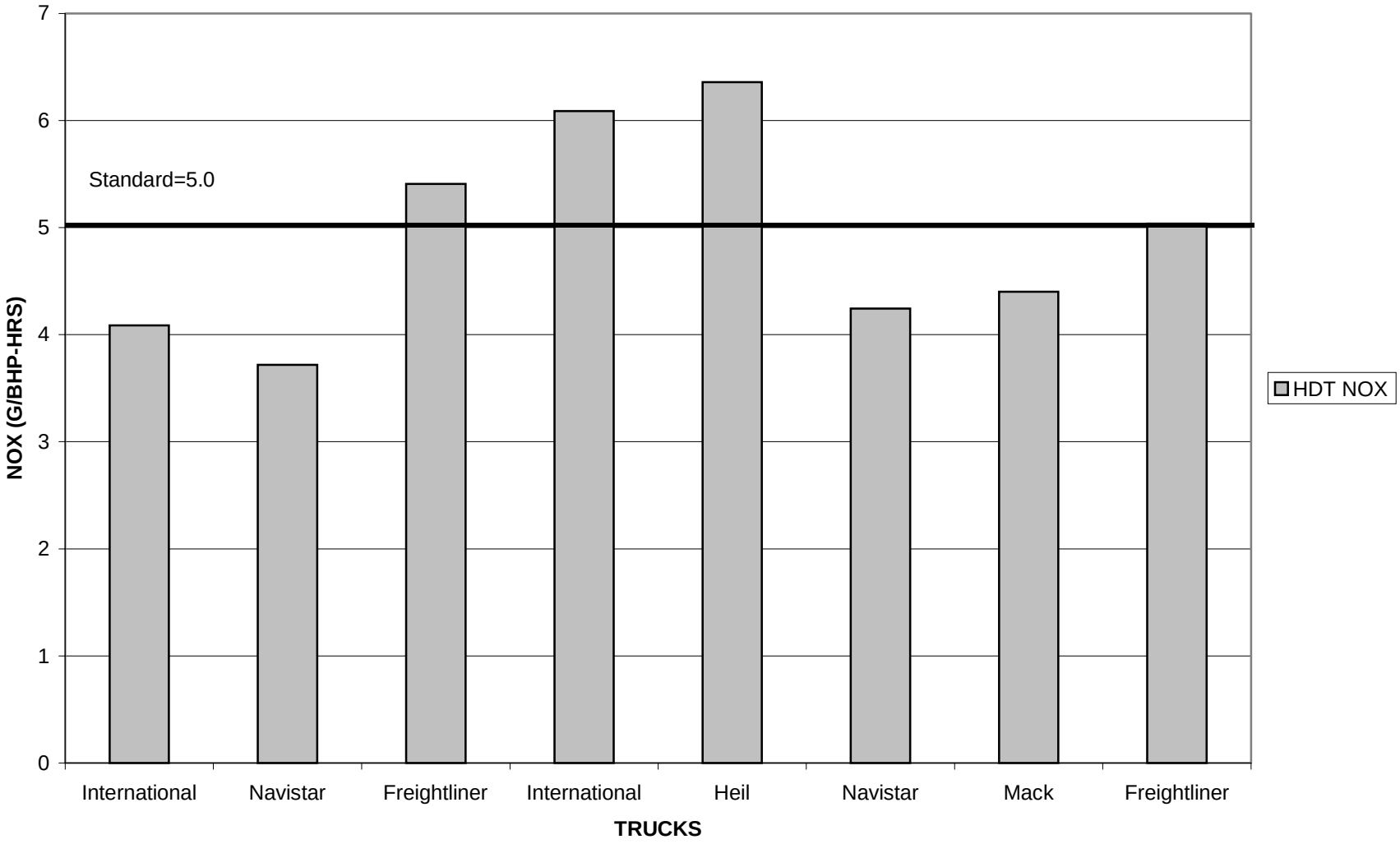
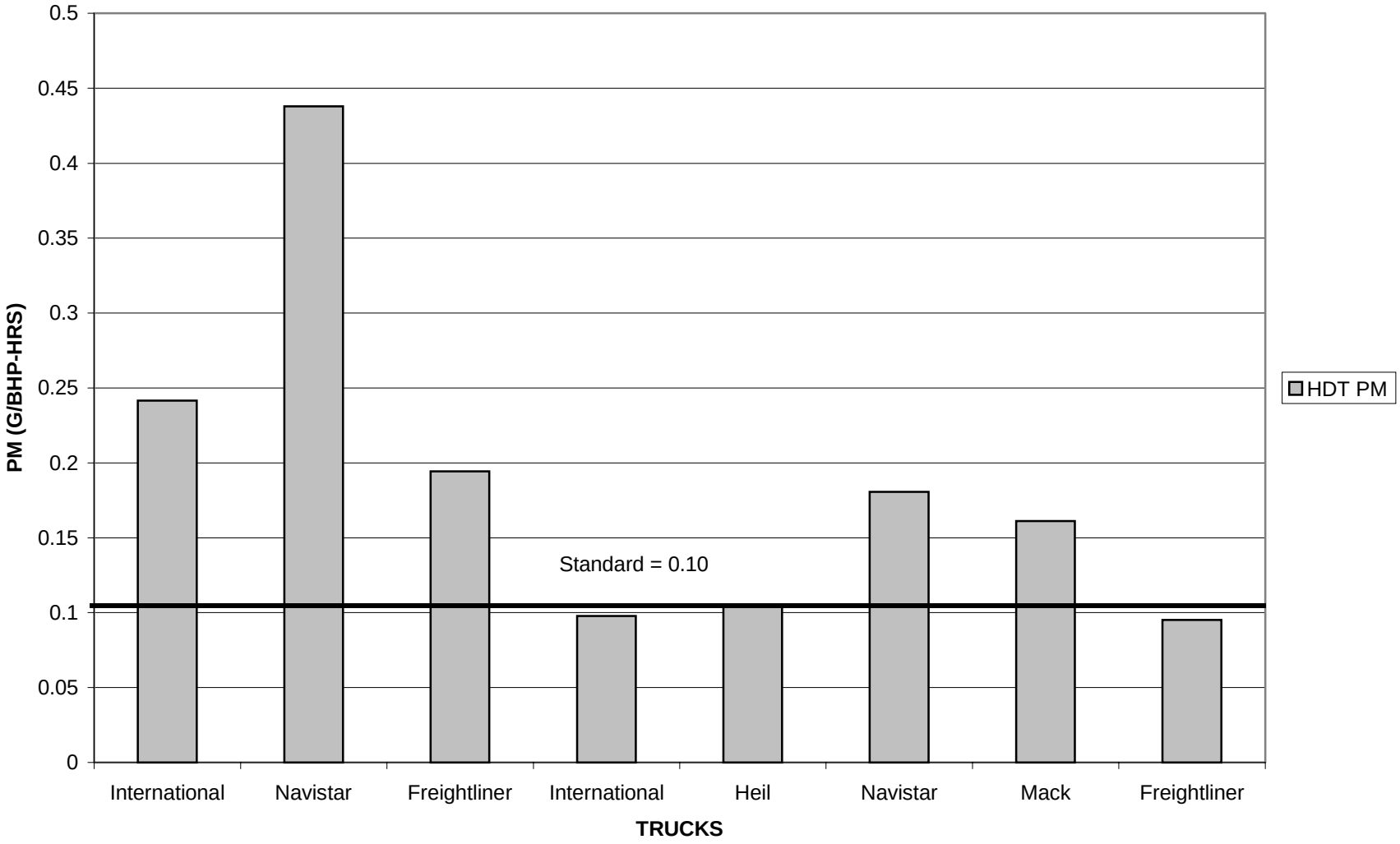


FIGURE 5-20

TEST ROUTE D: 1994-1999-HDT PM



malperformances is excluded. It should be noted that three of the eight vehicles had emissions almost exactly at the 0.10 g/BHP-hr PM standard, but all others had emissions above the standard.

5.3 DISCUSSION OF RESULTS

Given the uncertainties introduced by the chassis test and the conversion process to g/BHP-hr space, the results are remarkably consistent with expectations from engine test based emission results, and with applicable emission standards.

Pre-1990 engines were not certified to very stringent standards, and the majority of trucks have HC, CO and NO_x emissions well below applicable standards. While PM emissions averages are in line with expectations from engine based emission tests, some high PM emitters were noted.

All post-1990 trucks exhibit very low CO and HC emissions in the absence of any serious malperformance. NO_x emissions, however, are very close to standards, with a significant fraction of the sample exhibiting emissions slightly above standards. (Note that we do not wish to imply that these engines will fail standards on the engine certification test, as the test methods are only approximately comparable). PM emissions, on the other hand, are typically above standards, with a significant fraction exhibiting emissions over twice the applicable standard.

Only one of the 37 trucks sampled appeared to have serious malperformances that resulted in very high HC, CO, and PM emissions. This is not inconsistent with the general expectation that less than five percent of the on-road fleet have major malperformances that cause large increases in emissions. Given that 37 trucks were tested, a rate of five percent would indicate only one or two trucks in the sample were likely to have serious malperformances.

6. PARAMETERS AFFECTING EMISSION RATES

6.1 INTRODUCTION

As with any emissions test program, there are a variety of factors that can influence the measured emission rates of test program vehicles. Most obvious among these is the makeup of the trucks subjected to testing. In a program of this size, there is no way to ensure that the fleet tested is entirely representative of the overall operational fleet, but Section 2 describes the steps taken in this project to recruit vehicles representative of those operating in the New York City metropolitan area. Even a properly stratified sample of the small size tested under this study can be influenced by vehicles with non-representative odometer readings, maintenance states, etc. Of equal concern are those factors that can influence test results even for a select sample of vehicles completely representative of the in-use fleet. There are no "standard" conditions for heavy duty chassis dynamometer testing. Therefore, care must be taken in establishing and controlling test conditions to maintain consistency from vehicle to vehicle.

Inconsistencies in test weight and power absorber settings can influence the effective load placed on any given test vehicle. Variations in ambient conditions can affect vehicle emissions performance. The characteristics of the driving cycle and the driver's ability to adhere to those characteristics can determine how emissions from one truck compare to those of another. These and other potential influences should be controlled to the maximum extent possible in comparing emissions measurements across trucks. This section examines the vehicle emissions test data collected in this study to determine the potential effect of some of these influences. As will be seen, both the size of the dataset and the field nature of the study limit the overall ability to draw firm conclusions regarding the significance of many of these potential influences, but this same lack of definitive influence also lends a degree of confidence to the belief that the data represents a random snapshot of overall vehicle performance in the New York City metropolitan area.

6.2 TEST WEIGHT INFLUENCES

Dynamometer inertia weight and power absorber settings determine the effective load placed upon vehicles during emissions testing. The latter is a function of vehicle frontal area, which can be measured with relative accuracy, and is thus generally not considered to be an important issue in determining emissions variability. However, vehicle test weight is usually considered to be an important consideration since vehicles can operate over a broad weight range in practice, from vehicle curb weight (no cargo load) through gross vehicle combined weight (full cargo load), or more in some cases. Defining a single test weight that accurately reflects all in-use test conditions is not possible since every vehicle will operate over a variety of load conditions. However, it should be possible to define a test weight that generates emissions at typical (or average) in-use rates. Unfortunately, there is no one approach to determining test weight that works for all vehicles operating in all areas. Typical test weight values are even less certain in the heavy duty truck sector since certification testing is not performed on a chassis dynamometer basis so that no standard practices have evolved. While WVU typically sets a 70 percent of gross vehicle weight (GVW) target for test weight, this practice not based on any rigorous investigation of vehicle operating practices.

To determine the potential effect of vehicle test weight on emissions, 2 study vehicles were tested over the identical Routized Test D cycle at three different test weight settings. A ConEd service truck (vehicle ConEd-C60309, 52,000 pounds GVW, and 34,450 pounds curb weight) with a 1990 Ford 7.8 liter MHDT engine was tested at 26,000, 36,400, and 52,000 pounds. A Mendon tractor truck (vehicle Mendon-14713, 65,000 pounds GCW, and 12,900 pounds curb weight) with a 1994 Cummins L10 HHDT engine was tested at 27,000 pounds, 42,000 pounds, and 50,000 pounds. Measured emission rates across these test weights were subjected to regression analysis to investigate the magnitude and significance of any test weight relation.

Like all statistical analysis performed in this study, a simple linear regression technique was employed. This technique is somewhat limited in that it ignores other potential influences and higher order relationships, but the level and range of data available for analysis currently acts as a constraint in the sophistication of allowable analysis. Nevertheless, the simple linear approach

should provide an initial indication of not only whether a significant relationship might exist, but also the strength of that relationship. Subsequent analyses following the collection of more focused and robust test data might be used to more accurately define promising relations, but for this study all test weight relationship analysis is based on linear regression analysis of the form:

$$g/bhp\text{-}hr \text{ of predicted species} = a + b\,(\text{test weight}/1{,}000)$$

Since the regression is performed independently for each test weight vehicle, truck-to-truck variability is not an issue. However, test-to-test variability for a given truck can still influence measured emission results and thus affect regression results (to an unknown extent).

Table 6-1 presents the results of the regression analysis and Figures 6-2 through 6-5 graphically depict the underlying datapoints. As indicated in the table, not a single significant test weight coefficient is evidenced for any of the four measured emission species emitted by either test weight vehicle. In fact, 5 of the 8 test weight coefficients are negative, implying a possible decline in emissions with increasing test weight (although again, the coefficients are not significant). This may at first seem counterintuitive, but given the work-specific nature of the

Species	Vehicle	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
PM	ConEd-C60309	3	0.45	0.70	0.0001	0.02	0.00	0.02
	Mendon-14713	3	0.32	0.94	-0.0017	0.75	0.85	0.75
NO_x	ConEd-C60309	3	1.53	0.94	-0.0035	0.46	0.44	0.46
	Mendon-14713	3	1.34	0.90	-0.0033	0.35	0.28	0.35
CO	ConEd-C60309	3	4.09	0.98	0.0017	0.33	0.26	0.33
	Mendon-14713	3	3.67	0.91	0.0059	0.28	0.18	0.28
HC	ConEd-C60309	3	0.36	0.96	-0.0016	0.81	0.91	0.81
	Mendon-14713	3	1.03	0.92	-0.0082	0.76	0.86	0.76

"Obs" indicates the number of observations in the dataset. "Sig_x" indicates the statistical significance of the parameter "x."

TABLE 6-1. EMISSION RATES VS. TEST WEIGHT, ROUTIZED TEST D CYCLE

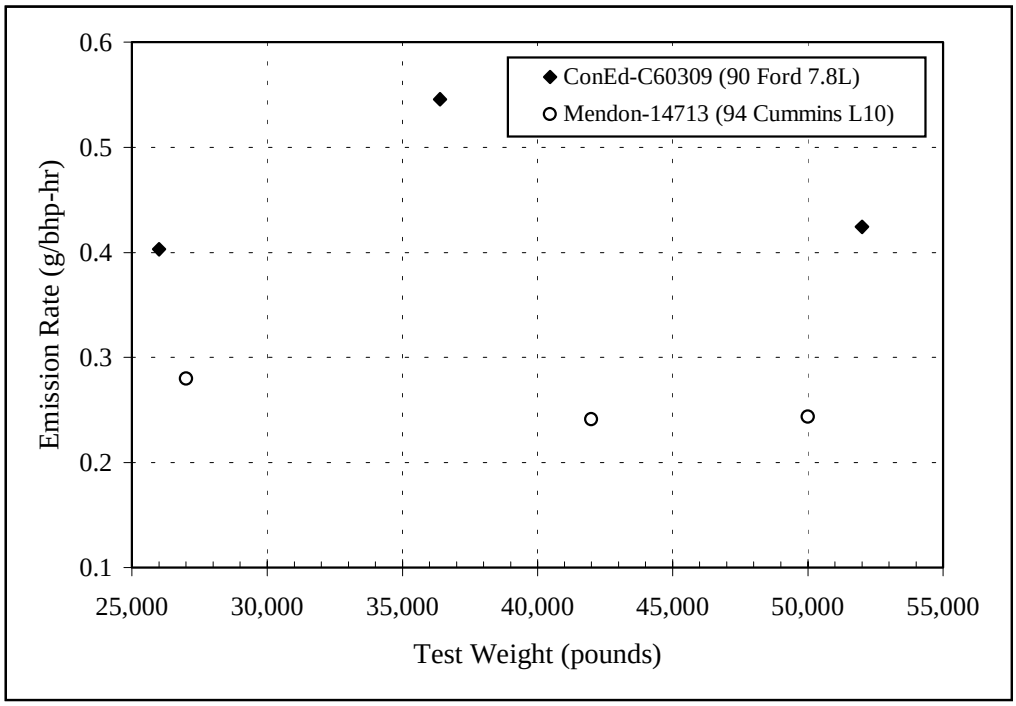


FIGURE 6-1. TEST WEIGHT VS. PM, ROUTIZED TEST D CYCLE

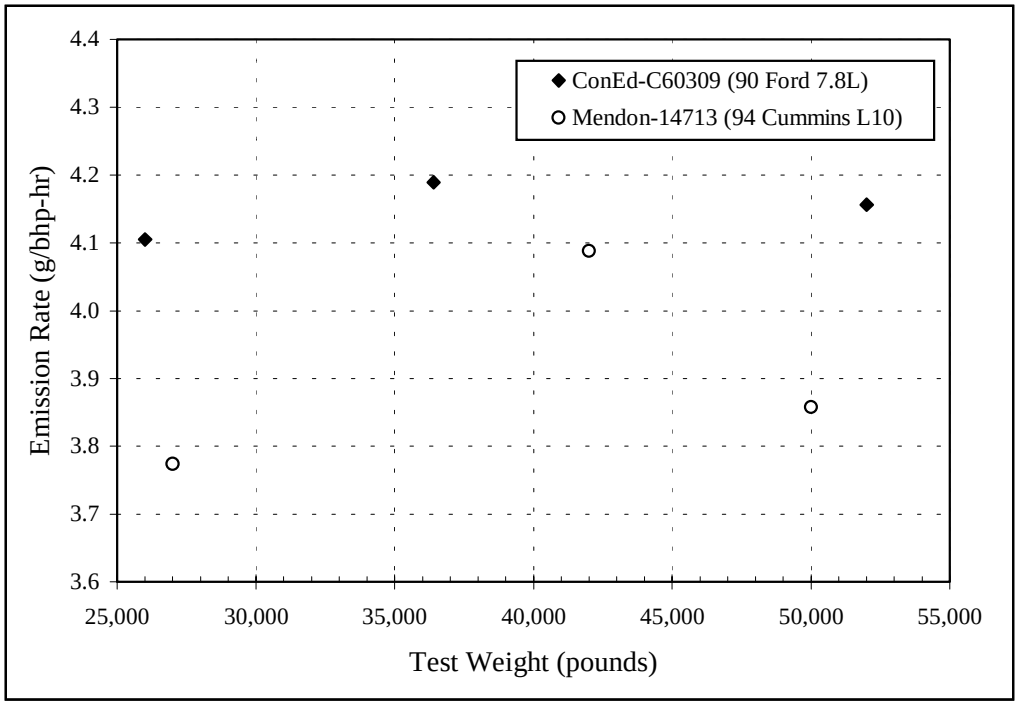


FIGURE 6-2. TEST WEIGHT VS. NO_x, ROUTIZED TEST D CYCLE

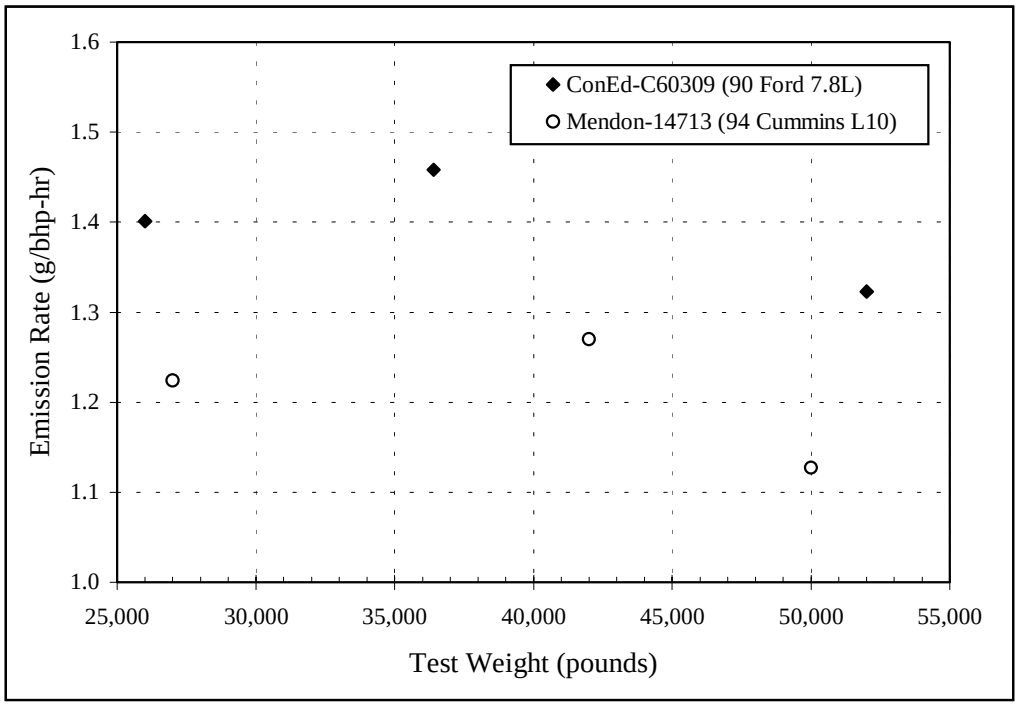


FIGURE 6-3. TEST WEIGHT VS. CO, ROUTIZED TEST D CYCLE

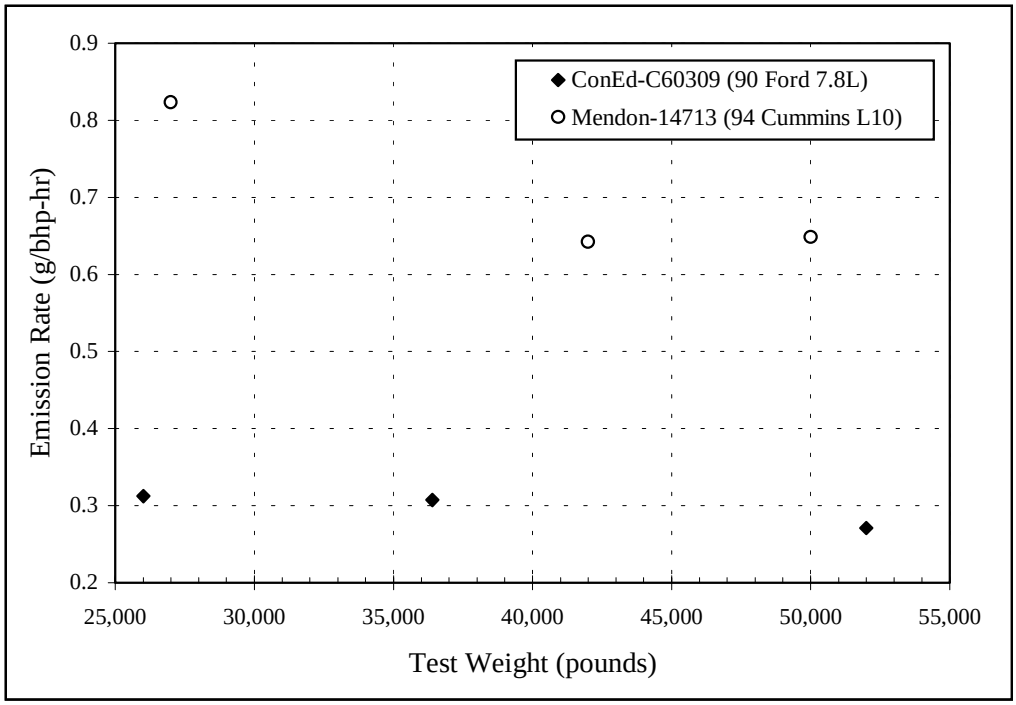


FIGURE 6-4. TEST WEIGHT VS. HC, ROUTIZED TEST D CYCLE

emission rates and the relatively modest load factors associated with the Routized Test D cycle (generally 0.2-0.3, see Section 6.3 below), test weight influence can be expected to be modest.

In g/bhp-hr, the theoretical variation of emission rate with load factor is generally a U-shaped curve, with the base of the U spanning the 30 to 60 percent load factor range. For the ConEd service truck, the effective load factors over the range of test weights are 0.31, 0.35, and 0.39. For the Mendon truck, the load factors are 0.22, 0.26, and 0.28. Load factors of these magnitudes would imply that both engines are operating (on average) near the bottom of the downslope of the U-shaped emission rate curve. Under such a situation, the entire window of the test weight regression falls over a relatively flat portion of the emission rate versus load factor curve and little influence between the two factors would be expected. As long as load factors in this range are considered typical of New York City metropolitan area driving conditions, there appears to be little concern in regards to the representativeness of vehicle test weights.

6.3 VEHICLE LOAD FACTOR

As discussed above, the effective load placed upon a vehicle engine during testing can influence emissions generation. Ideally, to best reflect real world conditions, the load factor during testing should match that encountered during actual in-use vehicle operation. Accordingly, the load factor should be a function of the overall vehicle design as opposed to engine specific parameters as it is the vehicle/engine combination that will dictate in-use loading conditions. For example, two vehicles with identical engines, but with gross vehicle weights that differ substantially, would be expected to exhibit different in-use load factors if they operate under similar traffic conditions (as would be expected in a geographically constrained study such as this).

In principle, this approach is recognized by WVU during testing through their protocol of testing all vehicles at a “standard” test weight of 70 percent of GVW. However, in practice, this protocol requires that vehicle GVW be accurately defined and EEA observed numerous instances during the study where this was not the case. The problem appears to be traceable to the WVU practice of utilizing vehicle “door post” GVW as the basis for determining all vehicle test weights. However, this seriously understates the actual vehicle in-use weights of tractor trucks

where the effective vehicle weight consists of the weight of the vehicle plus trailer, not the GVW of the vehicle alone. In effect, the trailer adds another two axles of weight carrying capacity to the vehicle/trailer combination and it this "gross combined weight (GCW)" that is the appropriate test weight parameter. Nevertheless, despite numerous discussions on this issue, WVU repeatedly tested tractor trucks at 70 percent GVW. In fact, it appears as though 6 of the 9 tractor trucks tested during this study were tested at only 30 to 50 percent of GCW.

An estimate of the effective load factor for program test vehicles can be derived by dividing the estimated brake horsepower hours expended over the cycle (bhp-hrs/mile time cycle mileage as discussed in Sections 2 and 5) by the maximum possible work that can be performed over the same cycle. Maximum work equals the rated engine horsepower times the cycle time duration. Although cycle time duration statistics were not provided by WVU, provided cycle mileages were quite consistent with cycle design mileages. The ratio of actual to design mileages averaged 1.003, with a standard deviation of ±1.3 percent, and minimum and maximum deviations of –4.5 and +9.9 percent respectively. Therefore, EEA used cycle design time durations to estimate actual WVU cycle times and calculate maximum cycle work. The fact that routized cycles (i.e., design mileage, variable time) were used for the transient testing performed in this project introduces a further, unknown element of error into this calculation, but it is expected that this error is minor based on observations that few of the test vehicles had difficulty following the various test cycles.

Figure 6-5 presents the estimated load factor by engine size for the Routized Test D cycles conducted during this study. Ideally, one would expect to see constant load factors across the entire range of engine sizes. However, as discussed above, some variability is expected due to real world variations in vehicle power to weight ratios. Additionally, the maximum test weight of the WVU equipment is in the 42,000-50,000 pound range, so the largest engines may be required to be tested at somewhat less than the 70 percent GVW/GCW standard. For example, the largest vehicle tested (85,000 pounds GCW) would dictate a standard test weight of 59,500 pounds, while actual tested was conducted at 48,000 pounds due to equipment constraints. Figure 6-5 clearly shows the effects of power to weight variability as the observed range of load

factor variation is substantial. Nevertheless, as indicated, 5 of the 9 tractor trucks tested were tested on the low end of this load factor range, and were, therefore, generally subjected to less severe loading than the bulk of other test vehicles.

The effects of this under-testing of tractor trucks on emissions measured during the study may be marginal in light of the apparent insensitivity of work-specific emission rates to test weight (over the range of test weights examined in this test program, see Section 6.2). From the discussion of vehicle test weight influences, it is clear that no definitive conclusions can be drawn from the limited dataset available for analysis through this study. Although no relationship between test weight and emission rate is evident, such a relation may emerge from a more focused study involving a larger test fleet under conditions that more finely control for other potential emissions influences. Until such data is in place, future test programs would benefit from a more consistent and appropriate assignment of vehicle test weight.

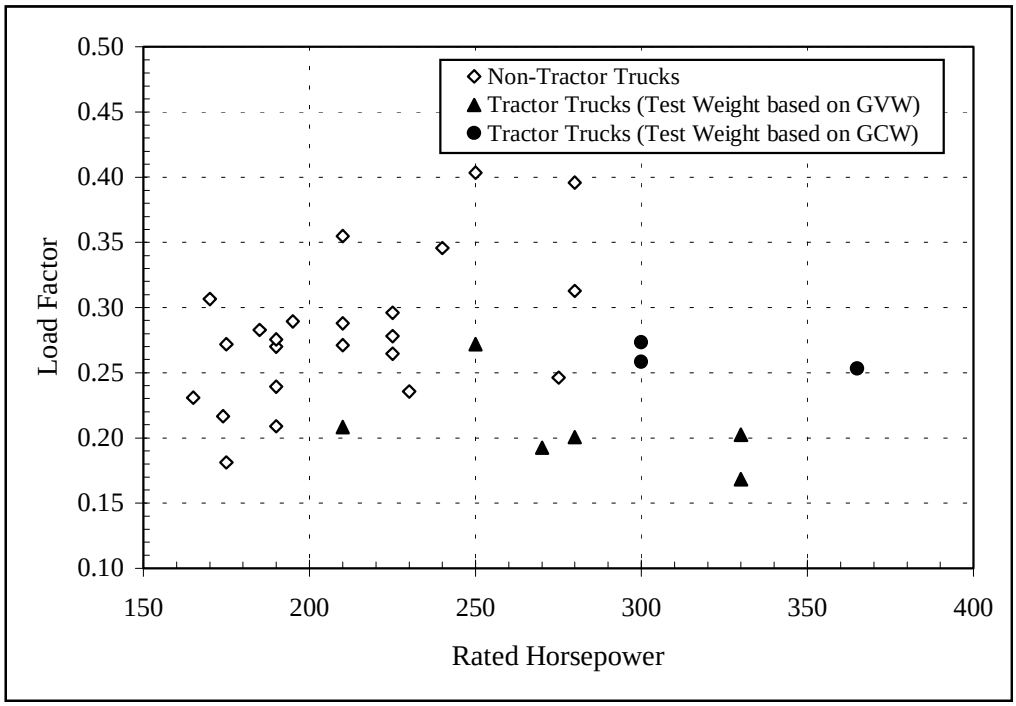


FIGURE 6-5. LOAD FACTOR VS. RATED HP, ROUTIZED TEST D CYCLE

6.4 TEST CYCLE RELATIONSHIPS

Since this study employed a variety of emission test cycles, including both transient, steady state, and I/M type cycles, it presents an opportunity to investigate not only the influence of the specific test cycle on measured emissions, but the ability of any included cycle to predict emission rates under one of the other included cycles. If significant inter-cycle relationships can be developed, it is possible to augment the test data collected under this study with data collected under other test programs that include any of the test cycles for which a significant relationship exists. For example, this study includes both the WVU 5 Mile Route and Routized Test D transient cycles. Although there has been significant testing of heavy duty vehicles over the former cycle, there has been relatively little over the latter. If, however, Routized Test D cycle emission rates are desired and a significant relationship between Routized Test D and WVU 5 Mile emission rates exists, the latter can easily be converted to the former.

Given the various test cycles performed for this study, comparative statistical analysis was performed for the Routized Test D, the WVU 5 Mile, the 20 mph steady state, the 40 mph steady state, the lugdown, and the snap acceleration cycles. The Routized Test D cycle is employed as the "gold standard" throughout this analysis and all other cycles are evaluated in terms of their ability to predict Routized Test D emission rates. This is not meant to impart some "official standing" to the Routized Test D cycle that does not apply to the other cycles evaluated, simply that the number of analysis permutations can be controlled by assigning one cycle as the "target" cycle and evaluating all other cycles relative to this target. Should relations between any two cycles demonstrate significance with the target cycle, they can be assumed to also have a significant relationship with each other.

Like all statistical analysis for this study, a simple linear regression technique was employed. As already stated, this technique is somewhat limited in that it ignores other potential influences and higher order relationships, but the level and range of data available for analysis currently acts as a constraint in the sophistication of allowable analysis. Nevertheless, the simple linear approach should provide an initial indication of not only whether a significant relationship might exist, but also the strength of that relationship. Subsequent analyses following the collection of more

focused and robust test data might be used to more accurately define promising relations, but for this study all test cycle relationship analysis is based on linear regression analysis of the form:

g/bhp-hr over Routized Test D cycle = a + b (g/bhp-hr over comparative cycle)

Table 6-2 presents the results of the analysis. As indicated, 19 of the 20 comparative cycle coefficients ("b") are significant at a 90 percent level of confidence. In fact, 16 of the 19 are significant at a 99 percent level of confidence. While this indicates that there is a significant directional relationship between emission species measured over the comparative cycle and the Routized test D cycle (excluding 40 mph steady state CO), the predictive ability of the comparative cycles varies substantially. The WVU 5 Mile Route cycle shows relatively good correlation for all emission species (r^2 = 0.71-0.87) indicating that an expansion of the test program dataset to include emission rate data from other studies collected over the WVU 5 Mile Route cycle may be a viable alternative to the direct collection of additional New York City metropolitan area data.

Conversely, both the 20 and 40 mph steady state cycles demonstrate poor correlations for all emission species. Together, the clearly significant species coefficients combined with the poor overall correlations reflect a situation where a strong directional trend exists in combination with a large degree of scatter. Therefore, while it is possible to make inferences on the overall Routized Test D cycle emission rate from emission rates generated over the steady state cycles (again excluding 40 mph steady state CO), the accuracy of these inferences, while good on an average basis, will be highly uncertain for any specific truck. While it may be possible to draw broad-brush conclusions from the steady state data, enforcement type decision-making will be limited. Figure 6-6 graphically depicts this situation for 40 mph steady state NO_x measurements (which exhibit the strongest correlation (r^2 = 0.62) of any steady state emission species).

For lugdown cycle PM and CO, the situation is similar to that for the steady state cycles. Species coefficients are significant at 90 percent confidence, but overall correlation is poor, with r^2 values of only about 0.5. Figure 6-7 graphically depicts the PM relationship, where the degree of

Species	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
Routized Test D vs. WVU 5 Mile (5 Mile independent)							
PM	32	0.02	0.31	1.10	0.99	0.71	0.99
CO	32	-0.17	0.56	1.15	0.99	0.74	0.99
NO_x	32	0.10	0.13	0.89	0.99	0.71	0.99
HC	32	-0.03	0.84	0.93	0.99	0.87	0.99
Routized Test D vs. 20 mph Steady State (20 mph independent)							
PM	27	0.16	0.99	0.56	0.99	0.22	0.99
CO	27	0.69	0.81	0.47	0.94	0.14	0.94
NO_x	27	2.57	0.99	0.40	0.99	0.38	0.99
HC	27	-0.03	0.41	0.74	0.99	0.60	0.99
Routized Test D vs. 40 mph Steady State (40 mph independent)							
PM	30	0.08	0.91	0.89	0.99	0.50	0.99
CO	30	1.23	0.99	0.37	0.52	0.02	0.52
NO_x	30	1.86	0.99	0.56	0.99	0.62	0.99
HC	30	0.12	0.99	0.43	0.99	0.35	0.99
Routized Test D vs. Lugdown (Lugdown independent)							
PM	7	0.12	0.83	0.33	0.92	0.49	0.92
CO	7	-0.27	0.29	2.61	0.93	0.52	0.93
NO_x	7	1.54	0.91	0.58	0.99	0.79	0.99
HC	7	-0.04	0.94	1.70	0.99	0.99	0.99
Routized Test D vs. Snap Acceleration (Snap independent)							
PM	30	0.13	0.99	0.28	0.99	0.55	0.99
CO	30	0.26	0.72	0.18	0.99	0.64	0.99
NO_x	30	2.09	0.96	0.62	0.99	0.29	0.99
HC	30	0.12	0.97	0.10	0.99	0.22	0.99

"Obs" indicates the number of observations in the dataset.

"Sig_x" indicates the statistical significance of the parameter "x."

TABLE 6-2. RELATIONS BETWEEN TEST CYCLES

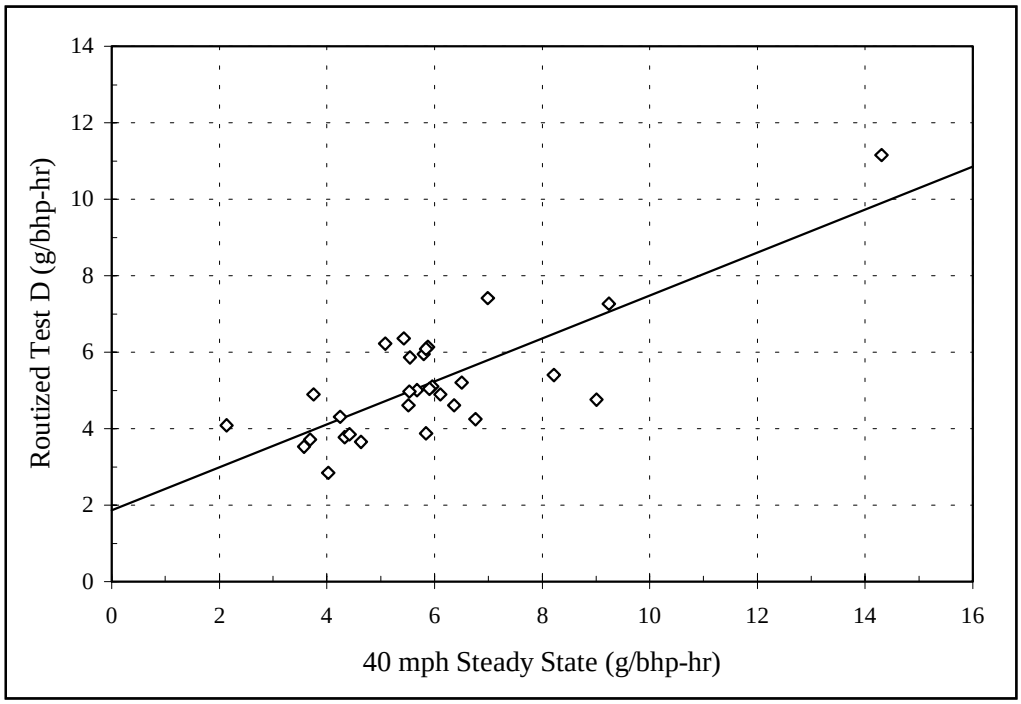


FIGURE 6-6. ROUTIZED TEST D VS. 40 MPH STEADY STATE, NO_x

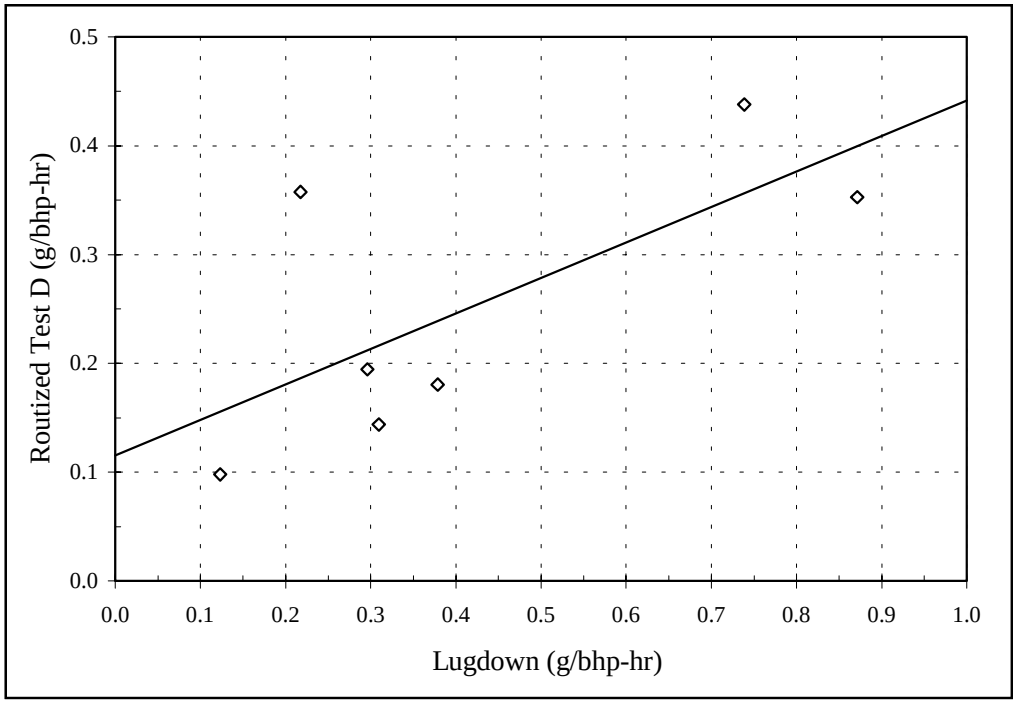


FIGURE 6-7. ROUTIZED TEST D VS. LUGDOWN, PM

variability is obvious. However, the situation for NO_x and HC more closely reflect that of the WVU 5 Mile Route cycle, with both relations showing strong species coefficients and good correlation (in fact, excellent correlation for HC). Figure 6-8 graphically depicts the NO_x relationship, where despite the limited sample size, the correlation of Routized Test D cycle predictions with observations is obvious. While it would be advantageous to assemble a larger dataset to confirm this relationship, it appears that the lugdown test can be used to accurately predict transient cycle NO_x emissions.

The near-zero load snap acceleration cycle behaves much like the steady state cycles, exhibiting strong coefficient significance but poor correlation. Figure 6-9 depicts the relationship for PM. Interestingly, despite the poor correlation, it appears that much of the variability derives from snap acceleration measurements above 1 g/bhp-hr. It may, therefore, be possible to draw broad conclusions from snap acceleration measurements, but the usefulness of this ability is uncertain. There are currently no instances where mass emissions data are routinely collected over the snap acceleration cycle. Moreover, it seems unlikely that in instances where mass emissions data were being collected, that the snap acceleration cycle would be considered the most appropriate test cycle. Therefore, while providing additional evidence that relative emission rates exhibit a surprising degree of test load independence, further use of the snap acceleration mass emission rate data appears limited.

6.5 VEHICLE ODOMETER AND CATALYST INFLUENCES

As would be expected, vehicle odometer readings exhibited a wide range of variability, even across vehicles of similar age. In a test program of the size of this one, there is little ability to ensure that test vehicles exhibit a representative range of odometer readings as the number of vehicles within model year and engine stratification categories alone is limited. Therefore, a basic investigation of the significance of odometer reading on measured emission rates was performed. Additionally, since there were a few test vehicles that incorporated oxidation catalysts in their exhaust streams, the potential for emissions influences due to the presence of these catalysts was incorporated into the odometer investigation. Ideally, on the basis of

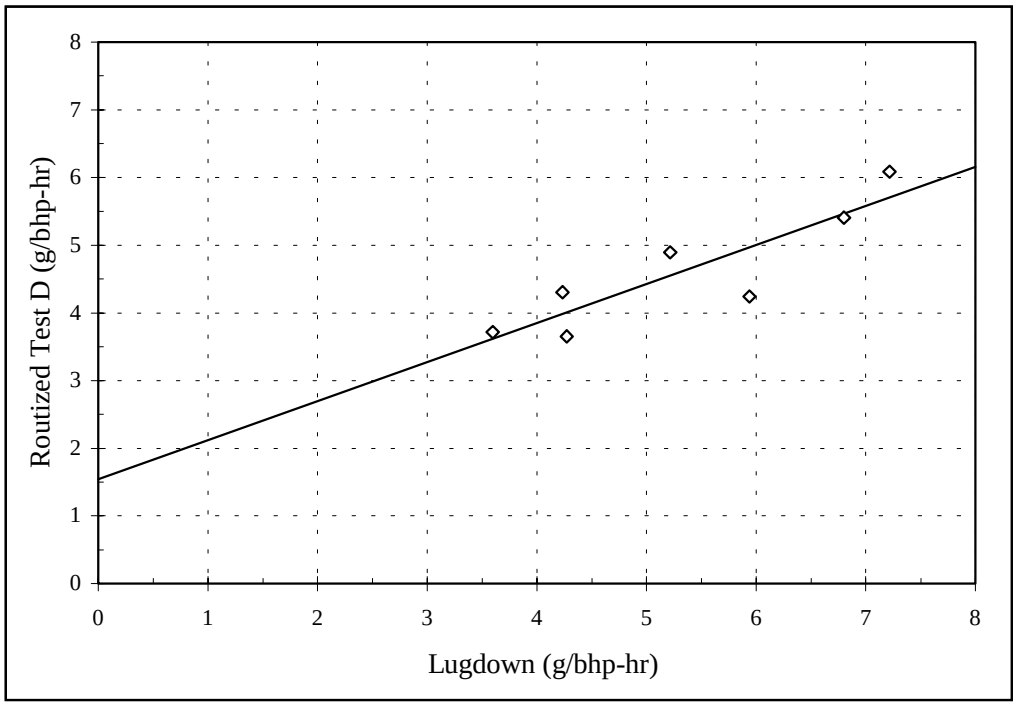


FIGURE 6-8. ROUTIZED TEST D VS. LUGDOWN, NO_x

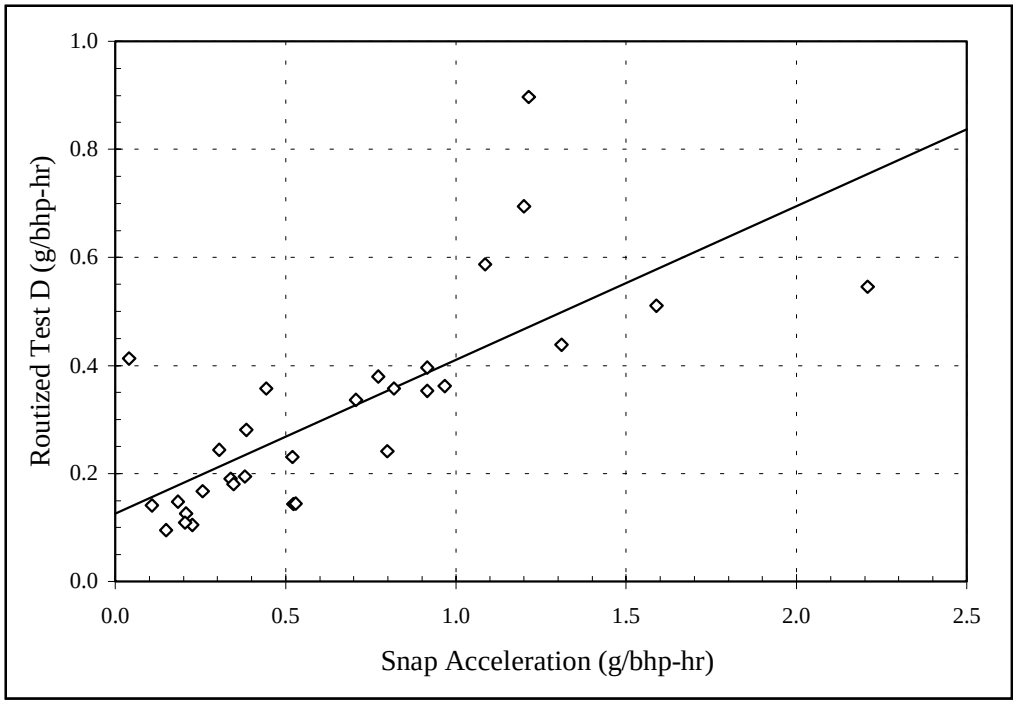


FIGURE 6-9. ROUTIZED TEST D VS. SNAP ACCELERATION, PM

oxidation catalyst design criteria, one would expect to see reduced CO and somewhat reduced HC and PM relative to non-catalyst vehicles of similar mileage.

Once again, the statistical analysis employed took the form of a simple linear regression. As previously stated, this technique is somewhat limited in that it ignores other potential influences and higher order relationships, but the level and range of data available for analysis currently acts as an analysis constraint. Nevertheless, the simple linear approach should provide an initial indication of not only whether a significant relationship might exist, but also the strength of that relationship. Subsequent analyses following the collection of more focused and robust test data might be used to more accurately define promising relations, but for this study all odometer reading relationship analysis is based on linear regression analysis of the form:

$$g/bhp\text{-}hr \text{ over Routized Test D cycle} = a + b\,(\text{odometer reading}/100{,}000)$$

As indicated, the Routized Test D cycle was used as the basis for this analysis to avoid the confounding influences of alternative test cycles. The Routized Test D cycle was selected for convenience as well as in recognition to it tenuous ties to the heavy duty vehicle engine certification cycle. Additionally, given variations in emission test standards over time, the analysis was performed for specific model year groups, within which applicable emissions design criteria is expected to be roughly constant.

Table 6-3 presents the results of the analysis and Figures 6-10 through 6-21 graphically depict the regression results and underlying data. As indicated in Table 6-3, only 3 of the 12 analysis groups (pre-1990 NO_x, 1994 and newer CO, and 1990-1993 HC) exhibit significant odometer reading relationships at the 90 percent level of confidence. Moreover, one of these 3 significant relations (1990-1993 HC) exhibits a negative coefficient (i.e., emission decline with increasing mileage). Regardless of the analysis group, the correlation between prediction and observation is very poor, with the maximum r^2 approaching 0.6, but most falling in the 0.0-0.2 range. In some cases, more significant relationships were evident for subsets of the dataset. For example, the four 1994 and newer non-catalyst MHDT engines considered alone exhibit a PM relation of:

$$g/bhp\text{-}hr = \underset{(sig=0.99)}{0.12} + \underset{(sig=0.99)}{0.1026}\,(odometer\ reading/100{,}000) \qquad (r^2=0.98)$$

This improved relationship is presented as a dashed line in Figure 6-10. Unfortunately, this relationship falls apart when otherwise equivalent catalyst equipped vehicles are considered. Additionally, the same level of data selectivity provides no consistent insight for other emission species or model year groups. Therefore, it is likely that this relationship is simply an artifact of inappropriate data selectivity and should be ignored in favor of the more robust relations (or more appropriately non-relations) presented in Table 6-3.

Model Year Group	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
Particulate Matter							
Pre-1990	6	0.68	0.99	-0.0949	0.68	0.24	0.68
1990-1993	9	0.45	0.99	-0.0913	0.79	0.22	0.79
1994 and Newer	17	0.18	0.99	0.0071	0.22	0.01	0.22
Oxides of Nitrogen							
Pre-1990	6	4.43	0.97	1.6084	0.91	0.55	0.91
1990-1993	9	4.88	0.99	-0.5623	0.76	0.19	0.76
1994 and Newer	17	4.72	0.99	0.3780	0.82	0.12	0.82
Carbon Monoxide							
Pre-1990	6	2.74	0.83	0.2802	0.23	0.03	0.23
1990-1993	9	1.38	0.99	-0.0205	0.04	0.00	0.04
1994 and Newer	17	0.79	0.99	0.3569	0.98	0.33	0.98
Hydrocarbons							
Pre-1990	6	0.27	0.99	0.0307	0.67	0.23	0.67
1990-1993	9	0.33	0.99	-0.1193	0.98	0.59	0.98
1994 and Newer	17	0.19	0.97	0.0176	0.18	0.00	0.18

"Obs" indicates the number of observations in the dataset. "Sig_x" indicates the statistical significance of the parameter "x."

TABLE 6-3. ODOMETER RELATIONS, ROUTIZED TEST D CYCLE

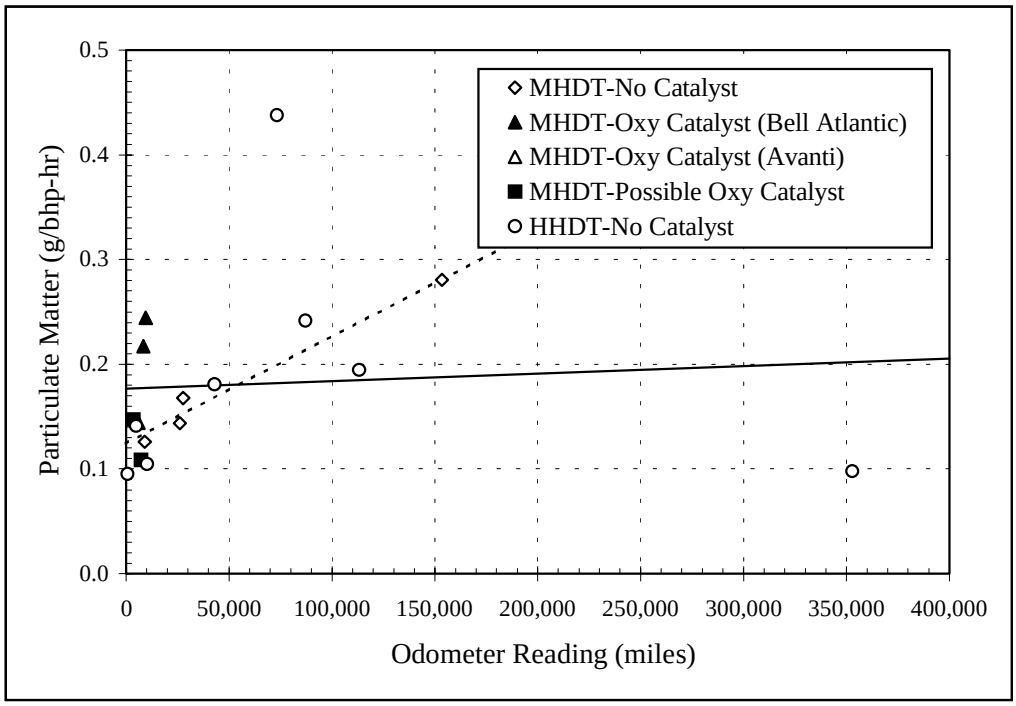


FIGURE 6-10. PM VS. ODOMETER, 1994 AND NEWER VEHICLES

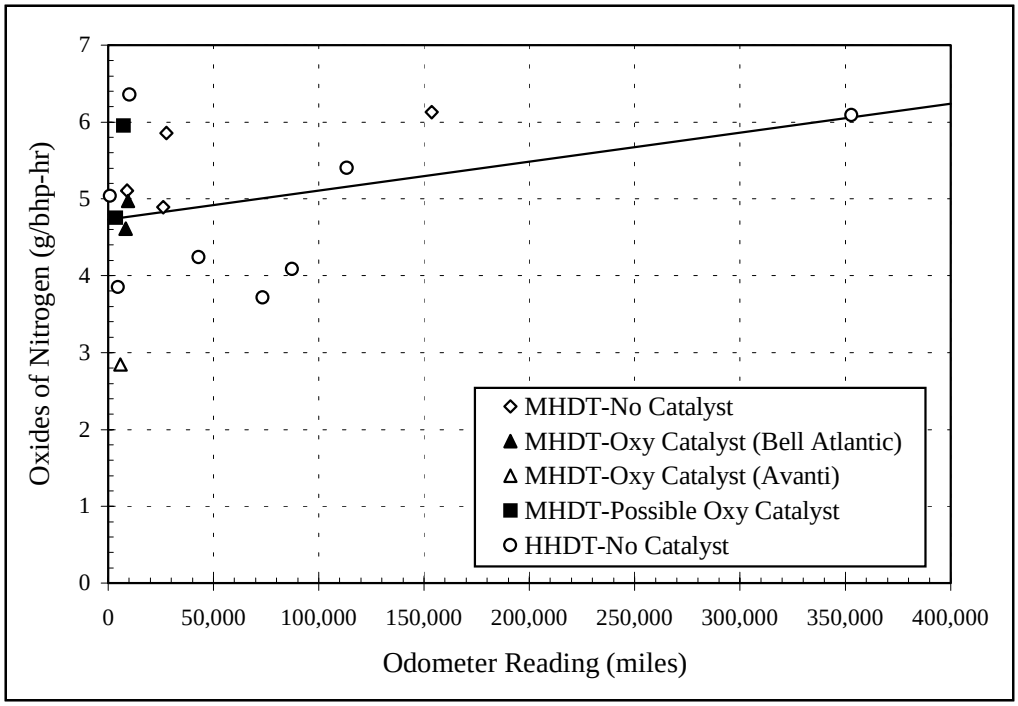


FIGURE 6-11. NO_x VS. ODOMETER, 1994 AND NEWER VEHICLES

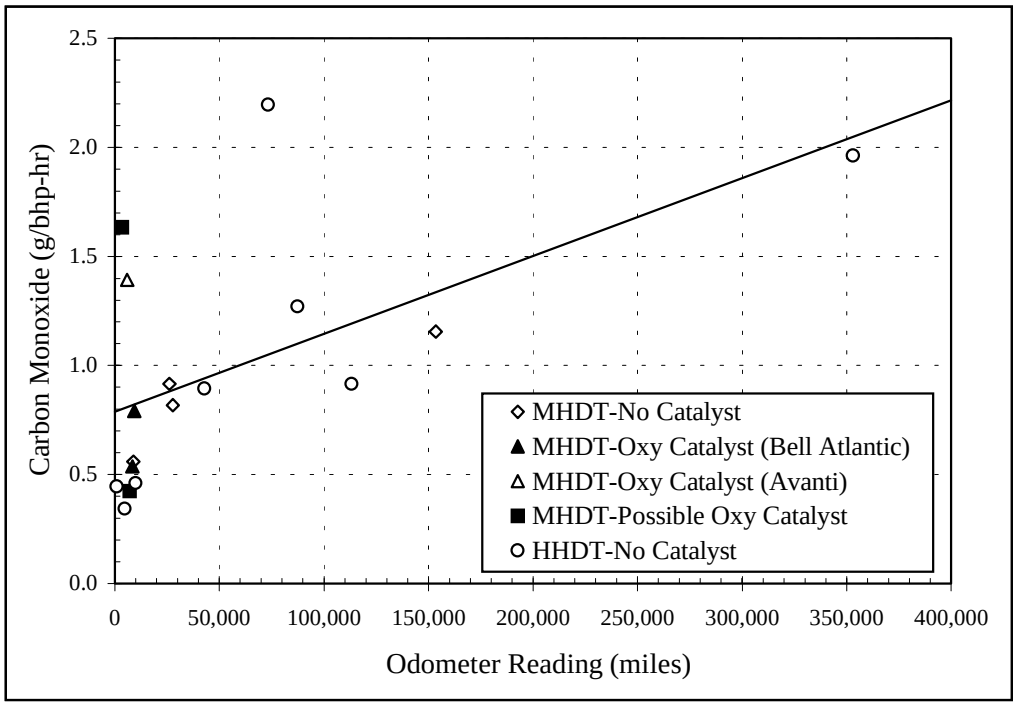


FIGURE 6-12. CO VS. ODOMETER, 1994 AND NEWER VEHICLES

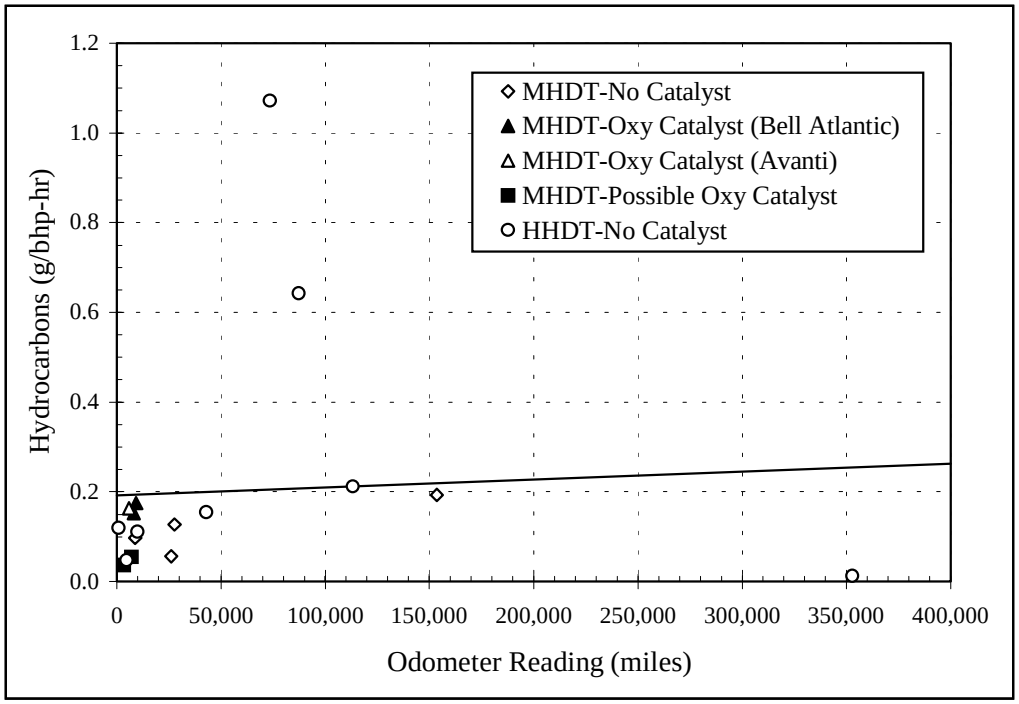


FIGURE 6-13. HC VS. ODOMETER, 1994 AND NEWER VEHICLES

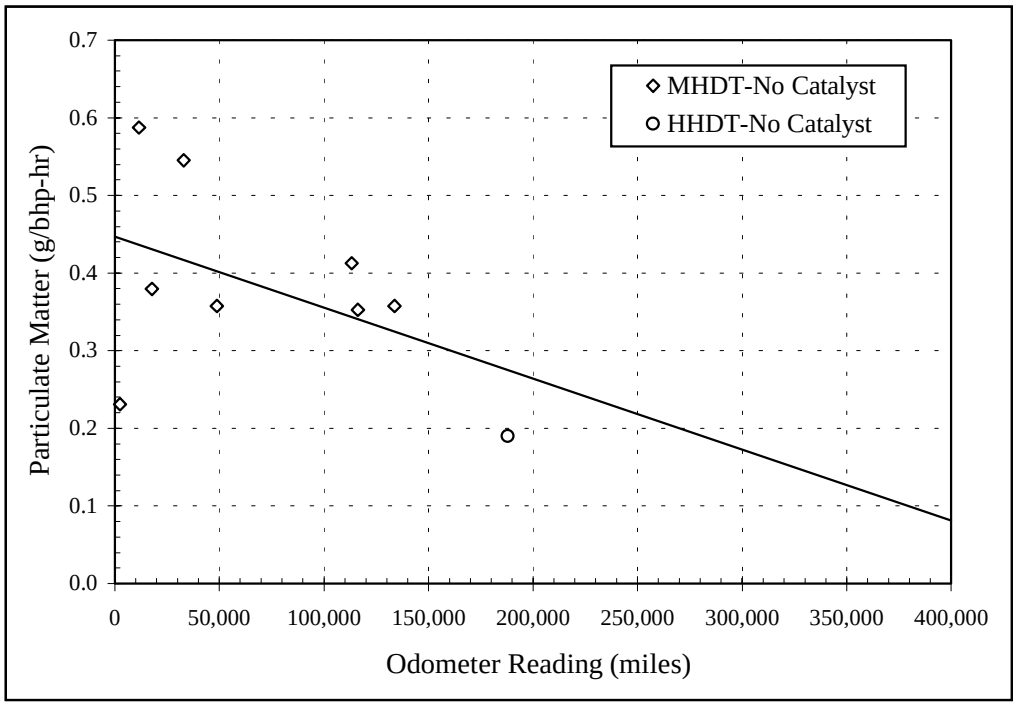


FIGURE 6-14. PM VS. ODOMETER, 1990-1993 VEHICLES

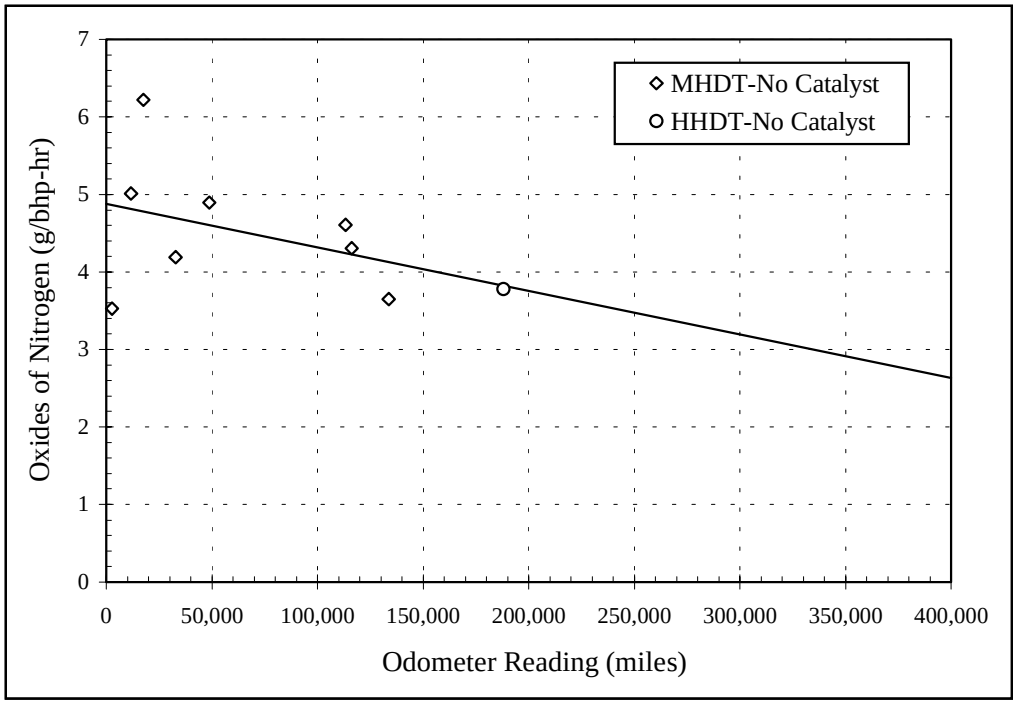


FIGURE 6-15. NO_x VS. ODOMETER, 1990-1993 VEHICLES

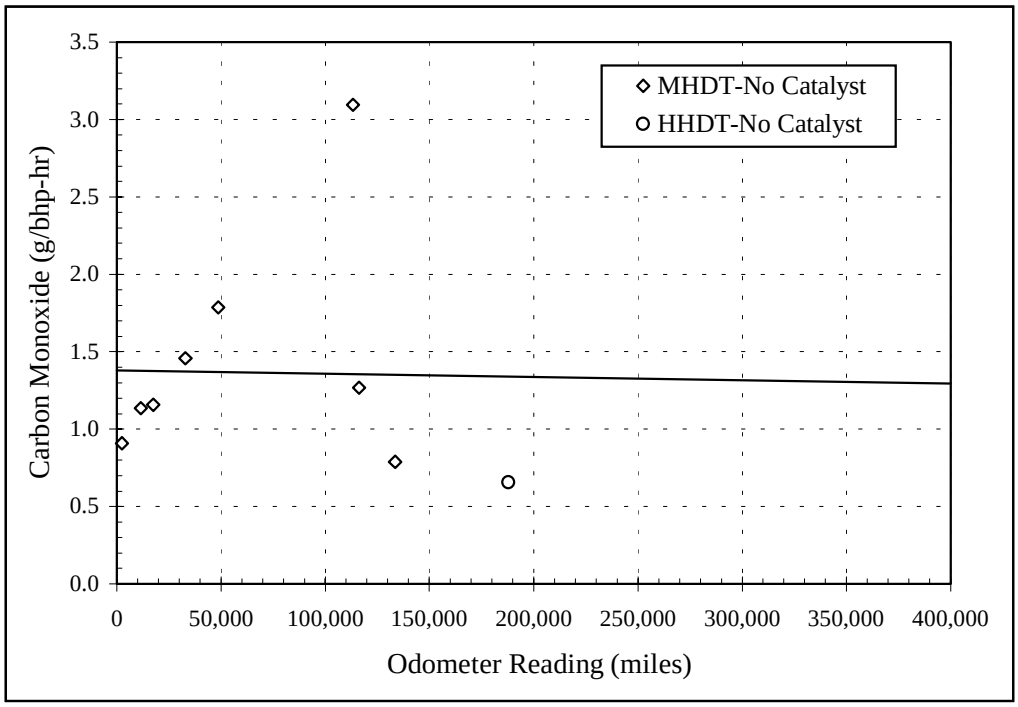


FIGURE 6-16. CO VS. ODOMETER, 1990-1993 VEHICLES

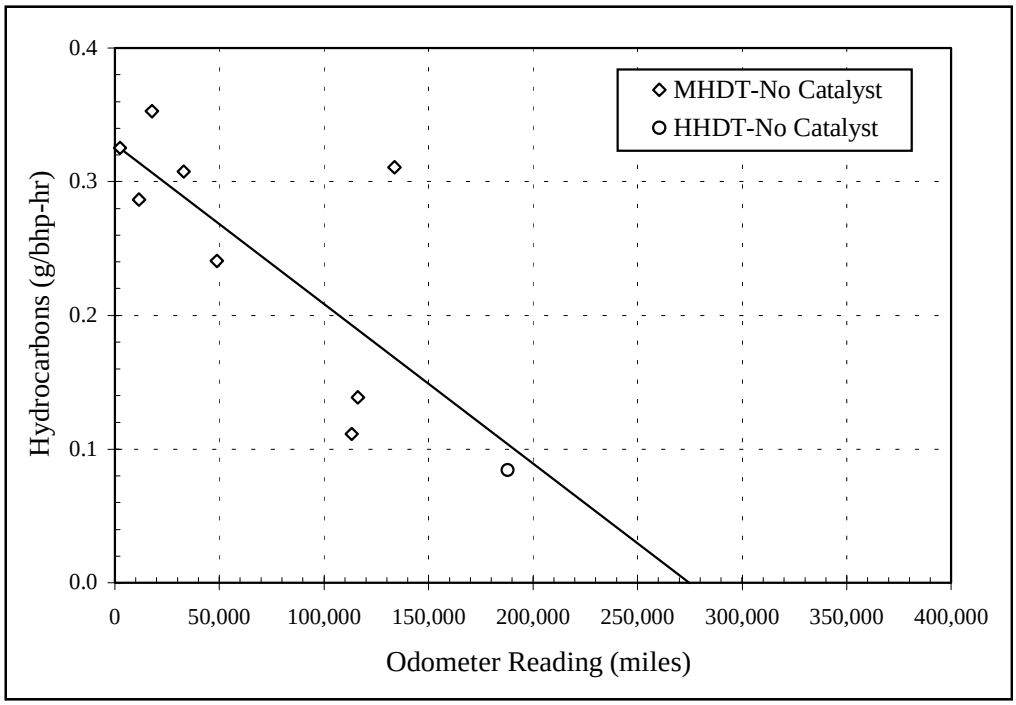


FIGURE 6-17. HC VS. ODOMETER, 1990-1993 VEHICLES

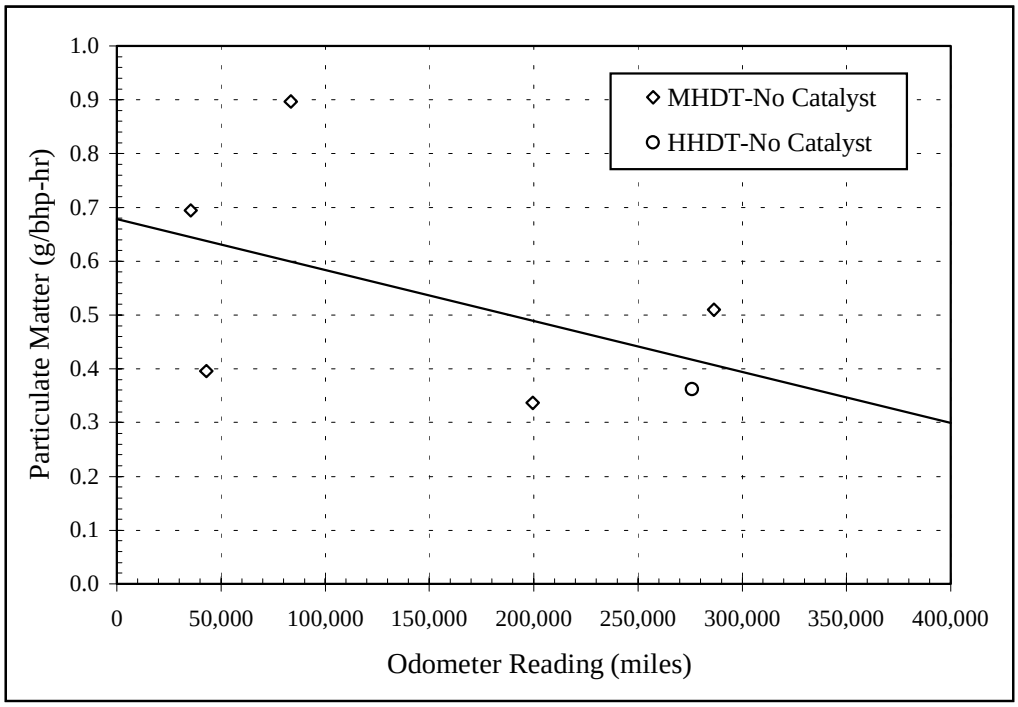


FIGURE 6-18. PM VS. ODOMETER, PRE-1990 VEHICLES

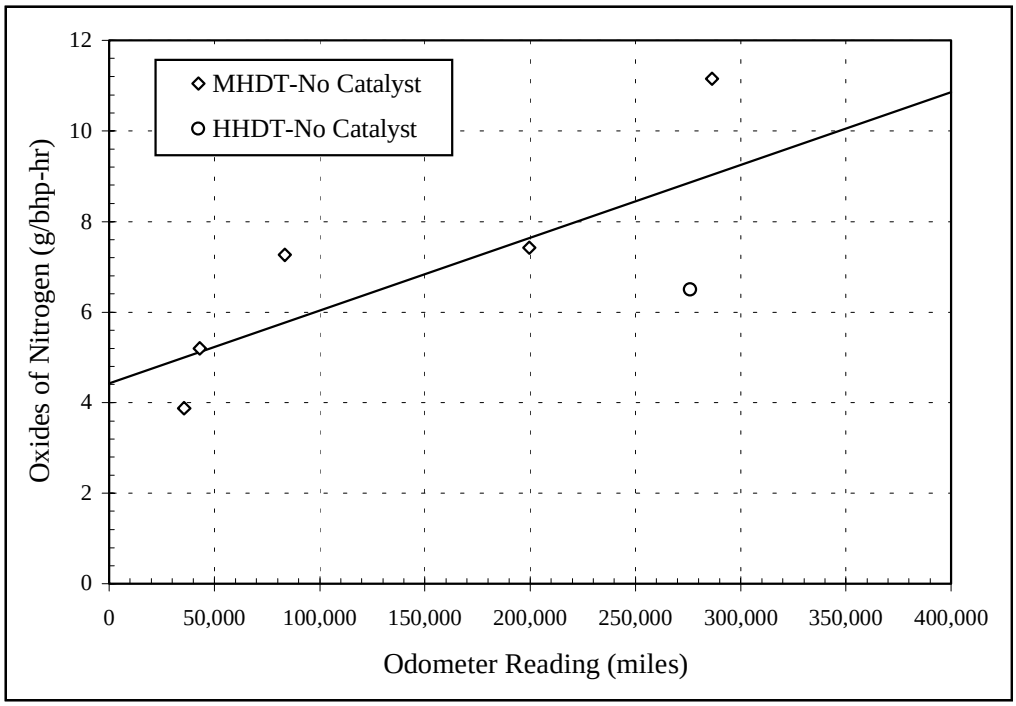


FIGURE 6-19. NO_x VS. ODOMETER, PRE-1990 VEHICLES

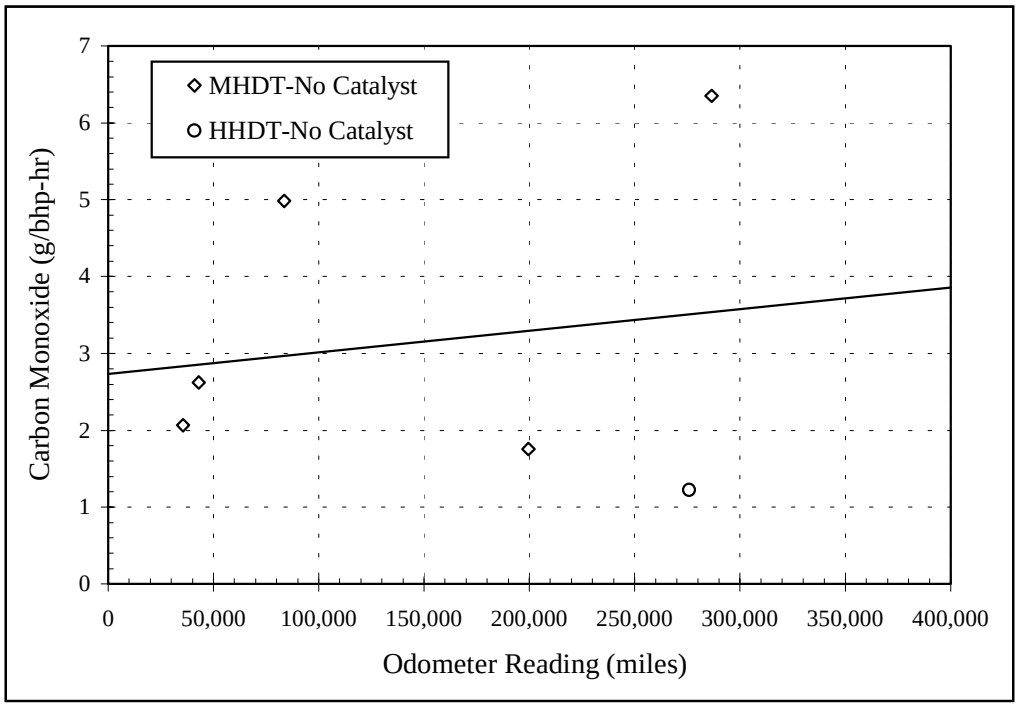


FIGURE 6-20. CO VS. ODOMETER, PRE-1990 VEHICLES

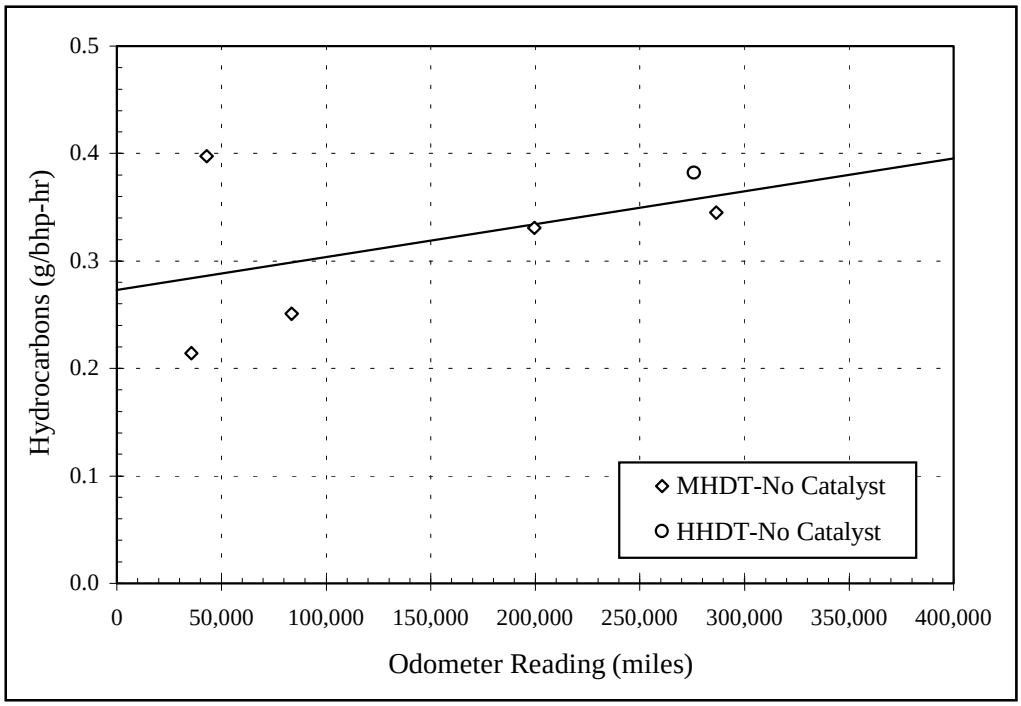


FIGURE 6-21. HC VS. ODOMETER, PRE-1990 VEHICLES

It should be emphasized that the inability to isolate an emissions deterioration component through the analysis of emissions versus vehicle odometer reading should not be interpreted as a positive indication that such deterioration does not exist, but as yet another indication that the limited size and scope of the analysis dataset is not sufficient to “tease out” all the nuances of heavy duty vehicle emissions behavior. In short, truck-to-truck emissions variability is sufficiently broad to preclude the ability to isolate the various contributing components of fleetwide emissions behavior. This in no way inhibits the ability to represent net fleetwide emissions behavior for the study sample, but does limit the ability to disaggregate that net behavior into its various component factors.

Oxidation catalyst equipped vehicle emissions behavior is a bit more troublesome. In total, four Bell Atlantic trucks were tested in this study, two known to be catalyst equipped and two suspected to be catalyst equipped. In addition, a single Avanti oxidation catalyst equipped vehicle was tested. The resulting three catalyst vehicle groupings are presented separately in Figures 6-10 through 6-13 (all catalyst equipped vehicle were of 1994 and newer vintage). As indicated, there is not a single emission species for which these five vehicles behave markedly better than non-catalyst equipped vehicles of similar mileage. In fact, for both PM and CO emissions, catalyst equipped vehicles appear to be among the worst performers.

While this study did not include any physical examination of vehicle components or followup analysis to evaluate catalyst performance, it appears as though the catalysts installed on study vehicles may be nonfunctional. It is doubtful that this nonfunctionality is intentional as there was no sign of tampering on any of the test vehicles, but practical influences such as a high fuel sulfur content may have accomplished similar results. In fact, sulfate formation might help to explain the high PM readings. If fuel sulfur is a contributing factor, its effect is dramatic as all catalyst equipped vehicles reflect less than 10,000 miles of operation (so that normal catalyst deterioration does not appear to be a viable explanatory influence). While follow-up study of these observations might be beneficial in evaluating the in-use emission rates of catalyst equipped vehicles, it appears for purposes of this study that these vehicles (at best) perform no better from an emissions standpoint than their non-catalyst counterparts.

6.6 AMBIENT CONDITIONS

Ambient conditions are a known influence on certain diesel emission rates. For example, humidity can influence NO_x formation rates through the effect of water vapor on overall combustion temperatures. Air density has also been shown to influence smoke opacity as well as the effective combustion air to fuel ratio. Unfortunately, in a field testing program such as that which forms the basis of this report, there is no mechanism for controlling ambient conditions. Moreover, although WVU collected basic ambient data prior to each vehicle test, that data has not been made available to EEA for analysis. However, there is reason to suspect that the influence of ambient conditions on observed vehicle test data is marginal.

First, all testing was performed in Brooklyn, New York over the two month period from mid-May through mid-July, 1999, during which the overall ambient conditions were consistently hot and humid. Although there were certainly day-to-day variations in temperature and humidity, those variations were not dramatic. Second, the range of emissions performance across test vehicles, as discussed in Sections 4 and 5 above, is substantially greater than one would expect were ambient conditions a major factor influencing emissions test results. In short, vehicle-specific influences seem to be substantially more significant.

Perhaps most important is the fact that even were ambient data available for analysis, there is no mechanism available to isolate any ambient impacts from those associated with vehicle-specific influences. There was no replicate testing performed on individual test vehicles while controlling for influences other than ambient conditions. As a result, the test data available for analysis considers all emissions influences in the aggregate. Were the test data sample large enough, a multi-variate statistical analysis might be able to ascribe a level of significance to the various factors of influence, but the current dataset in not sufficient to support this level of analysis. Therefore, at this time, it is not possible to assign a specific level of influence on measured test program emissions due to variations in ambient conditions, although that influence is expected to be small given the short test program time frame and relatively consistent observed conditions.

7. RELATIONS BETWEEN EMISSION SPECIES

Given difficulties in the measurement of diesel PM, the DEC was interested in the ability to predict PM emission rates using surrogate emission species such as CO. To investigate this potential, EEA examined Routized Test D cycle data as well as both 20 and 40 mph steady state data. For the Routized Test D cycle, NO_x versus CO data was also examined under the premise that any relationship between PM and CO would also imply a relationship between NO_x and CO given the known relationship between PM and NO_x. Finally, the relationship between snap acceleration cycle PM and opacity data was examined to determine the potential for direct PM reductions under an opacity-based inspection program.

Like all the other statistical analysis performed in this study, a simple linear regression technique was employed to determine inter-species relations. This technique is somewhat limited in that it ignores other potential influences and higher order relationships, but the level and range of data available for analysis currently acts as a constraint in the sophistication of allowable analysis. Nevertheless, the simple linear approach should provide an initial indication of not only whether a significant relationship might exist, but also the strength of that relationship. Subsequent analyses following the collection of more focused and robust test data might be used to more accurately define promising relations, but for this study all inter-species relationship analysis is based on linear regression analysis of the form:

$$\textit{g/bhp-hr of predicted species} = a + b\ (\textit{g/bhp-hr of measured species})$$

Table 7-1 presents the results of the analysis between the measured emissions species of the Routized Test D cycle. Figures 7-1 and 7-2 graphically present the strongest model year group relations for PM and NO_x respectively. For PM, a significant relationship between measured CO and PM over the Routized Test D cycle was found only for the 1994 and newer model year group. The coefficient for CO was significant at a 96 percent level of confidence, but the range of variability observed in the data is extensive as shown in Figure 7-1 and as indicated by the

Model Year Group	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
PM versus CO (CO independent)							
Pre-1990	6	0.37	0.90	0.0528	0.67	0.24	0.67
1990-1993	9	0.31	0.98	0.0540	0.58	0.10	0.58
1994 and Newer	17	0.10	0.98	0.7777	0.96	0.24	0.96
NO_x versus CO (CO independent)							
Pre-1990	6	4.07	0.95	0.8948	0.90	0.54	0.90
1990-1993	9	4.05	0.99	0.3041	0.51	0.07	0.51
1994 and Newer	17	5.36	0.99	-0.4286	0.65	0.06	0.65

"Obs" indicates the number of observations in the dataset. "Sig_x" indicates the statistical significance of the parameter "x."

TABLE 7-1. INTER-SPECIES RELATIONS FOR THE ROUTIZED TEST D CYCLE

poor correlation coefficient (r^2 = 0.24) of the regression. More importantly, the variability increases with measured emissions, so that high CO emissions are not a good indicator of high PM emissions. For example, in just the 17 vehicle 1994 and newer dataset that was analyzed for this report, there is about a ±70 percent variation in measured PM for similar CO measurements at about 2 g/bhp-hr. Pre-1994 vehicles exhibit no statistical relationship between PM and CO.

As shown in Table 7-1 the correlation between measured CO and NO_x over the Routized Test D cycle is at least as poor as that for PM versus CO. Only the pre-1990 model year group indicates a relationship between measured CO and NO_x at a 90 percent level of confidence. However, even for this vehicle group the variation between predicted and measured emissions is large (r^2 = 0.54), although as indicated in Figure 7-2, this variation is more constant across the range of measured CO than was the case for PM versus CO. For 1990 and newer model year vehicles, NO_x and CO are statistically independent.

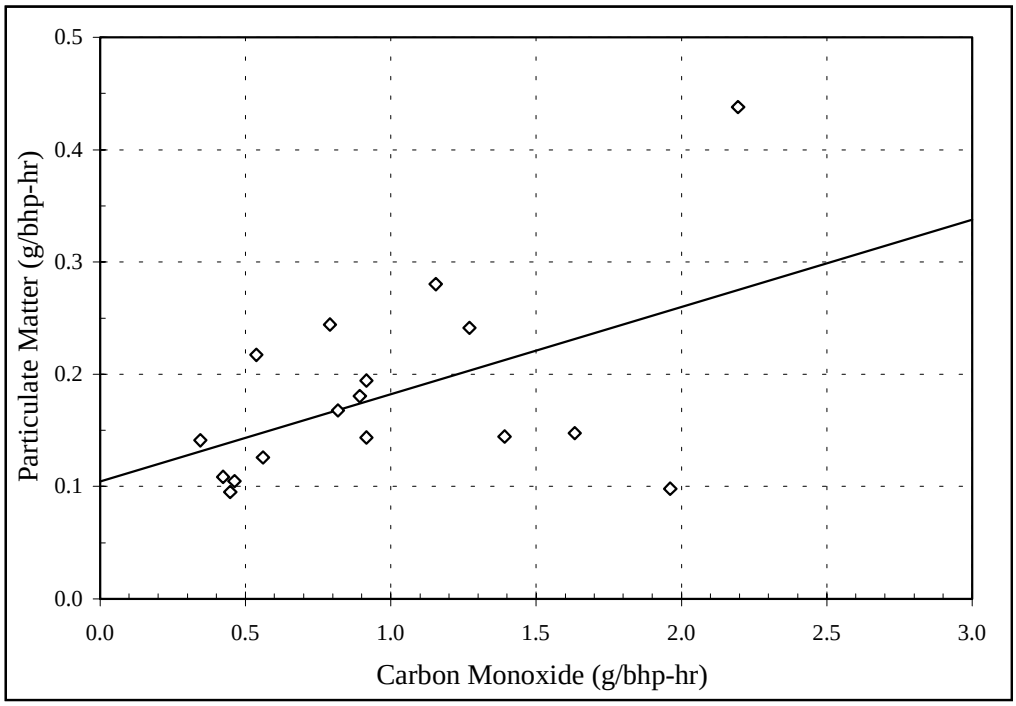


FIGURE 7-1. ROUTIZED TEST D PM VS. CO, 1994 AND NEWER VEHICLES

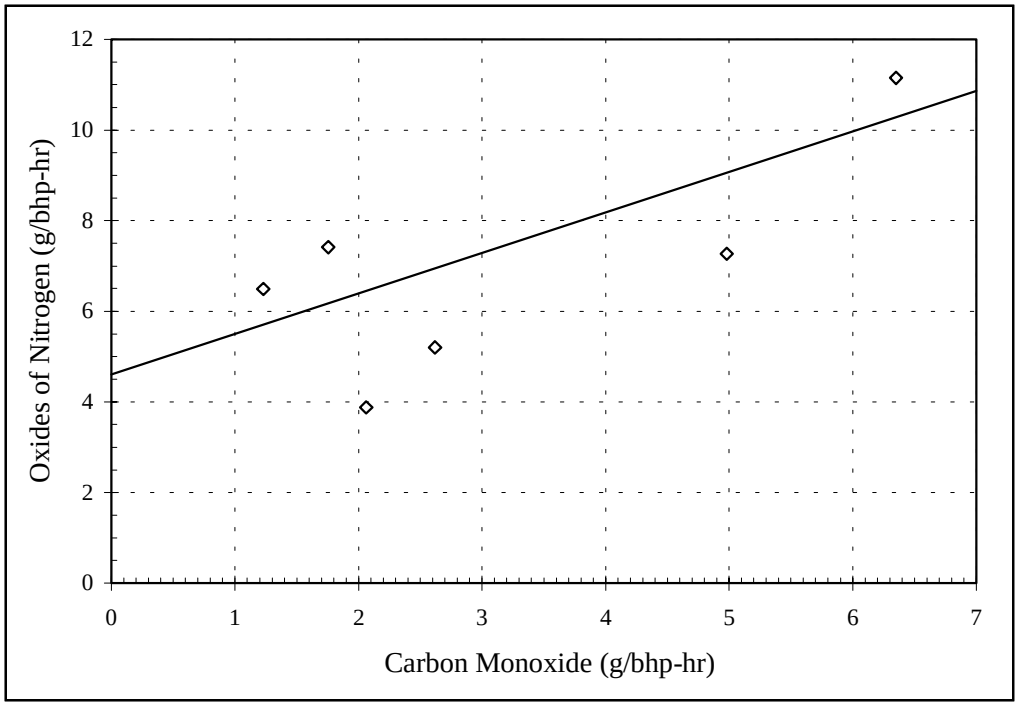


FIGURE 7-2. ROUTIZED TEST D NO_x VS. CO, PRE-1990 VEHICLES

Tables 7-2 and 7-3 present the results of the analysis of steady state cycle PM versus CO. As was the case with the Routized Test D cycle, the statistical relationship between the species over both the 20 and 40 mph cycles is poor. The lone exception is for the 1990-1993 model year group under the 20 mph cycle, where a significant relationship with reasonable correlation (r^2 = 0.84) is observed. However, from Figure 7-3, it is obvious that the slope of this relationship is dictated by a single datapoint (3.3 g/bhp-hr CO, 0.82 g/bhp-hr PM). Removing that datapoint reduces the significance of the apparent relationship to zero (there is only a 4 percent level of confidence that the slope is nonzero). Therefore, based on the analysis dataset constructed for this study, it does not appear that CO emissions are a good predictor of PM.

Model Year Group	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
Pre-1990	8	0.24	0.82	0.0351	0.41	0.05	0.41
1990-1993[1]	7	-0.34	0.96	0.3288	0.99	0.84	0.99
1990-1993[2]	6	0.17	0.76	0.0042	0.04	0.00	0.04
1994 and Newer	17	0.19	0.99	0.0039	0.10	0.00	0.10

"Obs" indicates the number of observations in the dataset. "Sig_x" indicates the statistical significance of the parameter "x."

1. Includes all data.
2. Excludes one datapoint that dominates the apparent relationships.

TABLE 7-2. PM VS. CO (CO INDEPENDENT) OVER THE 20 MPH CYCLE

Model Year Group	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
Pre-1990	8	0.31	0.89	0.0334	0.15	0.01	0.15
1990-1993	9	0.33	0.97	-0.0189	0.14	0.00	0.14
1994 and Newer	18	0.13	0.99	0.0542	0.57	0.04	0.57

"Obs" indicates the number of observations in the dataset. "Sig_x" indicates the statistical significance of the parameter "x."

TABLE 7-3. PM VS. CO (CO INDEPENDENT) OVER THE 40 MPH CYCLE

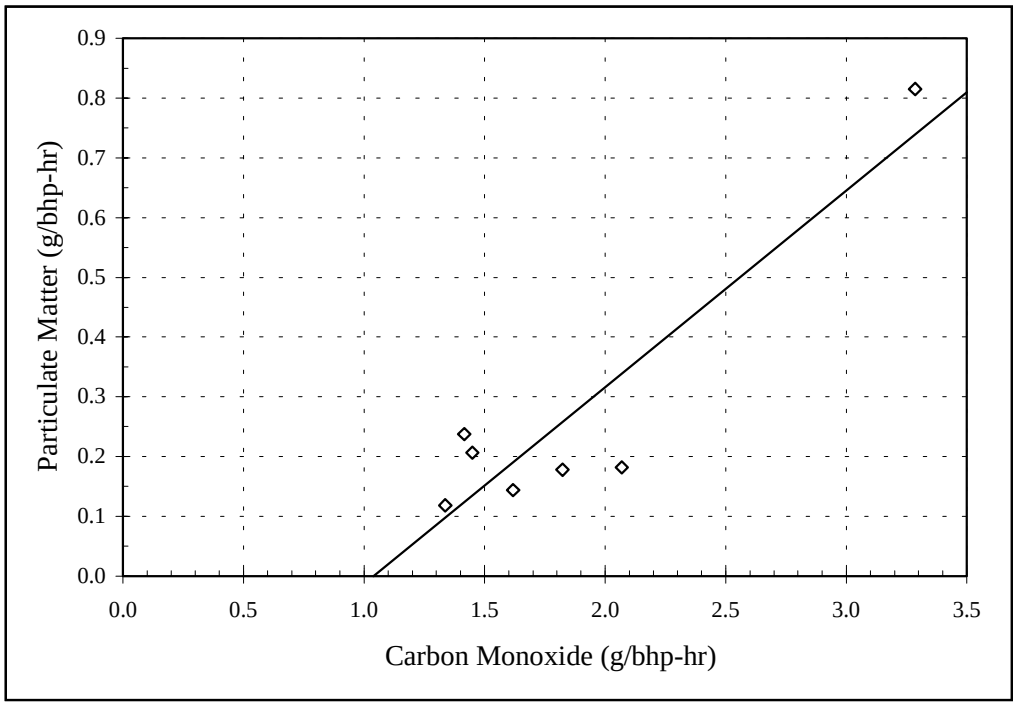


FIGURE 7-3. 20 MPH STEADY STATE PM VS. CO, 1990-1993 VEHICLES

Table 7-4 presents the results of an analysis of PM emissions versus measured opacity over the snap acceleration cycle (using the J1667 "peak" measurement method). Although this study presents an interesting opportunity to investigate the direct relationship between opacity and PM mass, the importance of this relationship should not be overstated. As indicated in Table 7-4 and Figure 7-4, a very strong relationship between PM and opacity is evidenced for the pre-1990 (mechanically controlled) engine population. A statistically significant relationship also exists between PM and opacity for 1994 and newer engines, but variability is too high to allow accurate predictions of PM from measured opacity. These are important findings that provide a level of basic support for ongoing opacity-based efforts toward controlling PM emissions, but the statistical relationships (or more importantly perhaps the lack thereof) should be kept in perspective.

Model Year Group	Obs	a	Sig_a	b	Sig_b	r^2	Sig_F
Pre-1990	7	0.67	0.99	0.0147	0.99	0.89	0.99
1990-1993	9	0.66	0.88	0.0094	0.33	0.03	0.33
1994 and Newer	13	0.20	0.87	0.0324	0.96	0.33	0.96

"Obs" indicates the number of observations in the dataset. "Sig_x" indicates the statistical significance of the parameter "x."

TABLE 7-4. PM VS. CO (CO INDEPENDENT) OVER THE 40 MPH CYCLE

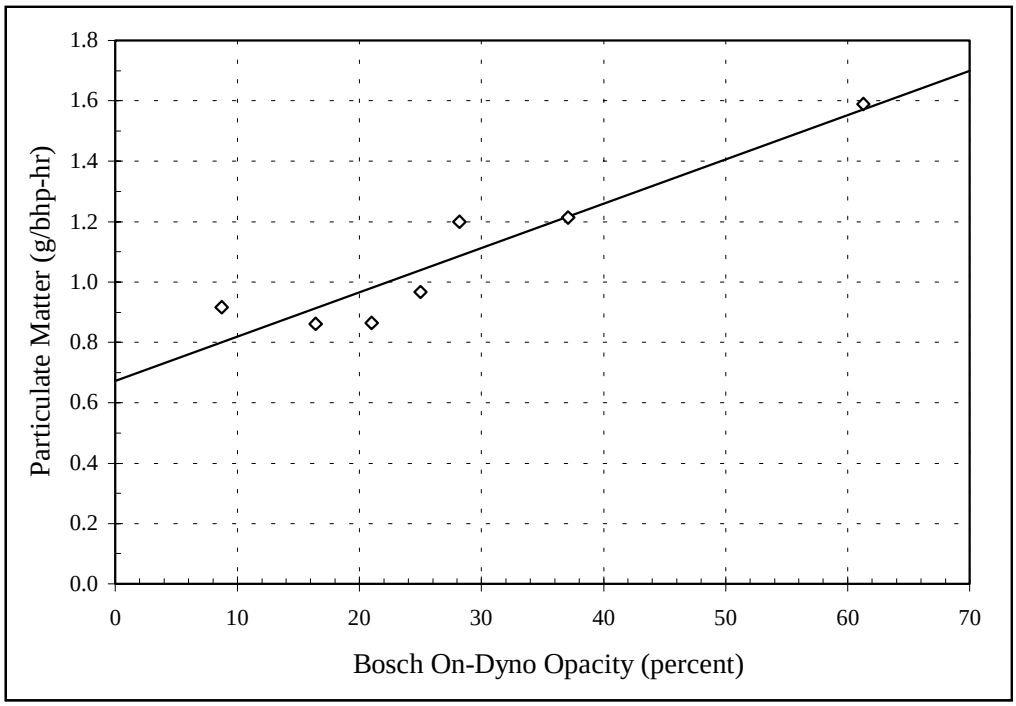


FIGURE 7-4. SNAP ACCELERATION PM VS. OPACITY, PRE-1990 VEHICLES

Opacity-based inspection programs are not designed on the basis of any direct correlation between measured opacity and PM, but rather on the premise that opacity-based inspections can successfully identify malperforming vehicles. Depending on the specific malperformance, the level of PM reduction expected due to vehicle repair can vary, so it is not unrealistic to expect considerable variability in PM emissions across vehicles for any given opacity measurement. Nevertheless, repairs to opacity-increasing malperformances have consistently been demonstrated to reduce PM emissions (albeit at levels that vary with the specific malperformance). Therefore, the lack of a *direct* correlation between measured opacity and PM is *not* an indication that current efforts targeting the control of PM emissions through opacity-based inspection programs are misguided.

8. EMISSION REDUCTIONS FROM POTENTIAL I/M PROGRAMS

8.1 OVERVIEW

Analysis of the potential of an Inspection/Maintenance (I/M) program to reduce emissions in the NYMA is required as part of the overall work effort. As noted in the previous sections, the data generated under the test program was on a relatively small sample of trucks randomly selected from the heavy-duty truck fleet operating in the NYMA. Only a few of the selected vehicles were tested on inspection type short tests of interest, such as the lug-down cycle. Hence, the data generated in this testing effort is insufficient by itself to conduct an analysis of "excess" emissions and potential reductions available from an I/M program.

The approach taken by EEA was to combine the data from this test program with existing data and models, to estimate the benefits of an inspection program for Heavy-Duty Diesel Trucks (HDDTs). Available data on I/M benefits covers only two short tests: the J1667 snap acceleration test, and the lug-down test. The benefits of these tests over a limited range of pass/fail standards have been estimated in previous modeling efforts for the ARB by Radian (1998), and by EEA in 1991 and 1994. In general, the models relied on data on from pre-1990 heavy-duty engines, and these data were extrapolated to post-1990 engines using engineering judgement.

In this effort, we have evaluated the baseline "no I/M" emissions using data on NYMA truck populations and VMT from the Task A(2) report by Jack Faucett Associates (JFA). The benefits of I/M have been estimated for the J1667 and lug-down procedures using the analysis methodology (updated with data from this test program) as described below.

8.2 METHODOLOGY

The methodology to evaluate the emission benefits of the inspection program relies on the Radian malperformance model developed for ARB.[1] The model was updated by EEA and has

been validated on a limited basis for pre-1990 engines, by EEA.[2] No validation had been attempted on 1990 and later engines' emissions, since there was very little in-use emissions data from such engines prior to this effort. The Radian malperformance model is required for two reasons:

- The current EPA MOBILE5b and PART5 models assume zero deterioration of emissions for most modern HDD engines, thereby implying no benefit for I/M.
- The links between emissions, malperformances and inspection are direct in the Radian model.

While the Radian model and its updates have been comprehensively documented in earlier reports, a brief summary of the methodology is provided here. Emission increases from diesel engines, with age or mileage, are associated with a range of component malperformances only. This implies that a well-maintained engine should have near zero emissions deterioration over its useful life, and this implication has been confirmed using certification data from engine durability tests. This result will remain true as long as engines do not utilize aftertreatment devices, such as catalysts, which lose emission conversion efficiency with age. To date, very few HDD engines employ any aftertreatment devices, and this is likely to be the case to at least 2004, and possibly, to 2008. Light-heavy duty diesels employed in trucks under 18,000 lbs GVW employ oxidation catalysts, but their function is quite limited and their deterioration small. As a result, the basic premise of the model is correct for the period analyzed.

The Radian model has a comprehensive list of malperformances that has been developed from direct repair evidence from ARB repair studies and by consultation with engine manufacturers. The rate at which they occur is based on the ARB repair studies and is designated as r_k for each malperformance type, k. Each malperformance type has an effect on the emissions of pollutant i, that is labeled ΔE_{ik}, which represents the <u>incremental</u> emission effect (either as a percent of baseline emissions or as an absolute number) due to the presence of malperformance type k. Hence the <u>excess</u> emissions are given by

$$\Delta E_i = \Sigma \left(r_k \cdot \Delta E_{ik.} \right)$$

The Radian model data on malperformance types, rates of occurrence and emission increases are documented in Appendix A in three spreadsheets, for light-heavy, medium-heavy and heavy-heavy-duty engines. ΔE_i is reported as a percent increase in emissions from the zero-mile level. Here, the rates (r_k) of malperformance are fleet averages, and are associated with the rate at the mid-point of a vehicle's useful life. The useful life estimates are about 180,000 miles for light-heavy engines, 300,000 miles for medium-heavy engines, and 500,000 miles for heavy-heavy-duty engines. (Using the VMT weights implied in MOBILE5b, the average mid-point of the useful life is 190,000 miles for the fleet.)

The Radian model directly indicates the percentage increase in emissions at the mid-point of HDDV useful life, and it is assumed that the deterioration occurs linearly with mileage, as is common in all EPA emission inventory models. The impact of inspection and repair is modeled as a reduction in the rate of occurrence (r_k) of malperformances. This reduction is calculated from the malperformance identification rate, which is a function of the test and standard used, and a repair rate that represents the percent of properly repaired vehicles. The identification rate of each malperformance has been developed in earlier studies by EEA for the California Bureau of Automotive Repair at only one cutpoint (55 percent for the J1667 test, and 15 percent opacity for the lug-down test for pre-1990 engines).[3] These rates can be scaled by the observed failure rate at different cutpoints from the opacity distribution curves of a random sample of trucks, to obtain rates for any arbitrary set of cutpoints, assuming proportional changes in detection rates.

It should be noted that there are several assumptions required to complete the calculations of emission benefits, starting from the "no-I/M" baseline, as detailed below. The Radian model based rates of occurrence of malperformances are for a "no I/M program" situation. The presence of any type of enforced I/M has a deterrent effect that leads to better maintenance and less tampering (this effect is likely independent of test type and standard). Studies conducted in California before and after the introduction of the Heavy-Duty Vehicle Inspection Program indicated that deterrence effects reduced malperformances (and failure rates) by one-third,[4] and this 33 percent reduction is likely to happen in the NYMA if any new program is introduced. However, all calculations of benefits are referenced to a "no I/M program" baseline, so that all

comparisons are consistent. In addition, the analysis assumes that any I/M program will address all HDDTs that operate in the NYMA, including those registered out-of-state.

Other minor assumptions are noted in the appropriate subsections that detail the benefit calculation.

8.3 "NO-I/M" BASELINE

The baseline emissions inventory for the NYMA was developed using the MOBILE5b and PART5 models which are EPA's "official" emissions inventory models. Rather than attempt to correct the models themselves (which is a complex undertaking), the understatement of heavy-duty diesel vehicle emissions is estimated (using the Radian model) as a percentage correction to the MOBILE5b/PART5 model output. According to the JFA report, the areawide total 1998 VMT was 2514.75 million miles due to heavy-duty diesel vehicles. "Baseline" estimates of areawide inventory attributable to HDDVs in 2005 are as follows in tons/day:

HC:	18.1
NO_x:	81.9
PM-10:	4.2

It should be noted that the MOBILE5b and PART5 models used to estimate these inventories contain no estimate of excess emissions due to malperformance.

The baseline estimates of "excess" emissions using the Radian Model are shown in Table 8-1 and are obtained directly from the detailed spreadsheets in Appendix A. Actual inputs for the VMT weighted "all years" calculations require absolute emission rates and mileage accumulation rates (MAR) by model year, and these are shown in Table 8-2. The "zero-mile" emission rates are derived from MOBILE5b, while the absolute deterioration in grams/mile per 10k mile is assumed as zero in MOBILE5b. Registration fractions as a function of vehicle age, and MAR values are from MOBILE5b, although total VMT was matched to the JFA report data.

TABLE 8-1
EXCESS EMISSIONS CALCULATION

Model Year Group	Vehicle Type	Excess HC (percent)	Excess NO_x (percent)	Excess PM-10 (percent)	In-Group VMT Weight (percent)	Overall VMT Weight (percent)
1981-1987	LHDD	80.7	0.1	86.6	8.9	0.4
	MHDD	83.0	4.0	128.9	28.4	1.3
	HHDD	70.7	2.7	136.6	62.7	2.8
	All HDD	75.1	2.8	130.0	100.0	4.5
1988-1990	LHDD	82.3	1.6	84.0	8.2	0.4
	MHDD	78.9	6.5	114.0	26.7	1.2
	HHDD	61.3	8.3	118.2	65.1	2.8
	All HDD	67.8	7.2	114.3	100.0	4.4
1991-1993	LHDD	134.0	10.2	157.1	9.2	1.1
	MHDD	126.1	11.1	160.4	25.0	2.9
	HHDD	81.0	19.4	153.7	65.8	7.6
	All HDD	97.1	16.5	155.7	100.0	11.6
1994-2005	LHDD	135.4	11.7	169.4	13.2	10.5
	MHDD	127.3	12.2	168.2	20.7	16.5
	HHDD	81.4	19.4	152.6	66.0	52.6
	All HDD	98.0	16.9	158.0	100.0	79.6
All	LHDD	132.0	10.9	163.2	12.3	12.3
	MHDD	122.0	11.3	162.0	21.8	21.8
	HHDD	80.0	18.2	150.5	65.8	65.8
	All HDD	95.6	15.8	154.6	100.0	100.0

TABLE 8-2
MOBILE5b/PART5 BASELINE DATA FOR HDDs

	HC		NO_x		PM-10		Travel		
Model Year	Zero Mile Rate	Deterioration Rate	Zero Mile Rate	Deterioration Rate	Zero Mile Rate	Deterioration Rate	Annual Mileage	Cumulative Mileage	Registration Fractions
	(g/mi)	(g/mi/10K mi)	(g/mi)	(g/mi/10K mi)	(g/mi)	(g/mi/10K mi)	(2005)	(2005)	
1981	3.170	0.000	21.470	0.000	2.015	0.000	11396	570925	0.016
1982	2.780	0.000	18.840	0.000	1.910	0.000	12025	559529	0.005
1983	2.660	0.000	18.060	0.000	1.950	0.000	12692	547504	0.007
1984	2.820	0.000	19.080	0.000	1.865	0.000	13399	534812	0.009
1985	2.590	0.000	17.530	0.000	1.799	0.000	14150	521413	0.011
1986	2.280	0.000	17.560	0.000	1.809	0.000	14947	507263	0.016
1987	2.230	0.000	17.180	0.000	1.709	0.000	15792	492316	0.025
1988	2.180	0.000	16.770	0.000	1.186	0.000	16689	476524	0.029
1989	2.180	0.000	16.770	0.000	1.170	0.000	17641	459835	0.024
1990	2.130	0.000	11.650	0.000	1.160	0.000	18652	442194	0.020
1991	2.100	0.000	9.370	0.000	0.695	0.000	19727	423542	0.045
1992	2.100	0.000	9.370	0.000	0.672	0.000	20869	403815	0.057
1993	2.100	0.000	9.370	0.000	0.665	0.000	22083	382946	0.055
1994	2.100	0.000	9.370	0.000	0.213	0.000	23374	360863	0.065
1995	2.100	0.000	9.370	0.000	0.212	0.000	24748	337488	0.053
1996	2.100	0.000	9.370	0.000	0.211	0.000	26211	312740	0.051
1997	2.100	0.000	9.370	0.000	0.211	0.000	27769	286529	0.041
1998	2.100	0.000	7.490	0.000	0.210	0.000	29428	258760	0.040
1999	2.100	0.000	7.490	0.000	0.210	0.000	31198	229331	0.061
2000	2.100	0.000	7.490	0.000	0.209	0.000	33085	198134	0.072
2001	2.100	0.000	7.490	0.000	0.214	0.000	35098	165049	0.067
2002	2.100	0.000	7.490	0.000	0.214	0.000	37248	129950	0.067
2003	2.100	0.000	7.490	0.000	0.214	0.000	39545	92702	0.067
2004	2.100	0.000	7.490	0.000	0.214	0.000	42000	53157	0.067
2005	2.100	0.000	7.490	0.000	0.215	0.000	44625	11156	0.034

The modifications made to the Radian model were to ensure that the forecast emission rates from a combination of MOBILE5b base rates and Radian model predictions of excess emission rates were reasonably comparable to the observed emission rates. Table 8-3 shows the emission rates of pre-1990, 1990 – 1993 and 1994 – 1997 vehicles as measured in the program. (Since only one heavy-heavy duty truck was tested in each of the pre-1990 and 1990-1993 model year groups, this data is not displayed in Table 8-3). In comparison to the MOBILE5b emission rates, NO_x and PM appear to be significantly higher than MOBILE5b levels but HC emissions from MOBILE5b are very high, almost six times the observed rate for 1994+ trucks. This is because MOBILE5b assumes that 1994+ engines are certified at 0.7 g/BHP-hr relative to the 1.3 standard. In reality, the engines are certified at 0.1 to 0.2 g/BHP-hr, readily explaining the MOBILE5b error.

Since all adjustments relative to MOBILE5b were to estimate "excess" emissions due to deterioration, malperformance and tampering, no modification to MOBILE5b's incorrect HC emission estimate has been made in the inventory calculations reported in this section. However, the Radian model's predictions for excess PM emissions of 1994+ trucks were adjusted to match the measured values in the program. The Radian model predicted increases of about 280 percent relative to the 0.07 g/BHP-hr average certification level for 1994 and later model year engines, so that the Radian model implied an actual emission rate of 0.27 g/BHP-hr. However, measured values were in the 0.19 g/BHP-hr range, so the model's over predictions were corrected. The other predictions of the Radian model appeared to be correct relative to the sample averages in an order of magnitude sense; no corrections were made to the model to match measured averages due to the small sample sizes for the pre-1990 and 1990-1993 model year group test results.

The MOBILE5b model understates HDD NO_x emissions by about 16 percent, HC emissions by 95 percent and PM emissions by 155 percent based on the Radian model, suitably modified for NYMA calculations. (Although the PM excess emissions percentage appears very large, it should be noted that in 2005, the vast majority of engines in the fleet would be required to meet very low certification of standards of 0.1 g/BHP-hr, which is 80+ percent below pre-1991 engine emission levels).

TABLE 8-3
AVERAGE EMISSION BY MODEL YEAR
GROUP FROM TEST PROGRAM
(grams/mile)

	HC	**NO_x**	**PM**
Pre-1990 MHDT	0.94	19.80	1.74
1990-1993 MHDT	0.71	13.35	1.30
1994+ MHDT	0.38	13.09	0.54
1994+ HHDT	1.07*	21.25	0.73

* includes one very high HC emitter.

8.4 EMISSIONS BENEFITS OF I/M

Due to data availability limitations, an I/M program covering all heavy-duty trucks operating (as opposed to being registered) in the NYMA was modeled. For simplicity, we have assumed 100 percent compliance although any particular level of compliance can by easily modeled from the data presented in this report. The I/M program was assumed to use:

- a J1667 test with a 55 percent peak smoke opacity standard for pre-1990 vehicles and 40 percent standard for 1990 and later vehicles;
- a lug-down test with continuous smoke opacity standard at 15 percent for pre-1990 vehicles and 10 percent for 1990 and later vehicles;
- a program incorporating both tests.

For simplicity, it was also assumed that all repairs are done correctly and that a $1500 cost ceiling applies to the repair.

A detailed analysis of the lug-down test and snap test capability to identify malperformances at the California cutpoints for the J1667 test and at the 15 percent cutpoint for lug-down test has been conducted by EEA for the California Bureau of Automotive Repair. The results of that study are summarized in Table 8-4, which shows identification rates by malperformance type for the two test types. Repair rates are derived from the repair studies conducted by ARB, and are limited by the $1500 cost ceiling. As a result, repair of serious injector problems and replacement of turbochargers do not occur on some fraction of the fleet due to the costs exceeding the ceiling, while engine failures requiring rebuild (a $4000 to $6000 repair) do not occur at all as a result of I/M. We have assumed that similar cost ceiling will apply to the I/M program modeled for NYMA.

The identification and repair rates for malperformances are input into the Radian model to estimate excess emissions in the presence of an I/M program, where all vehicles are inspected and repaired as necessary (i.e., 100 percent compliance). The analysis also accounts for the deterrence effect of an I/M program, by assuming that malperformances occur at a rate 33 percent lower than the rates presented in Appendix A. The emissions benefits of the deterrent effect are estimated by zeroing out one-third of the malperformances since these

TABLE 8-4
DEFECT IDENTIFICATION AND REPAIR RATES

Defect	Identification Rate			Repair Rate
	J1667 Test	Lugdown Test	J1667 & Lugdown	
Timing Advanced	0%	0%	0%	0%
Timing Retarded	0%	20%	20%	0%
Minor Injector Problems	0%	35%	35%	0%
Moderate Injector Problems	60%	80%	80%	100%
Severe Injector Problems	85%	100%	100%	70%
Puff Limiter MissSet	60%	0%	60%	100%
Puff Limiter Disabled	100%	0%	100%	100%
Maximum Fuel Stop Set High	100%	50%	100%	100%
Clogged Air Filter	60%	60%	60%	100%
Wrong/Worn Turbo	85%	50%	85%	70%
Intercooler Clogged	0%	0%	0%	0%
Other Air Problems	85%	50%	85%	70%
Engine Mechanical Failure	100%	100%	100%	0%
Excess Oil Consumption	60%	20%	60%	0%
Electronics Failed	100%	100%	100%	100%
Electronics Tampered	0%	50%	50%	0%
Catalyst Removed	100%	100%	100%	100%
Trap Removed	100%	100%	100%	100%
EGR Disabled	0%	0%	0%	0%

malperformances never happen in the first place, and are an important contributor to overall I/M program benefits.

Table 8-5 shows the reduction in emissions attributable to using different tests (in the potential program). The numbers indicated are calculated for calendar year 2005, and are all relative to the MOBILE5b projected baseline emissions. The excess emissions in 2005 over the MOBILE5b estimate is 15.8 percent for NO_x, 95.6 percent for HC, and 154.6 percent for PM. The presence of any I/M program results in a deterrent effect that reduces these excess emissions by 33 percent for the fleet covered by these programs (which we have assumed is 100 percent of the total). For example, the deterrent effect for HC emissions is 5.8 tons per day, so that emissions decline from 35.4 tons per to 29.6 tons per day due to the deterrent effect alone.

The actual benefits of vehicles being failed by the inspection and properly repaired under the $1500 cost ceiling is shown for three different tests, (1) the J1667, (2) the lug-down and (3) both the J1667 and lug-down tests. The benefits in Table 8-5 include the deterrent effect, so that the following interpretation should be given to the values in the table. For example, the baseline excess HC emissions is 95.6 percent above MOBILE5b estimates. With the lug test, the excess emissions are reduced by 68.7 percent so that excess emissions decline from 17.3 tons per day to 5.4 tons per day, with the actual lug test providing about 50 percent of the reduction while the deterrent effect provides the other 50 percent. Note that the NO_x emissions benefits are derived almost <u>completely</u> from the deterrent effect, and not from the identification and repair of vehicles. In fact, some fraction of repairs on vehicles failing for excessive smoke will actually increase NO_x emissions.

The results of this modeling excersize should be viewed as very preliminary due to the weaknesses identified in the available data. They should also be viewed as the <u>maximum</u> possible benefit of I/M since the reductions are applied to all HDDTs operating in the NYMA regardless of their state of registration. (This can be accomplished to a large extent by the presence of an active roadside program.) It should also be noted that the HC emission rates in

TABLE 8-5
ESTIMATED EMISSION IMPACTS IN YEAR 2005

	HC	NO_x	PM-10
No Excess Emissions/No I/M Baseline (tons per day)	18.1	81.9	4.2
No I/M Excess Emissions (percent)	+95.6	+15.8	+154.6
No I/M Baseline with Excess Emissions (tons per day)	35.4	94.8	10.7
Estimated Emissions with I/M Deterrence Alone (tons per day)	29.6	90.5	8.5
Deterrence Effect on Emissions (tons per day)	-5.8	-4.3	-2.2
Deterrence Effect on Excess Emissions (percent)	-33.4	-33.2	-33.4
Deterrence Effect on Total Emissions (percent)	-16.3	-4.5	-20.3
Estimated Emissions with J1667 Test (tons per day)	24.6	90.5	7.0
J1667 Effect on Emissions (tons per day)	-10.8	-4.3	-3.7
J1667 Effect on Excess Emissions (percent)	-62.6	-33.0	-57.3
J1667 Effect on Total Emissions (percent)	-30.6	-4.5	-34.8
Estimated Emissions with Lugdown Test (tons per day)	23.5	90.7	6.8
Lugdown Effect on Emissions (tons per day)	-11.9	-4.1	-3.9
Lugdown Effect on Excess Emissions (percent)	-68.7	-31.4	-59.8
Lugdown Effect on Total Emissions (percent)	-33.6	-4.3	-36.3
Estimated Emissions with J1667 plus Lugdown (tons per day)	23.4	90.6	6.7
J1667 plus Lugdown Effect on Emissions (tons per day)	-12.0	-4.2	-4.0
J1667 plus Lugdown Effect on Excess Emissions (percent)	-69.1	-32.4	-61.7
J1667 plus Lugdown Effect on Total Emissions (percent)	-33.8	-4.4	-37.5

absolute tons are almost certainly incorrect due to the MOBILE5b estimate of basic emission rates, but the percentage reductions in base emissions may be more realistic.

The major conclusions are:

- a revised methodology using the available test data in conjunction with earlier models suggest significant amounts of "excess" emissions from HDDTs operating in the NYMA;
- the very presence of any effective I/M program creates a significant deterrent effect that is responsible for reducing about a third of all excess emissions;
- both the lugdown and J1667 tests provide sizeable additional reductions in HC and PM emissions over the deterrent effect. The benefits of the two tests are approximately equal, but are not additive if both tests are done together.
- NO_x benefits are primarily from the deterrent effect. Repairs associated with the J1667 or lugdown test failure actually result in a (small) increase in NO_x emissions.

9. CONCLUSIONS

The relatively small sample of 37 trucks tested on a variety of emission cycles provided data to reach some preliminary conclusions. Several conclusions are consistent with data from other testing conducted outside of New York, while several conclusions are limited by the small sample.

1) The 'bsfc' based method to convert emissions per unit distance to emissions per unit of work provides reasonable estimates of emissions in g/BHP-hr that is unlikely to be in error by more than ±10 percent, except for trucks with significant accessory drives. This is consistent with analysis of data from Colorado.
2) Emissions of <u>all</u> pollutants from HDDVs show a definite downward trend with newer model years, even though the emission standards have never been binding constraints on HC and CO emissions. This is also consistent with data from Colorado.
3) NO_x emissions from HDDV have declined from about 7 g/BHP-hr for pre-1990 trucks to 4.8 g/BHP-hr for the 1991-1997 trucks certified to the 5.0 g NO_x standard.
4) PM emissions have declined from about 0.6 g/BHP-hr for pre-1990 trucks to less than 0.2 g/BHP-hr for 1994 and later trucks. However, even the average PM emissions levels of 1994+ trucks are twice as high as standards.
5) Only one in 37 truck had malperformances severe enough to cause high HC/CO/PM emissions.
6) Test weight was not found to influence emissions in g/BHP-hr significantly, although the range of load factors that the engine was subjected to by the different test weights used was very small.
7) Emissions of a given pollutant measured on different test cycles (ranging from "stylized" cycles to steady-state) are related with a high degree of statistical certainty, on average. However, emissions measured on steady-state cycles correlate poorly with emissions measured on transient cycles, for individual trucks. The results from stylized WVU 5 mile cycle does show reasonable correlation with results from the EPA 'D-cycle' for all emission species (r^2 of 0.7 to 0.8).
8) Measured HC and NO_x emissions on the 'lugdown' short cycle show good correlation with measured HC/NO_x emissions on the D-cycle. However, the sample size is very limited (seven vehicles) and this interesting conclusion must be viewed in the context of a small sample.

9) Mass PM emissions on the snap acceleration test (a rarely measured value) shows good correlation with the PM emissions on the D-cycle for pre-1990 trucks.

10) No statistically significant effect of vehicle odometer on emissions could be discerned, but the small sample and wide variety of engine models tested makes it unlikely that odometer influences can be detected.

11) Only a few correlations between different emissions species measured on the same test cycle could be observed. PM and CO emissions were found to be slightly correlated from 1994 and newer vehicles, although the correlation is skewed by the presence of the one high emitter that had very high HC/CO/PM emissions. Modest correlation between NO_x and CO was observed for pre-1990 vehicles, although this correlation is based on six data points. As a result, we are unable to state with any confidence that any correlations will be observed in larger samples of heavy-duty diesel vehicles.

These findings suggest a number of fruitful areas for follow-on studies. The test data showed that a more detailed specifications of test procedures, especially determination of inertia weight and PAU settings, is necessary. This should be a pre-requisite for any future test programs.

The correlations found between (1) HC/NO_x emissions on the lug-down test and on the D cycle and (2) mass PM emissions on the snap idle test and PM emissions on the D cycle are interesting, and need further investigation. Sample size increases will be particularly useful in determining if these correlations are an artifact of the small sample.

Light-heavy diesels, which were excluded from this program, are a major and growing part of the diesel population in the NYMA. Emissions test data on these vehicles would be particularly important for emission inventory in the NYMA.

Based on an existing model of heavy-duty truck inspection/maintenance augmented with data from this program, it appears that either the J1667 snap acceleration test or lug down test can identify a significant fraction of “excess” emissions from the these vehicles.

An obvious next step is to conduct pre-repair and post-repair studies on vehicles with relatively high emissions. If this work is done in conjunction with additional evaluation of short tests, a detailed control program evaluation will be possible.

APPENDIX A

RADIAN MODEL CALCULATION OF EXCESS EMISSIONS

TABLE A-1

RADIAN MODEL OF EXCESS EMISSIONS
HEAVY-HEAVY DUTY DIESEL VEHICLES

	Frequency of Occurrence (percent)				Emissions Increase of Individual Defect (percent)				Net Emissions Increase (percent)				Emissions Increase of Individual Defect (percent)				Net Emissions Increase (percent)			
	Model Year Group				Model Year Group				Model Year Group				Model Year Group				Model Year Group			
	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+
Defect					NO_x								HC							
Timing Advanced	8	12	5	5	50	50	60	60	4.0	6.0	3.0	3.0	20	20	30	30	1.6	2.4	1.5	1.5
Timing Retarded	15	10	3	3	-20	-20	-20	-20	-3.0	-2.0	-0.6	-0.6	50	50	50	50	7.5	5.0	1.5	1.5
Minor Injector Problems	20	18	15	15	0	0	0	0	0.0	0.0	0.0	0.0	10	10	20	20	2.0	1.8	3.0	3.0
Moderate Injector Problems	12	10	8	8	-5	-5	-5	-5	-0.6	-0.5	-0.4	-0.4	150	150	300	300	18.0	15.0	24.0	24.0
Severe Injector Problems	3	3	3	3	-10	-10	-10	-10	-0.3	-0.3	-0.3	-0.3	500	500	1100	1100	15.0	15.0	33.0	33.0
Puff Limiter MisSet	29	21	2	0	0	0	0	0	0.0	0.0	0.0	0.0	10	10	10	10	2.9	2.1	0.2	0.0
Puff Limiter Disabled	30	23	5	0	0	0	0	0	0.0	0.0	0.0	0.0	20	20	20	20	6.0	4.6	1.0	0.0
Maximum Fuel Stop Set High	24	18	3	3	10	10	10	10	2.4	1.8	0.3	0.3	0	0	0	0	0.0	0.0	0.0	0.0
Clogged Air Filter	18	14	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Wrong/Worn Turbo	11	8	5	5	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Intercooler Clogged	3	7	5	5	10	20	25	25	0.3	1.4	1.3	1.3	-20	-20	-20	-20	-0.6	-1.4	-1.0	-1.0
Other Air Problems	13	15	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Engine Mechanical Failure	1	1	1	1	-10	-10	-10	-10	-0.1	-0.1	-0.1	-0.1	200	200	300	500	2.0	2.0	3.0	5.0
Excess Oil Consumption	4	4	4	4	0	0	0	0	0.0	0.0	0.0	0.0	300	300	300	300	12.0	12.0	12.0	12.0
Electronics Failed	0	1	3	3	0	0	0	0	0.0	0.0	0.0	0.0	0	30	50	50	0.0	0.3	1.5	1.5
Electronics Tampered	0	6	20	20	0	30	80	80	0.0	1.8	16.0	16.0	0	0	0	0	0.0	0.0	0.0	0.0
Catalyst Removed	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	100	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	40	100	0.0	0.0	0.0	0.0
EGR Disabled	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
All Defects									2.7	8.3	19.4	19.4					70.7	61.3	81.0	81.4
Defect					PM								Fuel Consumption							
Timing Advanced	8	12	5	5	10	10	0	0	0.8	1.2	0.0	0.0	0	-2	-5	-5	0.0	-0.2	-0.3	-0.3
Timing Retarded	15	10	3	3	30	40	100	100	4.5	4.0	3.0	3.0	7	7	10	10	1.1	0.7	0.3	0.3
Minor Injector Problems	20	18	15	15	35	35	70	70	7.0	6.3	10.5	10.5	2	2	2	2	0.4	0.4	0.3	0.3
Moderate Injector Problems	12	10	8	8	200	200	400	400	24.0	20.0	32.0	32.0	5	5	5	5	0.6	0.5	0.4	0.4
Severe Injector Problems	3	3	3	3	700	700	1400	1400	21.0	21.0	42.0	42.0	10	10	10	10	0.3	0.3	0.3	0.3
Puff Limiter MisSet	29	21	2	0	20	20	50	50	5.8	4.2	1.0	0.0	1	1	1	1	0.3	0.2	0.0	0.0
Puff Limiter Disabled	30	23	5	0	50	50	100	100	15.0	11.5	5.0	0.0	2	2	2	2	0.6	0.5	0.1	0.0
Maximum Fuel Stop Set High	24	18	3	3	20	20	20	20	4.8	3.6	0.6	0.6	2	2	2	2	0.5	0.4	0.1	0.1
Clogged Air Filter	18	14	8	8	40	40	50	50	7.2	5.6	4.0	4.0	2	2	2	2	0.4	0.3	0.2	0.2
Wrong/Worn Turbo	11	8	5	5	40	40	50	50	4.4	3.2	2.5	2.5	1	1	1	1	0.1	0.1	0.1	0.1
Intercooler Clogged	3	7	5	5	40	40	50	50	1.2	2.8	2.5	2.5	2	2	2	2	0.1	0.1	0.1	0.1
Other Air Problems	13	15	8	8	40	40	40	40	5.2	6.0	3.2	3.2	1	1	1	1	0.1	0.2	0.1	0.1
Engine Mechanical Failure	1	1	1	1	150	150	300	500	1.5	1.5	3.0	5.0	7	7	6	6	0.1	0.1	0.1	0.1
Excess Oil Consumption	4	4	4	4	150	150	300	500	6.0	6.0	12.0	20.0	0	0	0	0	0.0	0.0	0.0	0.0
Electronics Failed	0	1	3	3	0	30	60	60	0.0	0.3	1.8	1.8	0	3	3	3	0.0	0.0	0.1	0.1
Electronics Tampered	0	6	20	20	0	0	50	50	0.0	0.0	10.0	10.0	0	0	-5	-5	0.0	0.0	-1.0	-1.0
Catalyst Removed	0	0	0	0	0	0	40	0	0.0	0.0	0.0	0.0	0	0	-1	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	200	300	0.0	0.0	0.0	0.0	0	0	-3	-3	0.0	0.0	0.0	0.0
EGR Disabled	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
All Defects									136.6	118.2	153.7	152.6					4.5	3.4	0.8	0.6

TABLE A-2

RADIAN MODEL OF EXCESS EMISSIONS
MEDIUM-HEAVY DUTY DIESEL VEHICLES

	Frequency of Occurrence (percent)				Emissions Increase of Individual Defect (percent)				Net Emissions Increase (percent)				Emissions Increase of Individual Defect (percent)				Net Emissions Increase (percent)			
	Model Year Group				Model Year Group				Model Year Group				Model Year Group				Model Year Group			
	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+
Defect					NO_x								HC							
Timing Advanced	10	12	5	5	50	50	60	60	5.0	6.0	3.0	3.0	20	20	30	30	2.0	2.4	1.5	1.5
Timing Retarded	6	5	4	4	-20	-20	-20	-20	-1.2	-1.0	-0.8	-0.8	-10	-10	50	50	-0.6	-0.5	2.0	2.0
Minor Injector Problems	20	18	15	15	0	0	0	0	0.0	0.0	0.0	0.0	10	10	20	20	2.0	1.8	3.0	3.0
Moderate Injector Problems	15	13	10	10	-5	-5	-5	-5	-0.8	-0.7	-0.5	-0.5	150	150	300	300	22.5	19.5	30.0	30.0
Severe Injector Problems	5	5	5	5	-10	-10	-10	-10	-0.5	-0.5	-0.5	-0.5	500	500	1100	1100	25.0	25.0	55.0	55.0
Puff Limiter MisSet	18	13	2	0	0	0	0	0	0.0	0.0	0.0	0.0	10	10	10	10	1.8	1.3	0.2	0.0
Puff Limiter Disabled	15	12	4	0	0	0	0	0	0.0	0.0	0.0	0.0	20	20	20	20	3.0	2.4	0.8	0.0
Maximum Fuel Stop Set High	14	10	2	2	10	10	10	10	1.4	1.0	0.2	0.2	0	0	0	0	0.0	0.0	0.0	0.0
Clogged Air Filter	23	19	10	10	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Wrong/Worn Turbo	10	9	5	5	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Intercooler Clogged	1	4	3	3	10	20	25	25	0.1	0.8	0.8	0.8	-20	-20	-20	-20	-0.2	-0.8	-0.6	-0.6
Other Air Problems	14	12	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Engine Mechanical Failure	1	1	1	1	-10	-10	-10	-10	-0.1	-0.1	-0.1	-0.1	200	200	300	500	2.0	2.0	3.0	5.0
Excess Oil Consumption	8	8	8	8	0	0	0	0	0.0	0.0	0.0	0.0	300	300	300	300	24.0	24.0	24.0	24.0
Electronics Failed	0	2	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	30	50	50	0.0	0.6	4.0	4.0
Electronics Tampered	0	3	10	10	0	30	80	80	0.0	0.9	8.0	8.0	0	0	0	0	0.0	0.0	0.0	0.0
Catalyst Removed	0	0	0	1	0	0	0	0	0.0	0.0	0.0	0.0	0	0	100	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	40	100	0.0	0.0	0.0	0.0
EGR Disabled	0	0	3	6	0	0	35	35	0.0	0.0	1.1	2.1	0	0	15	15	0.0	0.0	0.5	0.9
All Defects									4.0	6.5	11.1	12.2					83.0	78.9	126.1	127.3
Defect					PM								Fuel Consumption							
Timing Advanced	10	12	5	5	10	10	0	0	1.0	1.2	0.0	0.0	0	-2	-5	-5	0.0	-0.2	-0.3	-0.3
Timing Retarded	6	5	4	4	30	40	100	100	1.8	2.0	4.0	4.0	7	7	10	10	0.4	0.4	0.4	0.4
Minor Injector Problems	20	18	15	15	35	35	70	70	7.0	6.3	10.5	10.5	2	2	2	2	0.4	0.4	0.3	0.3
Moderate Injector Problems	15	13	10	10	200	200	400	400	30.0	26.0	40.0	40.0	5	5	5	5	0.8	0.7	0.5	0.5
Severe Injector Problems	3	3	3	3	500	500	1000	1000	15.0	15.0	30.0	30.0	10	10	10	10	0.3	0.3	0.3	0.3
Puff Limiter MisSet	18	13	2	0	20	20	50	50	3.6	2.6	1.0	0.0	1	1	1	1	0.2	0.1	0.0	0.0
Puff Limiter Disabled	15	12	4	0	50	50	100	100	7.5	6.0	4.0	0.0	2	2	2	2	0.3	0.2	0.1	0.0
Maximum Fuel Stop Set High	14	10	2	2	30	30	30	30	4.2	3.0	0.6	0.6	2	2	2	2	0.3	0.2	0.0	0.0
Clogged Air Filter	23	19	10	10	50	50	50	50	11.5	9.5	5.0	5.0	2	2	2	2	0.5	0.4	0.2	0.2
Wrong/Worn Turbo	10	9	5	5	40	40	50	50	4.0	3.6	2.5	2.5	1	1	1	1	0.1	0.1	0.1	0.1
Intercooler Clogged	1	4	3	3	40	40	50	50	0.4	1.6	1.5	1.5	2	2	2	2	0.0	0.1	0.1	0.1
Other Air Problems	14	12	8	8	40	40	40	40	5.6	4.8	3.2	3.2	1	1	1	1	0.1	0.1	0.1	0.1
Engine Mechanical Failure	1	1	1	1	150	150	300	500	1.5	1.5	3.0	5.0	7	7	6	6	0.1	0.1	0.1	0.1
Excess Oil Consumption	8	8	8	8	150	150	300	500	12.0	12.0	24.0	40.0	0	0	0	0	0.0	0.0	0.0	0.0
Electronics Failed	0	2	8	8	0	30	60	60	0.0	0.6	4.8	4.8	0	4	4	4	0.0	0.1	0.3	0.3
Electronics Tampered	0	3	10	10	0	0	50	50	0.0	0.0	5.0	5.0	0	0	-5	-5	0.0	0.0	-0.5	-0.5
Catalyst Removed	0	0	0	1	0	0	40	0	0.0	0.0	0.0	0.0	0	0	-1	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	200	300	0.0	0.0	0.0	0.0	0	0	-4	-4	0.0	0.0	0.0	0.0
EGR Disabled	0	0	3	6	0	0	-10	-10	0.0	0.0	-0.3	-0.6	0	0	1	1	0.0	0.0	0.0	0.1
All Defects									128.9	114.0	160.4	168.2					3.5	2.8	1.7	1.6

TABLE A-3

RADIAN MODEL OF EXCESS EMISSIONS
LIGHT-HEAVY DUTY DIESEL VEHICLES

	Frequency of Occurrence (percent)				Emissions Increase of Individual Defect (percent)				Net Emissions Increase (percent)				Emissions Increase of Individual Defect (percent)				Net Emissions Increase (percent)			
	Model Year Group				Model Year Group				Model Year Group				Model Year Group				Model Year Group			
	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+	60-87	88-90	91-93	94+
Defect					NO_x								HC							
Timing Advanced	10	8	5	5	20	30	60	60	2.0	2.4	3.0	3.0	-10	20	30	30	-1.0	1.6	1.5	1.5
Timing Retarded	10	6	4	4	-20	-20	-20	-20	-2.0	-1.2	-0.8	-0.8	0	0	50	50	0.0	0.0	2.0	2.0
Minor Injector Problems	20	18	15	15	0	0	0	0	0.0	0.0	0.0	0.0	10	10	20	20	2.0	1.8	3.0	3.0
Moderate Injector Problems	15	13	10	10	-5	-5	-5	-5	-0.8	-0.7	-0.5	-0.5	150	150	300	300	22.5	19.5	30.0	30.0
Severe Injector Problems	5	5	5	5	-10	-10	-10	-10	-0.5	-0.5	-0.5	-0.5	500	500	1100	1100	25.0	25.0	55.0	55.0
Puff Limiter MisSet	2	5	2	0	0	0	0	0	0.0	0.0	0.0	0.0	10	10	10	10	0.2	0.5	0.2	0.0
Puff Limiter Disabled	1	3	4	0	0	0	0	0	0.0	0.0	0.0	0.0	20	20	20	20	0.2	0.6	0.8	0.0
Maximum Fuel Stop Set High	15	13	5	5	10	10	10	10	1.5	1.3	0.5	0.5	0	0	0	0	0.0	0.0	0.0	0.0
Clogged Air Filter	21	19	10	10	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Wrong/Worn Turbo	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Intercooler Clogged	0	0	0	0	20	20	25	25	0.0	0.0	0.0	0.0	-20	-20	-20	-20	0.0	0.0	0.0	0.0
Other Air Problems	9	12	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	0	0	0	0.0	0.0	0.0	0.0
Engine Mechanical Failure	1	1	1	1	-10	-10	-10	-10	-0.1	-0.1	-0.1	-0.1	200	200	300	500	2.0	2.0	3.0	5.0
Excess Oil Consumption	10	10	10	10	0	0	0	0	0.0	0.0	0.0	0.0	300	300	300	300	30.0	30.0	30.0	30.0
Electronics Failed	0	2	8	8	0	0	0	0	0.0	0.0	0.0	0.0	0	30	50	50	0.0	0.6	4.0	4.0
Electronics Tampered	0	1	7	7	0	30	80	80	0.0	0.3	5.6	5.6	0	0	0	0	0.0	0.0	0.0	0.0
Catalyst Removed	0	0	0	3	0	0	0	0	0.0	0.0	0.0	0.0	0	0	100	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0	0	40	100	0.0	0.0	0.0	0.0
EGR Disabled	0	0	6	9	0	0	50	50	0.0	0.0	3.0	4.5	0	0	20	20	0.0	0.0	1.2	1.8
All Defects									0.1	1.6	10.2	11.7					80.7	82.3	134.0	135.4
Defect					PM								Fuel Consumption							
Timing Advanced	10	8	5	5	10	10	0	0	1.0	0.8	0.0	0.0	0	-2	-5	-5	0.0	-0.2	-0.3	-0.3
Timing Retarded	10	6	4	4	20	20	100	100	2.0	1.2	4.0	4.0	5	5	10	10	0.5	0.3	0.4	0.4
Minor Injector Problems	20	18	15	15	20	20	70	70	4.0	3.6	10.5	10.5	1	1	2	2	0.2	0.2	0.3	0.3
Moderate Injector Problems	15	13	10	10	100	100	400	400	15.0	13.0	40.0	40.0	3	3	5	5	0.5	0.4	0.5	0.5
Severe Injector Problems	3	3	3	3	500	500	1000	1000	15.0	15.0	30.0	30.0	5	5	10	10	0.2	0.2	0.3	0.3
Puff Limiter MisSet	2	5	2	0	20	20	50	50	0.4	1.0	1.0	0.0	1	1	1	1	0.0	0.1	0.0	0.0
Puff Limiter Disabled	1	3	4	0	50	50	100	100	0.5	1.5	4.0	0.0	2	2	2	2	0.0	0.1	0.1	0.0
Maximum Fuel Stop Set High	15	13	5	5	50	50	30	30	7.5	6.5	1.5	1.5	2	2	2	2	0.3	0.3	0.1	0.1
Clogged Air Filter	21	19	10	10	60	60	50	50	12.6	11.4	5.0	5.0	2	2	2	2	0.4	0.4	0.2	0.2
Wrong/Worn Turbo	0	0	0	0	40	40	50	50	0.0	0.0	0.0	0.0	1	1	1	1	0.0	0.0	0.0	0.0
Intercooler Clogged	0	0	0	0	40	40	50	50	0.0	0.0	0.0	0.0	2	2	2	2	0.0	0.0	0.0	0.0
Other Air Problems	9	12	8	8	40	40	40	40	3.6	4.8	3.2	3.2	1	1	1	1	0.1	0.1	0.1	0.1
Engine Mechanical Failure	1	1	1	1	150	150	300	500	1.5	1.5	3.0	5.0	7	7	6	6	0.1	0.1	0.1	0.1
Excess Oil Consumption	10	10	10	10	150	150	300	500	15.0	15.0	30.0	50.0	0	0	0	0	0.0	0.0	0.0	0.0
Electronics Failed	0	2	8	8	0	30	60	60	0.0	0.6	4.8	4.8	0	4	4	4	0.0	0.1	0.3	0.3
Electronics Tampered	0	1	7	7	0	0	50	50	0.0	0.0	3.5	3.5	0	-5	-5	-5	0.0	-0.1	-0.4	-0.4
Catalyst Removed	0	0	0	3	0	0	40	0	0.0	0.0	0.0	0.0	0	0	-1	0	0.0	0.0	0.0	0.0
Trap Removed	0	0	0	0	0	0	200	300	0.0	0.0	0.0	0.0	0	0	-4	-4	0.0	0.0	0.0	0.0
EGR Disabled	0	0	6	9	0	0	-10	-10	0.0	0.0	-0.6	-0.9	0	0	1	1	0.0	0.0	0.1	0.1
All Defects									86.6	84.0	157.1	169.4					2.2	1.8	1.8	1.8