REVIEW AND CRITIQUE OF CURRENT HEAVY-DUTY TRUCK EMISSION FACTORS

Contract No. A2-065-32
Task III

Prepared for:

CALIFORNIA AIR RESOURCES BOARD
El Monte, California

Prepared by:

ENERGY AND ENVIRONMENTAL ANALYSIS, INC.
1655 North Fort Myer Drive
Arlington, Virginia 22209

January 1985

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

LIST OF TABLES

LIST OF FIGURES

2. CORRELATION BETWEEN STEADY-STATE AND TRANSIENT EMISSION TESTS

2.1 OVERVIEW

"Steady-state" emission tests have been used to measure emissions from heavy-duty engines since the inception of emission standards. As the name implies, these tests involve measuring engine emissions at fixed speed/load operating conditions and expressing composite emissions as a weighted average of the emissions at the individual operating points. For gasoline engines, the test is referred to as the 9-mode test, while for diesel engines, the test is referred to as the 13-mode test. In both cases, tests are conducted on fully warmed-up engines.

Recently, EPA has promulgated new regulations for testing heavy-duty engines and will require a new test procedure referred to as the "transient test." Unlike the steady-state test, the transient test specifies speed/load as a continuously varying function of time. The new test procedure was developed to be more representative of real world driving conditions where speed and load are rarely held constant under urban driving conditions. Another requirement for the transient test is that each engine be tested twice, once from a cold start and once from a hot start. Emissions from the cold and hot tests are weighted by 1/7 and 6/7, respectively, to derive a composite emission factor.

This section examines the correlation between <u>composite</u> emissions on the transient test and composite emissions on the steady-state test separately for gasoline and diesel engines. A major difficulty with such an analysis is the variability of measured emissions from engines. The differences arise from engine-to-engine variations, test-to-test variations, lab-to-lab variations, and measurement errors. The largest single source is the variation from engine-to-engine. Engines of identical make and model meeting the same emission standards can display large variations in emissions. In order to eliminate this variability, emissions correlations were performed using data from steady-state and transient tests performed on the same engine. Other sources of variability were minimized by using average data from multiple (or repeat) tests of the same engine on a particular test.

The objectives of this correlation analysis were to:

- Obtain the transient emissions equivalent of steady-state emissions measured on current engines in order to develop an in-use emission factor
- Determine if there was a significant fraction of transient emissions that was not captured by the steady-state test
- Establish the relative stringency of transient test based emission standards in future model years in comparison to the optional steady-state test based standards for 1984-1986

2.2 GASOLINE ENGINES

A very small sample of test data exists for gasoline engines tested on both the transient cycle and 9-mode test. All of the available data was from tests conducted by SWRI and consist of the 12 gasoline engines tested to provide the 1979 EPA "baseline" and three additional engines from model years 1978 and 1979. The results from the 12 baseline engines have been previously analyzed by the CARB, EPA, and the National Academy of Sciences. None of the analyses showed good correlations and they reported a R^2 of 0.46 for HC, 0.12 for CO, and 0.73 for NO_x. These results were essentially replicated by EEA in a straightforward regression of transient emissions with steady-state emissions.

Since the data set was small, it was decided to examine each engine data point for anomalous behavior, and to identify the control technology utilized. It was found that one engine (the IH 345) showed exceptional behavior in that it exhibited higher HC emissions on the steady-state test than on the transient test, in sharp contrast to the results from

1. INTRODUCTION

Emission factors for heavy-duty gasoline and diesel trucks have traditionally been developed from limited test data on heavy-duty engines and are potentially subject to large errors. This report examines the available data from recent tests on heavy-duty engines as well as the methodology that was used by EPA to derive emission factors. Based on this examination, new methods to derive revised and more accurate emission factors are recommended. These new methods are used -- to the extent feasible from available data and consistent with CARB's requirements -- to derive revised heavy-duty emission factors that can be utilized by the CARB in their EMFAC model.

Apart from the data limitations, there are a number of topics related to heavy-duty vehicle emissions measurement that have a significant impact on the derived emission factors. Heavy-duty emission tests are based on tests of the engine alone and the emission standards are based on units of power output of the engine over the recommended engine test, i.e., they are specified in gm/BHP-hr. The test procedure itself is currently being revised, as the steady-state test that has been used until recently is not representative of actual in-use conditions. The new transient test procedure is more representative and emission factors should theoretically be based on the emissions measured from the new cycle.

Furthermore, emission factors are required to be stated in gm/mile of vehicle travel while both steady-state and transient test procedures provide results in gm/BHP-hr. The conversion factor to link the two emission variables -- BHP-hr/mile -- is a measure of power required to move the truck over a unit distance which in turn is a function of average truck weight and efficiency. Both average truck weight and efficiency have varied historically and are expected to vary in the future, thus making the conversion factor a variable independent of emissions or emission standards. It must also be noted that the definition of heavy-duty truck changed in 1979 to cover the vehicles greater in weight than 8,500 lbs GVW, rather than 6,000 lbs GVW used in 1978 and previous years.

Accordingly, all of these topics are addressed in this report. Section 2 examines the correlation between the steady-state test procedure and the transient test procedure for gasoline and diesel engines using the relatively limited data available in each category. Although previous analysis of these data by others showed poor correlation, EEA's analysis showed that proper choice of the data and revised regression techniques result in vastly improved correlations. These improved correlations can be utilized to estimate transient test emissions from the relatively larger data base on steady-state emissions.

In Section 3, a summary of EEA's analysis for the Motor Vehicle Manufacturer's Association (MVMA) on the conversion factor, BHP-hr/mile, is provided. The analysis shows that large changes to the conversion factor for diesel trucks can be expected in the future as diesel engines penetrate the lower weight classes of trucks. More recently, EPA has arrived at independent estimates of the conversion factor that are different from those derived by EEA. Both sets of conversion factors are provided in this report.

Section 4 examines the EPA derivation of the heavy-duty emission factors for use in MOBILEII and also in the California Air Quality model EMFAC. The basic exhaust emission rate, which consists of a zero mile emission level and a deterioration rate, is the only emission factor examined. Other correction factors for speed, temperature, and altitude are not analyzed in this report. The areas in which EPA's analysis were found deficient are in the conversion factor used and in the derivation of the deterioration factor.

Section 5 provides some qualitative discussion of the types of malperformances found in heavy-duty gasoline and diesel engines, so as to allow an intelligent estimate of the deterioration factor. The discussion is based on information supplied by the manufacturers on the topic. Based on this discussion, recommendations for improving the emission factor estimates from those made by EPA are provided.

To the extent possible from available data, EEA utilized the recommendations in Section 5 to derive new emission factors for heavy-duty trucks. This derivation depends largely on a small number of in-use trucks tested by the EPA. The results of our derivation are described in Section 6 of this report.

Appendix A includes the manufacturers' responses to the EEA questionnaire on malperformances in heavy-duty engines.

all other engines where transient test HC emissions were higher than steady-state emissions by a factor of 3 or 4. Since the results of the steady-state test were suspect, these data was dropped from the analysis. Of the remaining 14 engines, all but three were equipped with air pumps and thermal reactors. The three included the two 1978 engines and a 1979 Chrysler 440 (the engine has since been discontinued).

In order to improve the correlation, EEA studied the relationship between the steady-state and transient cycles. It was obvious that because of the cold start requirement on the transient test, there would be a large increment in HC and CO emissions over the transient test in comparison to the steady-state test. Secondly, the transient test had a greater percentage of light load operation than the steady-state test. Accordingly, it was thought likely that the idle mixture adjustment would have a relatively strong impact on transient test emissions and EEA decided to use the idle CO as an indicator of the idle mixture setting.

Examination of the idle CO revealed that there was considerable variation in the idle CO setting among the 14 different engines and idle CO values ranged from 0.1 percent to over 3.0 percent. Furthermore, testimony submitted to the EPA by manufacturers showed that transient test emissions were sensitive to idle mixture setting, with HC and CO emissions rising steeply for idle CO values in excess of 1 percent. At very lean idle CO settings, it is known from engineering principles that misfire at light load causes increases in HC and CO. Thus, the response of transient cycle emissions to the idle mixture setting was expected to be highly non-linear. Examination of typical gasoline engine behavior suggested that the minimum HC and CO emissions would occur slightly leaner than stoichiometry, which usually corresponds to an idle CO of approximately one percent. As a result, engineering analysis suggests that HC and CO emissions would increase as idle CO emissions diverged from 0.7 percent.

In order to account for the influence of the idle mixture setting when attempting to correlate transient test emissions and steady-state emissions, EEA adopted two new variables called DIV HC and DIV CO, measuring the influence of the divergence of the idle setting (from the optimum value of 0.7 percent) on transient HC and CO emissions, respectively.

$$\text{DIV HC} = \left[\frac{\text{ICO} - 0.7}{\text{HC}_9}\right]^2$$

$$\text{DIV CO} = \left[\frac{\text{ICO} - 0.7}{\text{CO}_9}\right]^2$$

where: ICO = the idle CO in percent

HC_9, CO_9 = steady-state composite HC and CO emissions in g/BHP-hr

In each case, the term (ICO - 0.7) is normalized by the steady-state emissions in order to measure the relative effect of the idle mixture setting in comparison to the rest of the steady-state test points. For example, a rich idle mixture setting will not have a large effect if the engine is calibrated to run rich during the rest of the cycle. This normalized term is then squared since transient emissions are likely to rise if the idle mixture is either richer or leaner than optimum. (The choice of 2 for the exponent was based simply on the fact that squared term was found to be prominent in earlier studies on LDV emissions. Estimating the value of the exponent from the data was not possible due to the relatively few points and the scatter in measured emissions.)

Utilizing this new variable, the regression equations between transient and steady-state emissions were:

$$HC_T = A_1 + B_1\ HC_9 + C_1\ DIV\ HC$$

$$CO_T = A_2 + B_2\ CO_9 + C_2\ DIV\ CO$$

$$NO_x = A_3 + B_3\ NO_{x9} + C_3\ DIV\ CO$$

where: subscript T = transient emissions

subscript 9 = 9-mode steady-state emissions

A_i, B_i, C_i = regression coefficients

These new regression equations immediately provided large improvements to the correlation coefficient. The intercept coefficients, A_i, represent that portion of transient emissions <u>independent</u> of emissions on the steady-state test and of idle emissions.

Using data from all 14 engines, the following equations were derived:

$$HC_T = \underset{(0.37)}{0.77} + \underset{(0.185)}{2.036}\ HC_9 + \underset{(0.555)}{1.08}\ DIV\ HC \qquad (R^2 = 0.92)$$

$$CO_T = \underset{(16.96)}{43.63} + \underset{(0.52)}{0.83}\ CO_9 + \underset{(8{,}475)}{23{,}232}\ DIV\ CO \qquad (R^2 = 0.41)$$

$$NO_{xT} = \underset{(0.87)}{0.63} + \underset{(0.11)}{0.944}\ NO_{x9} - \underset{(341.4)}{485.4}\ DIV\ CO \qquad (R^2 = 0.87)$$

(The terms under the coefficients in parenthesis are the standard errors of the coefficients.) It is obvious that the HC and NO_x regressions are very good because of high R^2 achieved. The relatively poor correlation for CO was explained by the presence of the three engines without air pumps. Removing the data from these three engines provided the following regression equations:

$$HC_T = \underset{(0.38)}{0.8} + \underset{(0.18)}{2.04\ HC_9} + \underset{(0.62)}{1.027\ DIV\ HC} \qquad (R^2 = 0.945)$$

$$CO_T = \underset{(14.08)}{32.46} + \underset{(0.40)}{0.817\ CO_9} + \underset{(18,346)}{72,794\ DIV\ CO} \qquad (R^2 = 0.687)$$

$$NO_{xT} = \underset{(0.90)}{0.87} + \underset{(0.11)}{0.97\ NO_{x9}} - \underset{(976)}{2,253\ DIV\ CO} \qquad (R^2 = 0.91)$$

Note the remarkable improvement in the r^2 for CO, and the directionally correct negative coefficient for DIVCO in the NO_x regressions. The NO_x intercept term is not significant at 0.05 levels (the T statistic for the parameter = 0 is 0.97). The dependence of transient CO on 9-mode CO also appears relatively weak (T = 2.05) but is significant at the 0.10 level. The predicted and obsserved data are shown in Figures 2-1 through 2-3, and it should be noted that relationship is not described by straight line because of the inclusion of the divergence variable.

In summary, it appears that good correlations between transient and steady-state HC and NO_x as well as a modest correlation between transient and steady-state CO can be obtained if a measure of idle mixture setting is incorporated. However, we caution the CARB that:

- The regression are only appropriate for the technology groups represented in the data, i.e., non-catalyst air pump equipped engines
- The range of HC, CO and NO_x emissions over which the regression is established is much higher than the 1985 standards of 1.3/15.5/5.1 g/BHP-hr for HC/CO/NO_x
- The large intercept term for the CO regressions is probably due to emissions during cold start and acceleration enrichment, which are not measured on the steady-state test. These emissions change dramatically if cold start emissions are controlled.

The regressions must, therefore, be viewed not as a predictive tool for alternative technology, but only as a means to establish relationships between transient and steady-state emissions for the 1979-1984 HD gasoline engines.

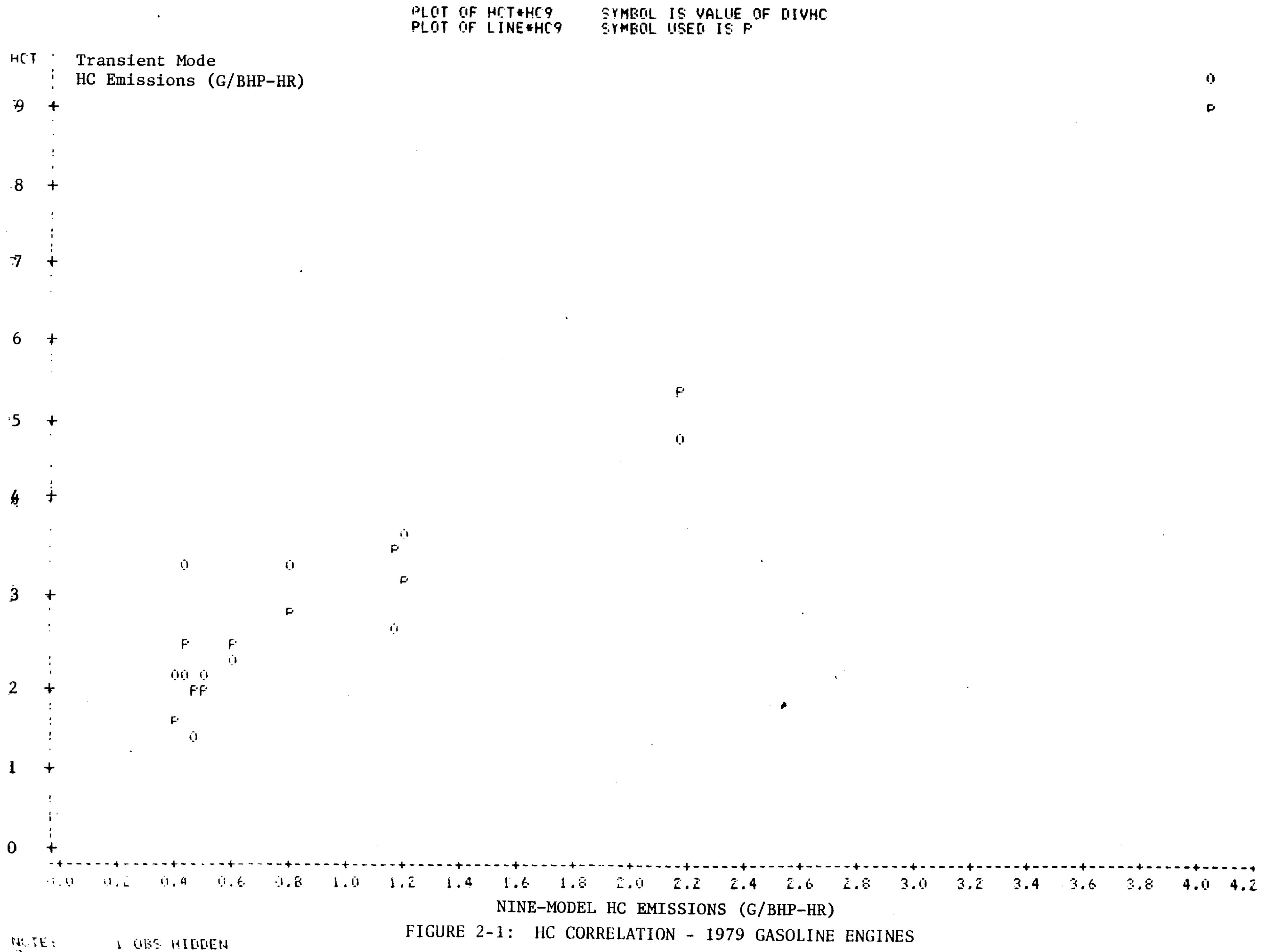
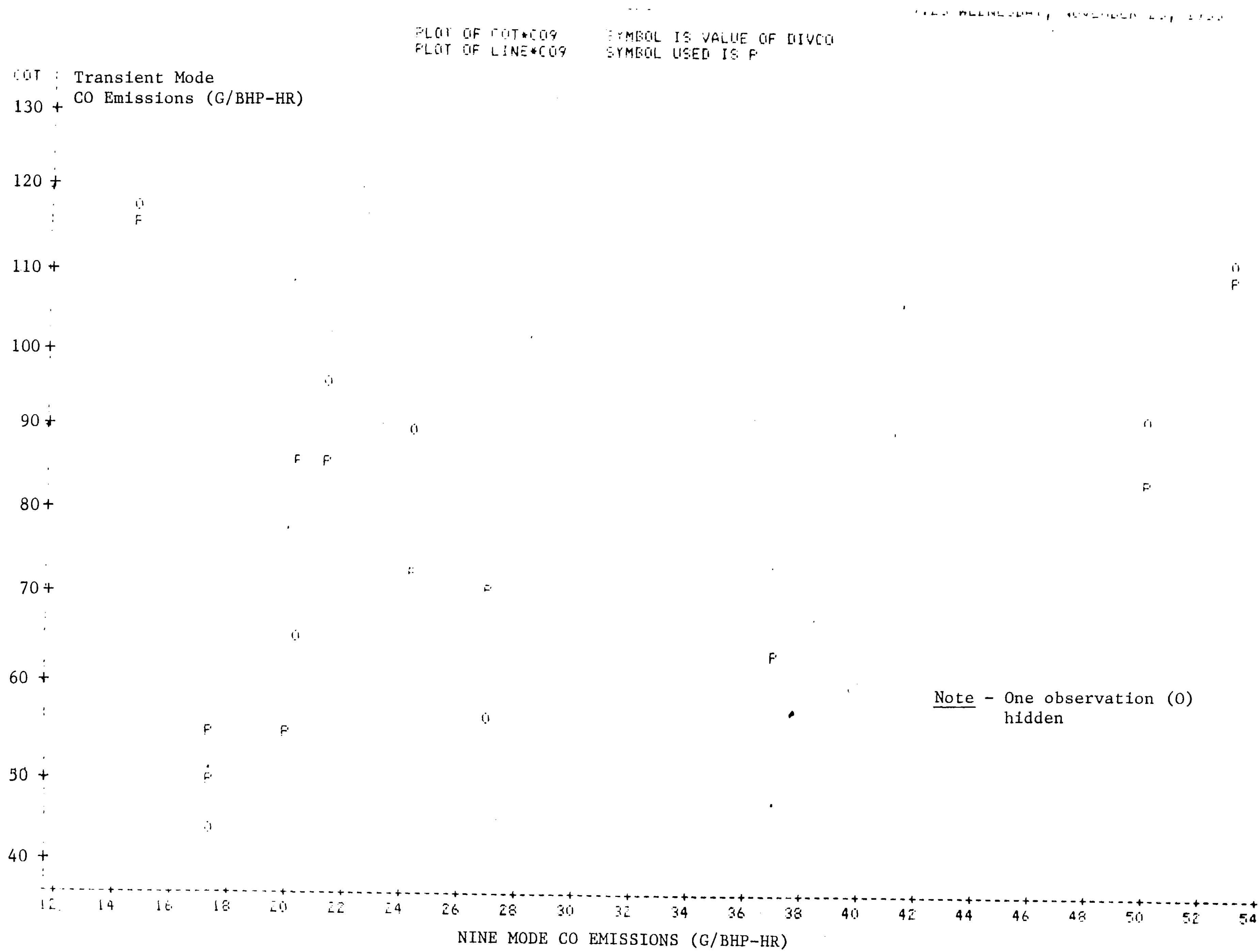


FIGURE 2-1: HC CORRELATION - 1979 GASOLINE ENGINES



FIGU 2-2: CO ATI... 197. ..SOL... ENGI...

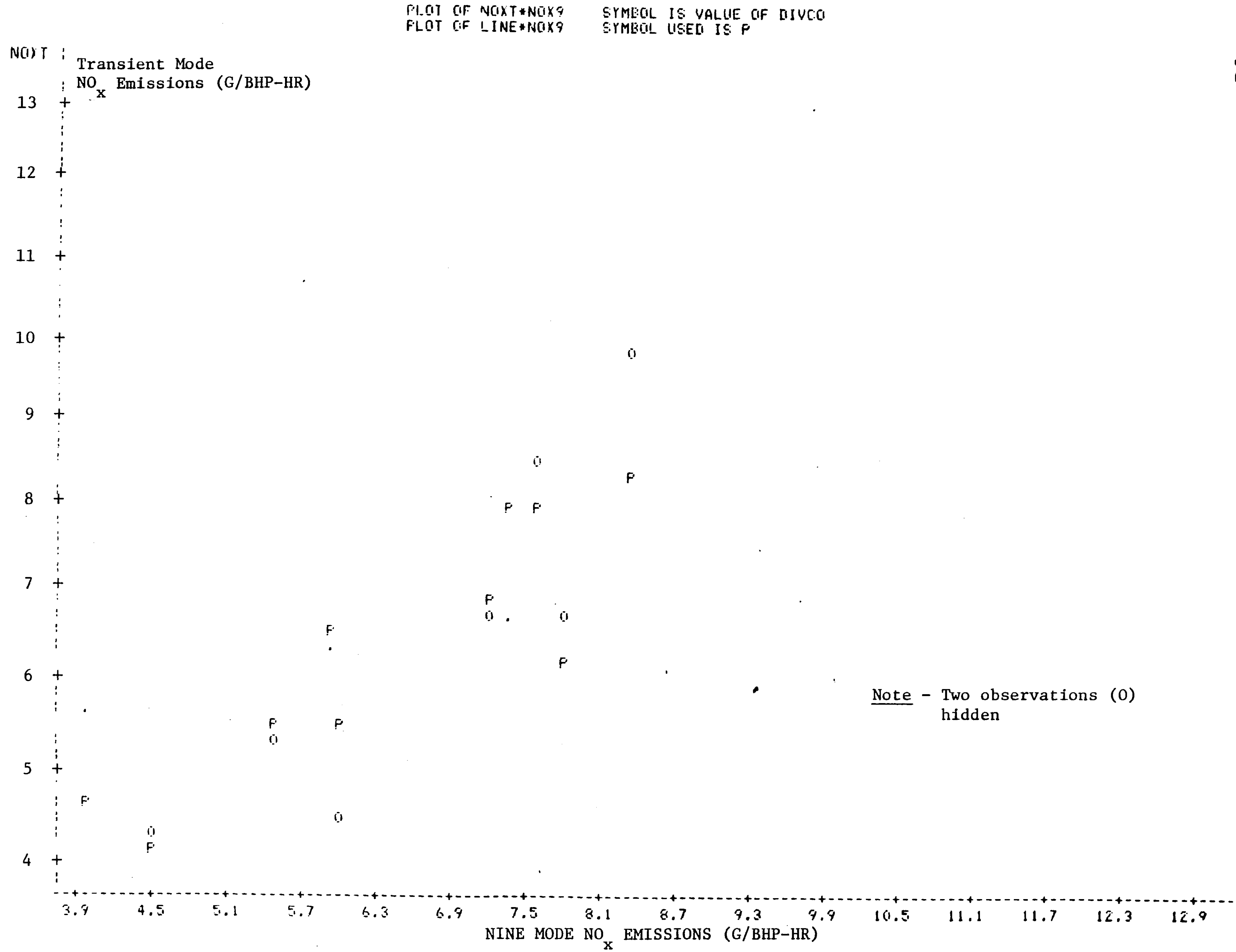


FIGURE 2-3: NO_x CORRELATION - 1979 GASOLINE ENGINES

2.3 DIESEL ENGINES

The correlation between steady-state and transient test emissions for diesel engines are more practical to attempt than for gasoline engines because of two reasons.

- Diesel engines do not require "acceleration enrichment" and air fuel ratio during transients is more carefully controlled than in a gasoline engine.
- Diesel engines require little cold start enrichment and therefore the inclusion of the cold start on the transient test is not likely to significantly influence the correlation between transient and steady-state test emissions.

As a result, the intercept term in the regression is likely to be smaller and steady-state emissions should predict transient emissions reasonably well. All major manufacturers of diesel engines have tested their own makes and models of diesel engines in an attempt to show correlations and a relatively large body of data on steady-state emissions and transient emissions from the same engines exists.

Although all of the data has been made available to EPA, EEA was unable to access this data and had to obtain individual data points from the following sources:

- 19 tests by SWRI on 1979 diesel engines
- Six engines tested by the CRC/EMA "round robin"
- Eight engines tested by Cummins with data submitted at an EPA hearing in 1979
- 15 Cummins engines tested only on the "hot start" phase of the transient cycle plus an additional four data points on the same engine with different injection timing on each test.

EEA could not obtain the individual test data points from other manufacturers such as Mack, Caterpillar, and International Harvester, but was able to obtain the correlations specific to each manufacturers' engines. Mercedes-Benz submitted pictorial data on tests from two engines for HC emissions only. EEA believes that a total of about 50 data points for correlation exist but only 33 are available. Since CO emissions from diesel engines are very low, there is little interest in correlating transient and steady-state CO emissions.

In a separate study on the correlation question, EPA, using all available data, found the correlation for HC emissions to be relatively poor with an r^2 of 0.51 and the correlation for NO_x emissions to be somewhat better with an r^2 of 0.71. However, EPA cautioned that there were several instances of engines with very low steady-state emissions (especially of HC) but high transient test emissions. It was for this reason that EPA rejected the proposal to allow steady-state tests for certification to standards equivalent to transient test based standards.

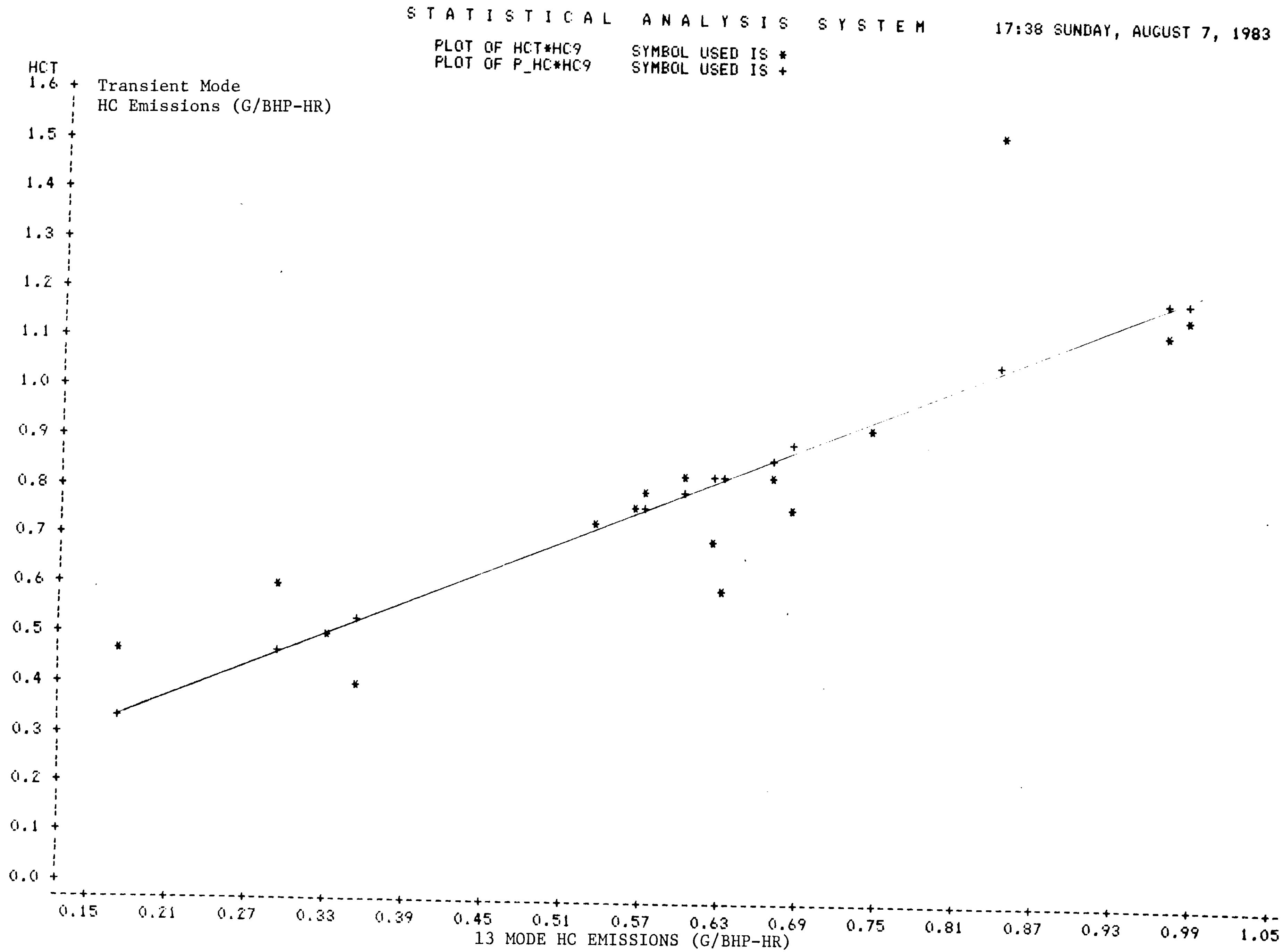
A detailed examination of the data revealed that the Cummins engines did not exhibit the same behavior as did engines from all other manufacturers. The Engine Manufacturers Association (EMA) recognized this and submitted an analysis to the EPA docket with separate correlations for data from engines that were not Cummins. Utilizing the same approach, EEA segregated the data between Cummins and "non-Cummins" engines.

As there are not alternative measures such as idle CO to gauge light load diesel engine performance, little could be attempted other than a straightforward regression of data. For the non-Cummins engines, EEA found the following:

$$HC_T = \underset{(0.117)}{0.167} + \underset{(0.184)}{1.05}\ HC_{13} \qquad (R^2 = 0.70)$$

$$NO_{xT} = \underset{(0.646)}{1.70} + \underset{(0.094)}{0.75}\ NO_{x13} \qquad (R^2 = 0.82)$$

These regressions were based on 15 data points, and are graphically shown in Figures 2-4 and 2-5. Surprisingly, even the CO emissions were found to be correlated for this data set with:

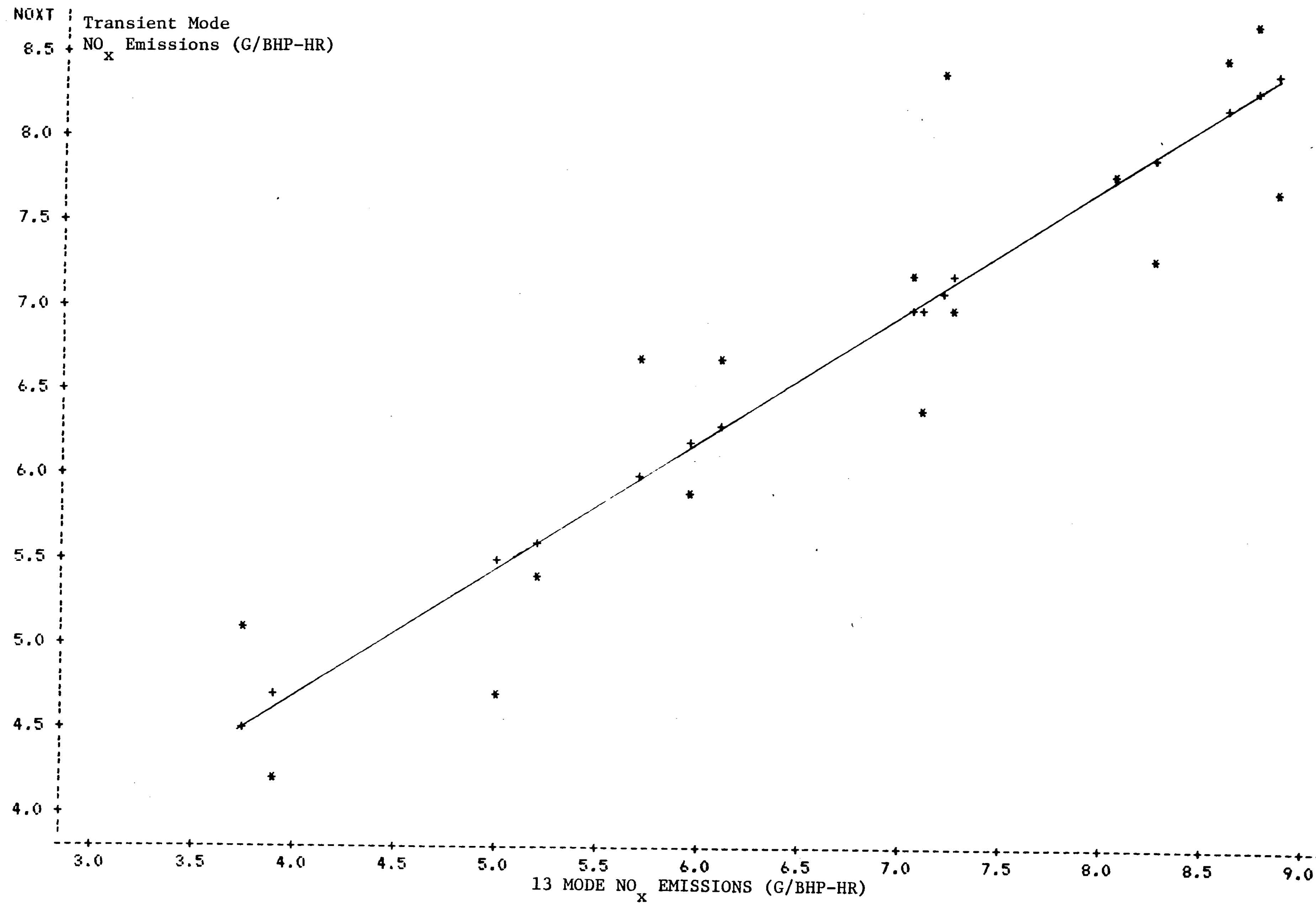


NOTE: 4 OBS HIDDEN

FIGURE 2-4: HC CORRELATION - ALL DIESELS EXCEPT CUMMINS

S T A T I S T I C A L   A N A L Y S I S   S Y S T E M   17:38 SUNDAY, AUGUST 7, 1983

PLOT OF NOXT*NOX9   SYMBOL USED IS *
PLOT OF P_NOX*NOX9   SYMBOL USED IS +



NOTE: 1 OBS HIDDEN
? LOGO***

FIGURE 2-5: NO_x CORRELATION - ALL DIESELS EXCEPT CUMMINS

$$CO_T = \underset{(0.27)}{1.055} + \underset{(0.093)}{0.514}\ CO_{13} \qquad (R^2 = 0.72)$$

Note that the intercept on the HC regression is not significant at the 0.05 level indicating that the effects of acceleration enrichment and cold-start on HC emissions are small. For the 15 Cummins engines on which composite transient data was available, EEA obtained the following:

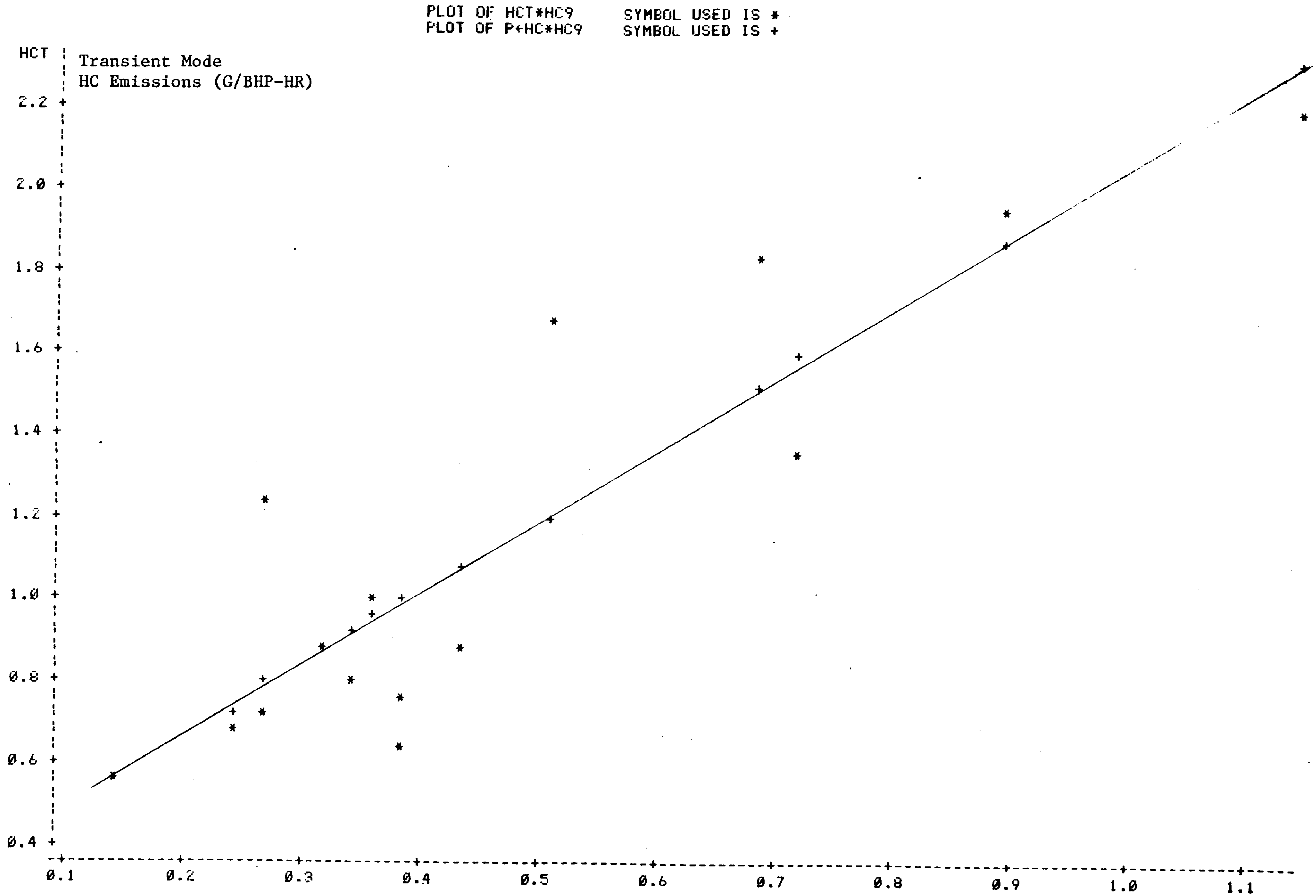
$$HC_T = \underset{(0.04)}{0.31} + \underset{(0.25)}{1.77}\ HC_{13} \qquad (R^2 = 0.79)$$

$$NO_{xT} = \underset{(1.04)}{1.03} + \underset{(0.134)}{0.81}\ NO_{x13} \qquad (R^2 = 0.74)$$

The predicted and observed values for HC and NO_x are shown in Figures 2-6 and 2-7, respectively. In this case, the correlation for CO (not shown) was very poor. Note that NO_x intercept term is not significant at 0.05 level for these engines, whereas the HC intercept term is. As noted previously, the intercept term represents the portion of transient test emissions independent of steady-state test emissions. However, the hot start transient data from 15 other Cummins engines revealed poor correlation for HC emissions with an r^2 of 0.48. The NO_x regression for the hot start data showed an excellent r^2 of 0.88.

Unlike the data on gasoline engines, these regressions included a significant number of data points near or below the statutory HC and NO_x standards. Given the sensitivity of the regressions to the number of available data points and the small size of the data set, it was decided to examine the individual manufacturers regressions for HC and NO_x emissions as submitted to EPA and the EEA regressions in terms of the predicted steady-state emission values that were equivalent to the transient HC and NO_x standards recommended by California by 1985. Each submission from the manufacturers utilized different data, which are subsets of the data base used by EPA.

S T A T I S T I C A L   A N A L Y S I S   S Y S T E M   17:50 SATURDAY, AUGUST 6, 1983   3



NOTE: 4 OBS HIDDEN

FIGURE 2-6: HC CORRELATION - CUMMINS DIESEL

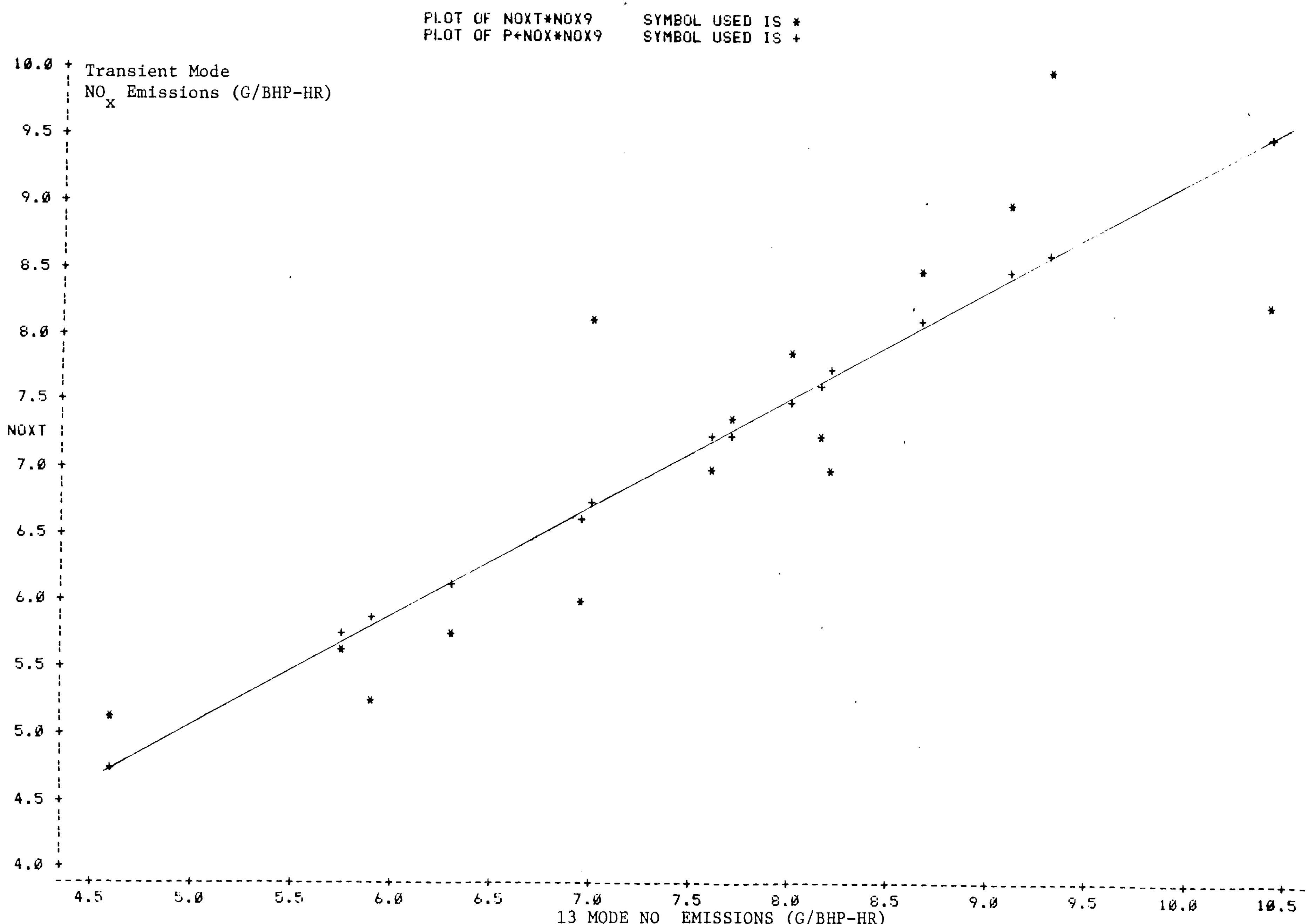


FIGURE 2-7: NO_x CORRELATION - CUMMINS DIESEL

Table 2-1 shows the comparison of HC regressions. The EEA (NC) and EEA (Cum) data refer to the regressions developed in this study by EEA for "Non-Cummins" and "Cummins" diesels respectively. The data from EPA are those developed by EPA using a larger data set (some data was unavailable to EEA) in support of the rulemaking on the new transient test procedure. The EMA (NC) and EMA (all) regressions are those provided by the Engine Manufacturers Association, for "Non-Cummins" and all engines, in their submission to the EPA docket under the rulemaking test procedures. Regressions from IHC, Mack and Mercedes-Benz are taken from individual company submissions to the same EPA docket. The regresson labelled Cummins (HS) is taken from a regression performed by EEA on the data on 15 Cummins engines tested only on the "hot start" phase.

The final column of Table 2-1 gives the predicted steady-state HC emission for transient HC standard of 1.3 g/BHP-hr. As can be seen, the equivalent steady-state emissions are between 1.0 and 1.1 g/BHP-hr for all engines other than Cummins and 0.56-0.58 g/BHP-hr for Cummins engines. Given measurement errors and lab-to-lab variations, these predicted values are in excellent agreement with each other. Note that regression of data from all engines predict a steady-state value of 0.89, approximately midway between the two sets of predictions for Cummins and non-Cummins engines.

Table 2-2 shows the comparison of NO_x regressions. Unlike the case with HC emissions, manufacturer specific differences at the 5.1 g/BHP-hr transient NO_x standard are not as severe and all manufacturers appear to have equivalent steady-state values between 4.5 and 5.0 g/BHP-hr. Again, given the measurement errors, the narrow range of values predicted show that the regressions are essentially in agreement.

TABLE 2-1

COMPARISON OF HC CORRELATIONS

	Regression	R^2	HCSS for HCT = 1.3
EEA (NC)[1/]	HCT = 0.167 + 1.05 HCSS	0.70	1.08
EEA (Cum)[2/]	HCT = 0.31 + 1.77 HCSS	0.79	0.56
EPA (all)	HCT = 0.45 + 0.96 HCSS	0.51	0.885
EMA (NC)	HCT = 0.162 + 1.04 HCSS	0.94	1.09
EMA (all)	HCT = 0.683 + 0.688 HCSS	0.33	0.89
IHC	HCT = 0.117 + 1.137 HCSS	0.96	1.04
Mack	HCT = 0.27 + 0.93 HCSS	?	1.11
Mercedes-Benz	N/A	-	0.99-1.27*
Cummins (HS)[3/]	HCT = 0.92 + 0.65 HCSS	0.48	0.58

[1/] NC = all engines except Cummins

[2/] Cum = Cummins engines only

[3/] HS = Hot start data

*Provided pictorially

TABLE 2-2

COMPARISON OF NO_x CORRELATIONS

	Regressions	R^2	NOXS for NOXT = 5.1
EEA (NC)	NOXT = 1.7 + 0.75 NOXS	0.82	4.53
EEA (Cum)	NOXT = 1.03 + 0.81 NOXS	0.74	5.02
EPA (all)	NOXT = 2.08 + 0.685 NOXS	0.72	4.41
EMA (NC)	NOXT = 0.173 + 0.987 NOXS	0.91	4.99
EMA (all)	NOXT = 0.418 + 0.87 NOXS	0.77	5.38
IHC	NOXT = -0.449 + 1.143 NOXS	0.98	4.85
Mack	NOXT = 0.5 + 0.95 NOXS	?	4.84
Cum (HS)	NOXT = 1.77 + 0.73 NOXS	0.88	4.56

In summary, EEA has established:

- The correlation between transient and steady-state diesel NO_x and HC emissions is improved significantly if Cummins engines are treated as a separate group.
- Although regression equations derived by each manufacturer, EPA, EMA, and EEA appear different, they are in excellent agreement at or near the statutory transient emission standards.
- The 1.3 g/BHP-hr transient HC standard is equivalent to a steady-state standard of 0.56-0.58 g/BHP-hr for Cummins engines and 1.0-1.1 g/BHP-hr for all other diesel engines.
- The 5.1 g/BHP-hr transient NO_x standard is equivalent to a steady-state standard of 4.5-5.0 g/BHP-hr for all diesel engines.

3. CONVERSION FACTOR FOR HEAVY-DUTY TRUCK EMISSIONS

3.1 OVERVIEW

The emission standards and engine emission tests are measured in units of mass emissions per horsepower, i.e., in gm/BHP-hr. Emission factors utilized for heavy-duty trucks are required to be in the units of gm/mile and, hence, a conversion factor is needed to link the two units. As can be seen:

$$\text{gm/mile} = \text{gm/BHP-hr} \times \text{BHP-hr/mile}$$

The conversion factor in BHP-hr/mile is the work required to move the HDT one mile, and is an average for all the HDT's sold. This factor is theoretically independent of the type of engine used for identical trucks, although in real life, the weight of the engine as well as the truck use pattern varies by engine type (diesel or gasoline) and affects the conversion factor.

The term "heavy-duty" truck also spans a wide range of truck weights from the light pick-up truck to an over-the-road 80,000 lb GVW truck. Since the work required to move the trucks is highly dependent on the truck weight and use pattern, the conversion factor must be derived for subsets of HDT weight classes that are relatively homogenous in weight, power and use pattern. Accordingly, the conversion factor was observed at the industry specified gross vehicle weight (GVW) class level with some minor exceptions. The analysis was performed for the Motor Vehicle Manufacturers Association and is summarized below. Since the definition of heavy-duty truck changed in 1979, EEA performed two separate analyses, one for the 1962-1978 period and the other for the 1979-2002 period.

3.2 CONVERSION FACTOR FOR THE 1962-1978 PERIOD

For this period, the following formula was used to develop the conversion factor by class:

$$\frac{\text{BHP-hr}}{\text{mi}} = \frac{\text{BHP-hr}}{\text{lb-fuel}} \times \frac{\text{lb-fuel}}{\text{gal}} \times \frac{\text{gal}}{\text{mile}}$$

$$= \frac{\text{Fuel Density}}{\text{BSFC x MPG}}$$

where BSFC is the brake specific fuel consumption of the engine and MPG is the fuel economy (in miles per gallon) of the vehicle.

This formula was utilized to derive the class specific conversion factor for the following GVW classes:

- Class II, light commercial trucks
- Class III-V, light-heavy trucks
- Class VI, 19,500-26,000 lb GVW
- Class VII, 26,000-33,000 lb GVW
- Class VIII, 33,000-80,000 lb GVW

Fuel economy estimates for each class during the 1962-1978 period were derived from a detailed analysis of the 1977 Truck Inventory and Use Survey (TIUS) which is a survey of trucks conducted by the Bureau of Census every five years. Figure 3-1 shows the fuel economy of gasoline trucks for each of the GVW classes, and are smoothed values of the TIUS data. Unfortunately, prior to 1978 there were very few diesel trucks sold in Classes II, III-V and VI and hence the survey has very small samples of diesel trucks in these categories. Figure 3-2 shows the nationwide diesel penetration of new trucks by GVW class. Since diesel truck sales in Classes II and III-V were essentially zero, their fuel economy was not important to the derivation, but a fuel economy estimate for Class VI diesel trucks was derived from the TIUS estimate for Class

FIGURE 3-1

FUEL ECONOMY (GASOLINE TRUCKS)

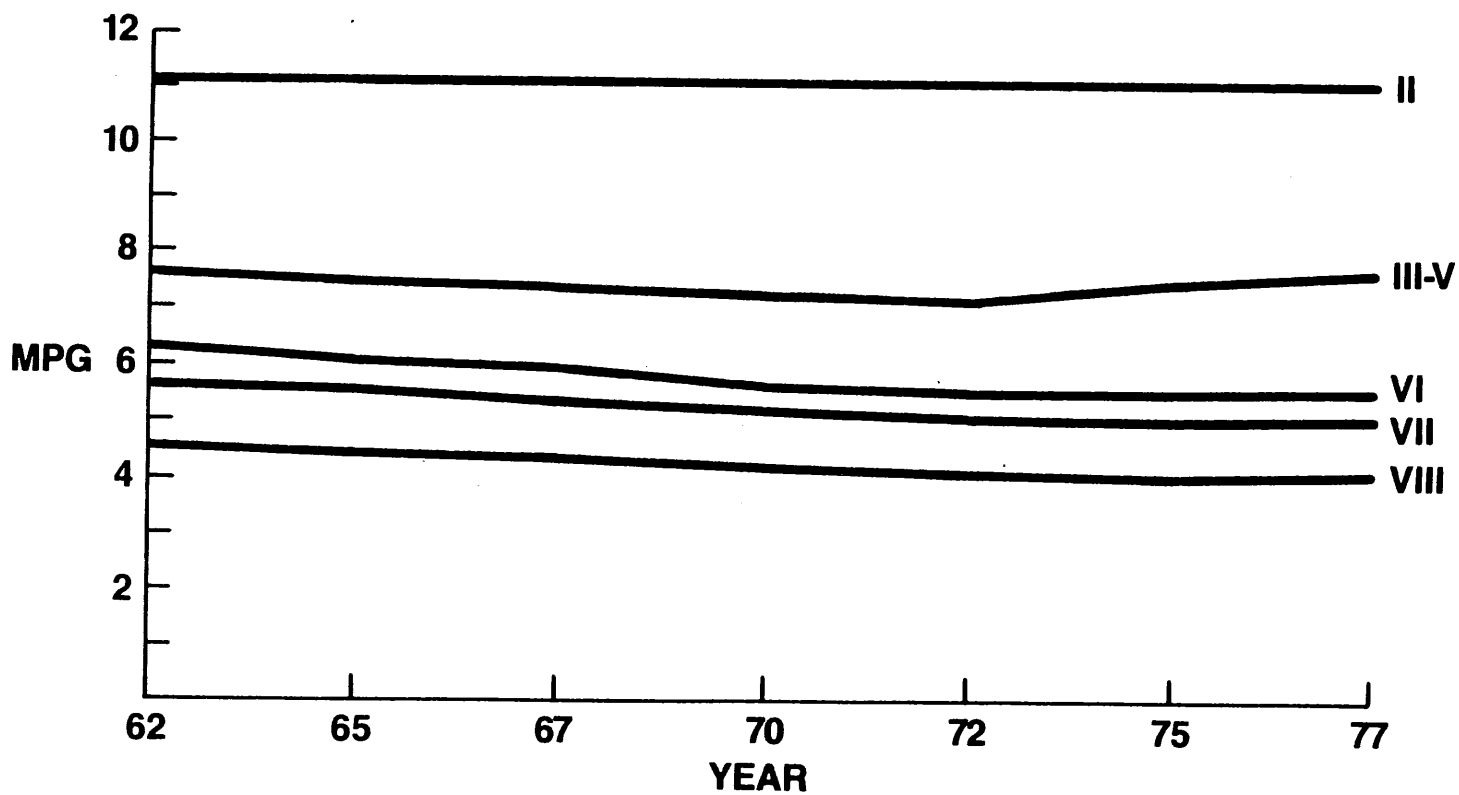
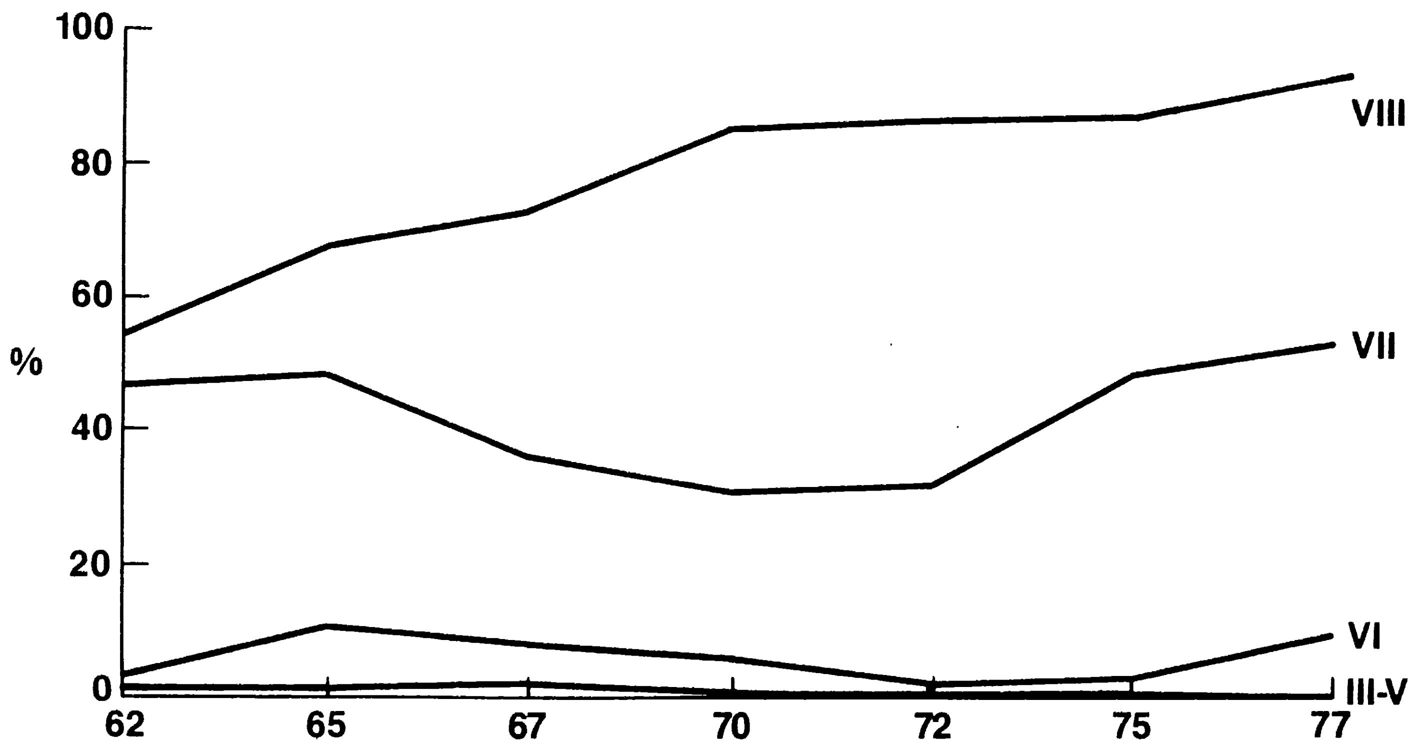


FIGURE 3-2

DIESEL PENETRATION (%)



VII diesel trucks by readjusting on the basis of the ratiosn of average GVW. EEA's estimate for fuel economy for Classes VI, VII and VIII diesel trucks are shown in Figure 3-3.

BSFC values for gasoline engines were based on the transient tests performed on gasoline engines, whose emission results were analyzed in Section 2 of this report. The test results showed little variation in BSFC between 1969, 1973 and 1979 engines with all results lying between 0.68-0.72 lb/BHP-hr. Accordingly, EEA assumed a value of 0.7 lb/BHP-hr for the BSFC of gasoline engines in the entire 1962-1978 period. For diesel engines, EEA obtained actual average brake specific fuel consumption by GVW class for 1977 from the engine manufacturers. The values were 0.43 for Class VIII vehicles and 0.45 for Class VI and VII vehicle. This BSFC was adjusted in the historical period by the estimated changes due to introduction of new technology. EEA estimated that BSFC for GVW Class VIII has declined 10 perent in the 1972 to 1977 time frame primarily as a result of increased turbocharging and decrease in rated RPM, and an additional 5 percent in the 1962-1972 time frame due to combustion chamber and fuel injection improvements as well as some increase in turbocharging. In the medium-duty Class VI and VII segment, BSFC remained approximately constant from 1962 to 1967 but began declining following the introduction of the advanced technology CAT 3208 in 1969. As the market share of the CAT3208 grew and International Harvester introduced the DT466 in 1975, BSFC declined by 10 percent in the 10 year period between 1967 and 1977.

Using these values of BSFC and MPG, the derivation of the class specific conversion factor is straightforward. The derived values for each class over the 1962-1978 time frame is shown in Table 3-1.

3.3 CONVERSION FACTOR FOR THE 1979-2002 PERIOD

The derivation of the class specific conversion factor follows a different methodology than the one used to estimate the historical conversion

FIGURE 3-3

FUEL ECONOMY (DIESEL TRUCKS)

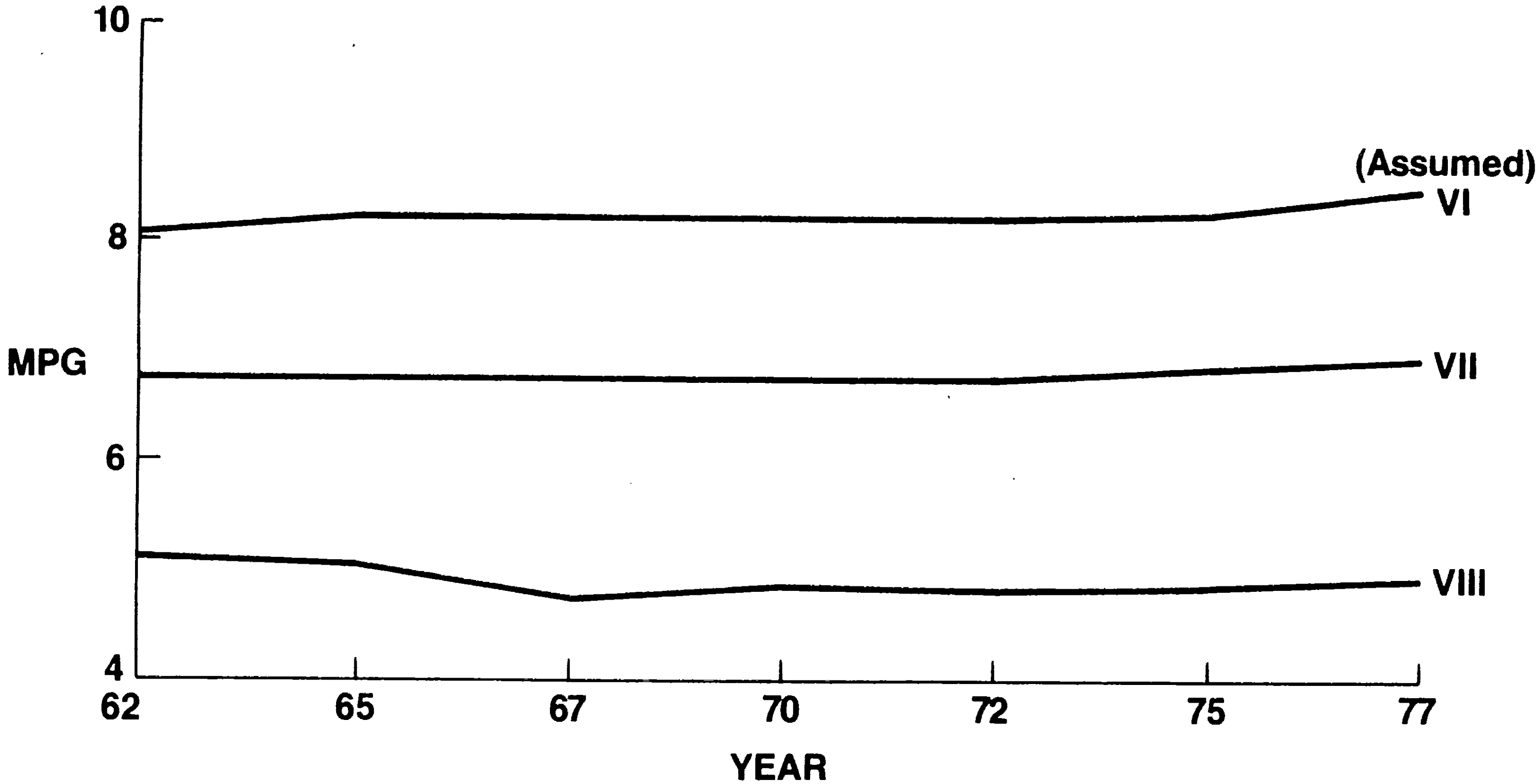


TABLE 3-1

GVW CLASS SPECIFIC CONVERSION FACTORS

1962-1978

	II		III-V		VI		VII		VIII	
	G	D	G	D	G	D	G	D	G	D
1962	0.79	0.87	1.15	-	1.38	1.71	1.37	2.19	1.92	2.80
1965	0.79	0.87	1.18	-	1.44	1.71	1.60	2.19	1.99	2.86
1967	0.79	0.87	1.19	-	1.48	1.71	1.64	2.23	2.02	2.97
1970	0.79	0.87	1.22	-	1.53	1.75	1.68	2.28	2.09	3.08
1972	0.79	0.87	1.24	-	1.57	1.82	1.71	2.28	2.15	3.19
1975	0.79	0.87	1.19	-	1.60	1.86	1.74	2.29	2.17	3.26
1977	0.79	0.87	1.15	-	1.57	1.87	1.72	2.27	2.12	3.34
1978	0.79	0.87	1.13	-	1.56	1.86	1.70	2.20	2.07	3.29

G = Gasoline

D = Diesel

factor. For this period, the year 1977 is used as a baseline from which conversion factors are projected forward from the 1977 values derived as discussed in Section 3.2. The conversion factor, BHP-hr/mi, is a measure of truck efficiency for all components other than the engine. (Note that in the formula based on MPG x BSFC, any decrease in BSFC is offset by an increase in MPG). The conversion factor can therefore be derived using the formula:

$$C.F. = (C.F.)_{1977} \times \text{(Non-engine related fuel economy improvements to trucks)}$$

Within each weight class, the non-engine related improvements to fuel economy are accomplished through new technology. A detailed survey by EEA revealed the following technologies to be significant in the time period considered.

- Weight reduction - The empty weight of the truck is being reduced through material substitution. Its effects are important primarily in light and medium trucks where the empty weight of the truck is a significant portion of the weight of the average payload.
- Drag reduction - The use of aerodynamic add-on devices or aerodynamic cab designs is increasingly prevalent. Since aerodynamic power increases as the cube of speed, its effects are most significant for over-the-road Class VIII trucks.
- Drivetrain improvements - The use of multispeed and overdrive transmissions aid in improving the efficiency with which the engine power is delivered at optimal operating conditions. Other improvements include the use of lower axle ratios, tag axles and torque converter clutches for automatic transmissions.
- Reduced rolling resistance is accomplished through the use of radial tires instead of bias-ply tires, and more recently, the use of the advanced "low profile" radial tire.
- Frictional and accessory power reduction is being accomplished through the use of advanced lubricants (with friction modifiers and/or viscosity index improvers) and redesigned accessories such as water pumps, vaccuum pumps and related accessory devices. The single largest improvement will arise from the fan clutch which couples the cooling fan to the engine only when necessary.

- Driver behavior modifiers such as shift indicators for manual gearboxes and speed limiters/cruise control devices will improve truck efficiency by helping drivers prevent wasteful driving modes.

Naturally, the influence of each of these technologies and the potential market penetration are functions of both the GVW class of the truck and its use patterns. The DOT also collects information on the market penetration of "fuel-efficient" technologies by GVW class and this information is publicly available for the 1977-1982 period.

In order to examine the future market penetration potential of each technology considered, the HDT fleet was separated into three groups, namely:

- Light-Heavy, covering the 8,501-16,000 lb GVW classes
- Medium-Heavy, covering vehicles over 16,000 to 50,000 lb GVW/GCW
- Heavy-Heavy, covering all vehicles over 50,000 lbs GVW

These weight class groups were based on similarity of operating characteristics, as well as the similarity of engines utilized in each vehicle. In fact, there are few vehicles sold between 10,000 and 20,000 lbs GVW and hence the class specifications are more narrow than it appears.

Based on a detailed study of manufacturer product plans in each segment, EEA has forecast technology improvement by weight class group in five-year segments from 1977 to 1997. Each technology's effect on fuel economy is shown in Tables 3-2, 3-3 and 3-4 for light-, medium-, and heavy-heavy duty trucks respectively.

Starting from the base conversion factors by class derived as shown in Section 3.2, it is then relatively straightforward to project conversion factor by GVW class. These projections are shown in Table 3-5.

TABLE 3-2

NON-ENGINE RELATED IMPROVEMENTS
TO LIGHT-HEAVY TRUCKS

(Percent Improvement in Fuel Economy)

	1977-1982	1982-1987	1987-1992	1992-1997
Weight reduction	3.3	-	3.3	-
Aerodynamic drag	1.7	-	1.7	-
Accessories	1.0	1.0	-	-
Lubricants (drivetrain)	-	0.5	0.5	0.5
AOD	-	1.6	1.6	1.6
MOD	0.5	0.5	0.5	0.5
ETC	-	-	1.5	1.5
Tires (Radials/Advanced Radials)	1.0	1.0	1.0	1.0
Total	7.5	4.6	10.1	4.1

TABLE 3-3

NON-ENGINE RELATED
IMPROVEMENTS TO MEDIUM-HEAVY TRUCKS

(Percent Improvement in Fuel Economy)

Technology	% F/E Gain	1977-1982 ΔF/E	1982-1987 ΔF/E	1987-1992 ΔF/E	1992-1997 ΔF/E
Weight reduction	*	1.5	1.5	1.5	1.5
Aerodynamics (Body)	4.0	1.0	1.0	1.0	1.0
Aerodynamics (Add-on)	6.0	0.2	0.1	0.2	0.3
Radial tires	4.0	0.3	-	(-0.3)	(-0.3)
Advanced radials	8.0	-	0.5	0.7	1.2
Drivetrain Lubricants	1.5	-	0.5	0.5	0.5
Fan drives	4.0	2.1	1.2	-	-
Shift Indicator/ETC	5.0	-	0.5	0.5	0.5
Speed control	6.0	0.3	0.1	0.2	0.3
Other accessories	2.0	0.3	0.3	0.3	0.3
Total		5.7	5.7	4.6	4.3

*1.5 percent fuel economy benefit for ~400lb reduction in empty weight.

TABLE 3-4

NON-ENGINE RELATED
IMPROVEMENTS TO HEAVY-HEAVY TRUCKS

(Percent Improvement in Fuel Economy)

Technology	% F/E Gain	1977-1982 ΔF/E	1982-1987 ΔF/E	1987-1992 ΔF/E	1992-1997 ΔF/E
Aerodynamics (Body)	9.0	2.0	2.0	2.5	2.5
Aerodynamics (Add-on)	6.0	0.7	0.7	0.9	0.6
Radial tires	6.0	2.4	(-1.2)	(-1.5)	(-1.2)
Advanced radials	12.0	0.2	2.8	3.0	2.4
Drivetrain Lubricants	1.5	-	0.5	0.5	0.5
Fan drives	6.0	3.0	0.2	-	-
Other Accessories	2.0	0.3	0.5	0.5	0.5
Drivetrain	3.0	1.0	1.0	1.0	-
Total		9.0	8.5	7.4	5.3

TABLE 3-5

GVW CLASS SPECIFIC CONVERSION FACTORS

1979-2002

	II(b)-IV		VI		VII		VIIIG(1)		VIIIG(2)	
	G	D	G	D	G	D	G	D	G	D
1979	0.87	0.89	1.56	1.82	1.70	2.14	1.97	2.94	-	3.30
1982	0.81	0.89	1.50	1.76	1.65	2.06	1.92	2.84	-	3.12
1987	0.77	0.85	1.44	1.66	1.58	1.95	1.83	2.68	-	2.88
1992	0.70	0.77	1.38	1.59	1.52	1.86	1.77	2.57	-	2.68
1997	0.67	0.74	1.33	1.50	1.46	1.77	1.69	2.43	-	2.54
2002	0.65	0.71	1.27	1.43	1.40	1.68	1.62	2.31	-	2.41

Weighted Average Conversion Factor

Since the MOBILEII and EMFAC models utilize one single heavy-duty emission factor for all heavy-duty trucks, the conversion factors derived for each GVW class must be averaged. The averaging must account for:

- Sales by weight category/model year
- Diesel penetration by weight category/model year
- Average truck travel by weight class (VMT/year)

In addition, since most air quality models are for urban areas, the travel must be further weighted by the percent of travel in urban areas. Thus, the average urban conversion factor for gasoline trucks, GCFU is given by:

$$GCFU = \frac{\sum_i SF_i \times (1-DF_i) \times VMT_{ig} \times UF_{ig} \times CF_{ig}}{\sum_i SF_i \times D_i \; (1-DF_i) \times VMT_{ig} \times UF_{ig}}$$

and the diesel urban conversion factor is:

$$DCFU = \frac{\sum_i SF_i \times DF_i \times VMT_{id} \times UF_{id} \times CF_{id}}{\sum_i SF_i \times DF_i \times VMT_{id} \times UF_{id}}$$

where SF = the sales fraction of class, i

DF = the in-class diesel fraction

$VMT_{i,d/g}$ = the annual vehicle miles of travel for trucks in class, gasoline or diesel

$UF_{i,d/g}$ = the fraction travel in urban areas

$CF_{i,d/g}$ = the conversion factor for the ith GVW class, gasoline or diesel.

These urban conversion factors are based on summing over all GVW classes in the heavy-duty fleet.

An analysis of TIUS data provided the average VMT and travel fraction by GVW class, for gasoline and diesel separately, as shown in Table 3-6. EEA was unable to obtain class specific sales and diesel penetration for California heavy-duty trucks. However, conversion factors derived using sales fractions and diesel penetration for the national fleet are shown in Figures 3-4 and 3-5 for the 1962-1978 and 1979-2002 period respectively.

The very sharp drop in diesel conversion factor for 1982 is primarily due to the introduction of diesels in the light-heavy (Class IIB) class of trucks. If the California mix of trucks and diesel penetration is not substantially different from the national fleet, EEA recommends that the national values for the conversion factor be utilized.

More recently, EPA published a set of alternative conversion factors that are based upon a slightly different weighting of urban travel fractions and a more conservative projection of future non-engine related technological improvements. In addition, buses are not included in the EEA conversion factor but are in the EPA conversion factor, since EEA believes that bus emissions should be treated separately. The EPA values were derived using the EEA analysis as a base. Although EEA believes that the conversion factors derived by EPA are too pessimistic, it is provided in Table 3-7 along with EEA values; the CARB can utilize either set of factors depending on its needs for consistency with EPA assumptions.

TABLE 3-6

USE PATTERNS OF HEAVY-DUTY TRUCKS
(Percent of Total VMT/Class)

		VMT(mi)	Urban	Short Range	Long Range
II(gas)		10,676	79.0	16.8	4.2
II(b)	G	11,614	79.0	16.8	4.2
	D*	11,614	79.0	16.8	4.2
III-V	G	9,832	78.1	19.6	2.2
	D	18,883	61.5	24.0	14.5
VI	G	9,734	75.0	22.0	3.0
	D	22,187	45.5	39.5	15.0
VII	G	11,223	71.4	25.0	3.8
	D	25,883	39.0	42.0	19.0
VIIIG(1)	G	15,560	71.3	24.5	4.2
	D	29,950	36.5	31.5	32.0
VIIIG(2)	D	62,500	13.0	34.0	52.0

*Class II(b) diesel use pattern assumed to be equal to that for Class II(b) gasoline.

FIGURE 3-4

CONVERSION FACTOR (BHP-hr/mi) 1962–1978 (INCLUDES CLASS II–VIII)

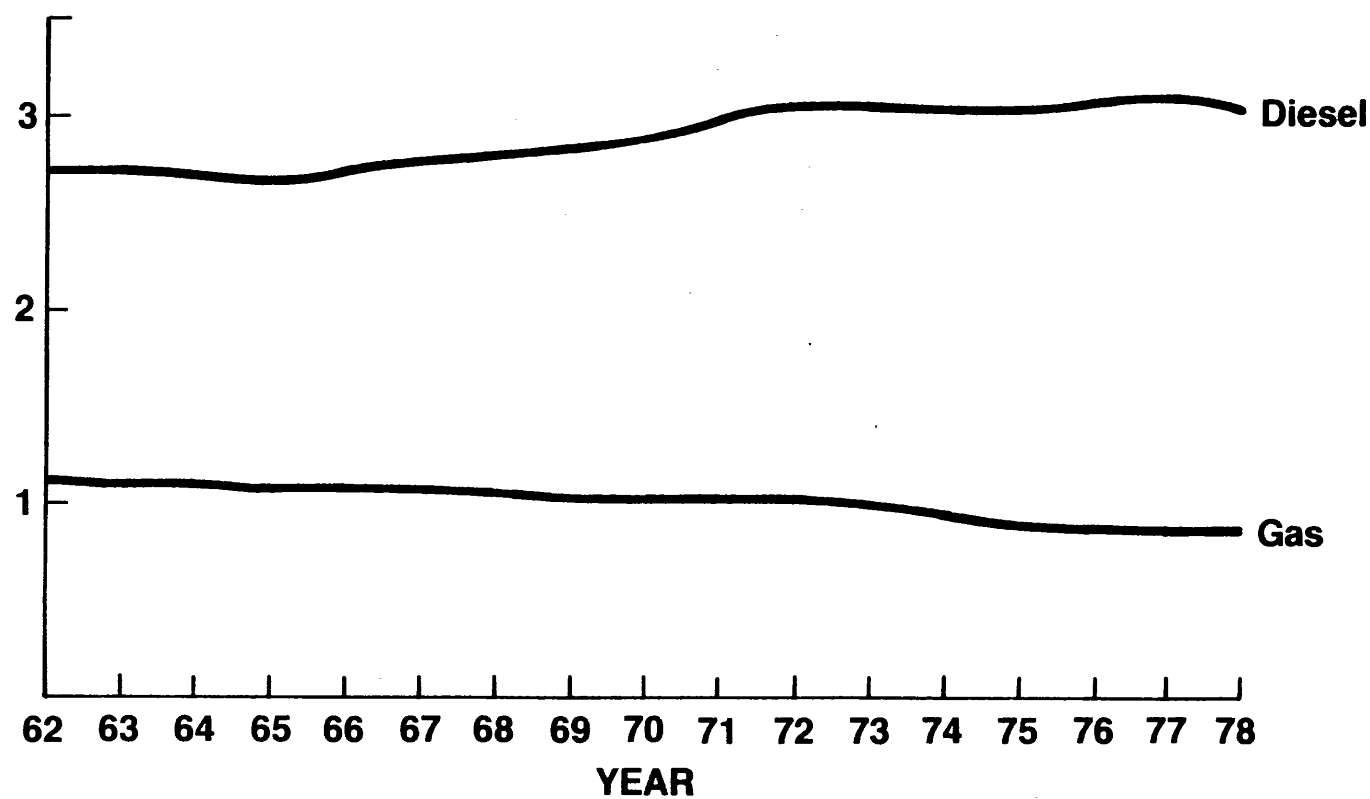


FIGURE 3-5

CONVERSION FACTOR (BHP-hr/mi) 1979–2002

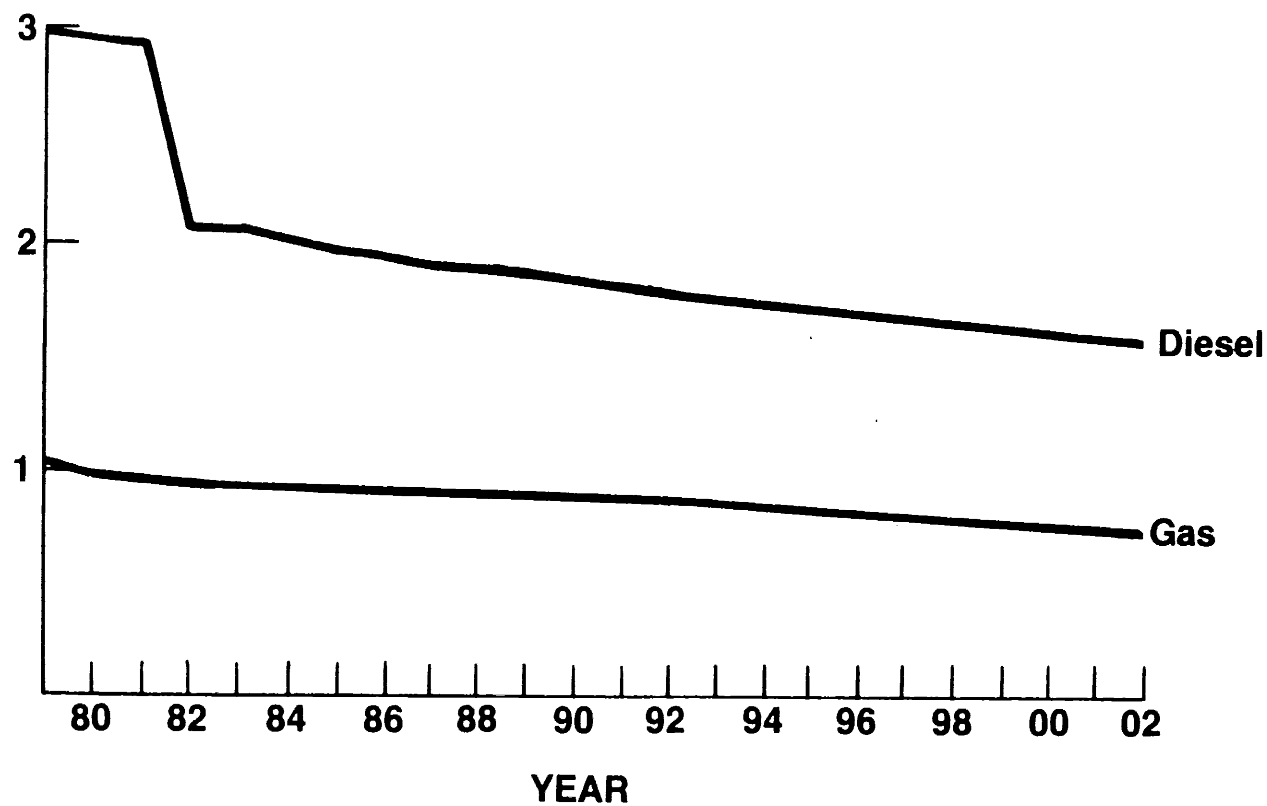


TABLE 3-7

CONVERSION FACTORS
EPA vs. EEA

Diesel	EPA	EEA	% Diff.
1962	2.74	2.58	6.2
1967	2.83	2.80	0
1972	3.19	3.12	2.2
1977	3.19	3.23	-1.25
1982	2.60	2.09	24.40
1987	2.38	1.89	25.92
1992	2.33	1.76	32.37
1997	2.28	1.68	36.07
Gasoline			
1962	*	1.110	--
1967	*	1.075	--
1972	*	1.018	--
1977	1.158	1.008	14.88
1982	0.941	0.900	4.55
1987	0.980	0.895	9.50
1992	0.967	0.822	17.64
1997	0.941	0.775	21.42

*Not comparable because EPA's conversion factor does not include Class II(a) trucks.

4. REVIEW OF EPA EMISSION FACTOR ESTIMATES

4.1 OVERVIEW

The emission factors for heavy-duty trucks utilized in both the EPA-MOBILEII model and the CARB-EMFAC model are identical and based on estimates prepared by EPA staff. The actual methodology utilized in estimating these factors was never published; however, EEA obtained an unpublished internal draft from the EPA, which outlined the procedure utilized to estimate the basic exhaust emission rates for Low-Altitude California vehicles. The basic emission rate (BER) consists of two factors--a zero mile (ZM) emission level and a deterioration rate (DR)--and is expressed as:

$$\text{Basic Emission rate} = ZM + (DR \times VMT)$$

where VMT is vehicle miles travelled. The BER's are derived for each particular set of standards and are, hence, applicable to those groups of model years having uniform emission standards. The following subsections summarize the EPA methodology used to derive the basic emission rates, for gasoline and diesel vehicles separately.

4.2 GASOLINE HDT EMISSION RATES

In general, the derivation of emission rates utilizes a methodology similar to that used for the derivation of the 49-state exhaust emission factor.

Pre-1969

These emission rates are identical to that for Federal vehicles of the same classification. The ZM rates were derived from test results on five 1969 engines tested by South-West Research Institute. The test results in gm/BHP-hr were converted to gm/mile by utilizing a conversion factor of 1.74. (The derivation of this conversion factor estimate, which appears to be incorrect, was not documented by EPA.)

The deterioration rate was estimated from the DR of pre-1970 light-duty gasoline vehicles by assuming that it varied proportionally with the ZM emissions, i.e.,

$$\frac{\text{HDGT (DR)}}{\text{HDGT (ZM)}} = \frac{\text{LDGT (DR)}}{\text{LDGT (ZM)}}$$

<u>1969-1971</u>

The California emission factors are identical to the Federal 1970-1973 HDGT emission factors. The ZM emissions are derived from test results on nine 1972/1973 engines tested at South-West Research Institute. The average emissions in gm/BHP-hr was converted to gm/mile utilizing the same conversion factor, 1.74. The DR's were estimated using the same formulae as for the pre-1969 vehicles.

<u>1972-1984</u>

The ZM levels for 1972-1974 for HC and CO are the same as those for 1969-1971 for HC and CO. The DR's however, are adjusted downward and are derived from the 1974-1978 LDGT vehicles using the same formulae described above.

The 1972 zero mile NO_x emission rates were derived from 1970/1971 LDGT NO_x emission rates using the following formula:

$$\frac{\text{HDGV (1972 ZM)}}{\text{HDGV (1971 ZM)}} = \frac{\text{LDGT (1972 ZM)}}{\text{LDGT (1971 ZM)}}$$

but the 1972 NO_x DR = 1971 NO_x DR.

The 1973-1974 NO_x emission rates were derived from the 1979 Federal NO_x emission rate (which, in turn, was determined from data on eleven 1979 engines detailed in Section 2 of this report).

All other basic emission rates (BER) up to 1984 were derived based on a ratio of appropriate emission standards. For example, the ZM levels for 1977-1979 California HDGV's was related to the Federal 1979 emissions using the formula:

$$\frac{\text{California ZM}}{\text{California Emission Standard}} = \frac{\text{Federal ZM}}{\text{Federal Emission Standard}}$$

for each pollutant. The DR's were then derived from DR's of previous model years in the ratio of the ZM emissions.

1984

The new transient test procedures, revised standards, new SEA requirements and the need for oxidation catalysts required a new methodology. The ZM was derived using the following equation:

$$ZM = (AF_{SEA} \times \frac{\text{Max. Pass Level}}{DF}) \times CF \times MF$$

where AF_{SEA} = the variability adjustment factors for the 10 percent AQL program. The factors are 0.81 for HC, 0.68 for CO and 0.63 for NO_x

DF = The full useful life deterioration factors which are 1.4 for HC, 1.3 for CO and 1.04 for HC

CF = The conversion factor BHP-hr/mi assumed to be 1.74

MF = The misfueling factors which are 1.188 for HC, 1.118 for CO and 1.0 for NO_x

The formula simply relates certification to zero mile emission levels, although EPA does not document the misfueling factor derivation. For the 1985+ (now 1987+) NO_x standards, the same formula is used except the DF's and MF's are changed to accomodate the use of three-way catalyst technology.

The DR's for catalyst-equipped trucks are once again based on the DR for LDGT's of the 1984 model year, and derived on the basis of proportionality between ZM levels.

The HDGT emission factors for all years are shown in Table 4-1. Note that recent developments in the promulgation of new emission standards have not been included.

4.3 DIESEL HDT EMISSION RATES

The ZM emission levels for pre-1984 HC and CO and pre-1977 NO_x are identical to the pre-1984 Federal emission rates for all three pollutants. The ZM emission rates were derived from a sales weighted average of the 1979 certification data (from 13-mode tests) and converted to transient cycle emissions based on regression developed by EPA and discussed in Section 2 of this report. The gm/BHP-hr emissions were converted to gm/mile based on a 2.82 conversion factor. (The derivation of this estimate was not documented in available EPA reports).

Deterioration rates for the diesel vehicles were related to pre-1975 DR's for light-duty diesel vehicles (LDDV). Further the DR's were divided by five to account for heavy-duty diesel engine having approximately five times greater useful life than a LDDV. The DR's were based on the following formula.

$$\frac{\text{HDDT (DR)}}{\text{HDDT (ZM)}} = \frac{\text{LDDV (DR)/5}}{\text{LDDV (ZM)}}$$

The NO_x emission rate for 1977 to 1984 was derived on the basis of the reduced $HC+NO_x$ California standard in comparison to the Federal level, using the following formula:

$$\frac{\text{ZM (1977+)}}{\text{ZM (pre-1977)}} = \frac{\text{Standard (1977+)}}{\text{Standard (pre-1977)}}$$

No change was made to deterioration rate estimates, however.

TABLE 4-1

EXHAUST EMISSION RATES FOR
CALIFORNIA
HEAVY DUTY GASOLINE POWERED VEHICLES

* BER = ZML + (DR * M)

Pol	Model Years	Zero Mile Emission Level (Grams/Mile)	Deterioration Rate (Gm/Mi/10K Mi)	50,000 Mile Emission Level (Grams/Mile)
HC	Pre-1969	18.26	0.35	20.01
	1969-1971	11.09	0.47	13.44
	1972	11.09	0.32	12.69
	1973-1974	11.09	0.32	12.69
	1975-1976	6.93	0.32	8.53
	1977-1979	3.25	0.14	3.95
	1980-1983	3.25	0.14	3.95
	1984+	1.62	0.39	3.57
CO	Pre-1969	227.63	5.46	254.93
	1969-1971	190.20	8.75	233.95
	1972	190.20	8.37	232.05
	1973-1974	190.20	8.37	232.05
	1975-1976	159.85	8.37	201.70
	1977-1979	144.67	6.37	176.52
	1980-1983	144.67	6.37	176.52
	1984+	15.82	3.48	33.22
NOx	Pre-1969	8.88	0.0	8.88
	1969-1971	11.40	0.0	11.40
	1972	12.65	0.0	12.65
	1973-1974	9.45	0.09	9.90
	1975-1976	9.45	0.09	9.90
	1977-1979	8.03	0.09	8.48
	1980-1983	5.67	0.09	6.12
	1984+	4.25	0.09	4.70

* WHERE:
- BER = Basic emission rate
- ZML = Zero mile level
- DR = Deterioration rate
- M = Cumulative mileage / 10,000

DATE: MARCH 31, 1981

1985+

The revised requirements for the SEA and the new test procedure requirements result in HC and NO_x ZM levels derived according to the following formula:

$$ZM = (AF_{SEA} \times (\text{Max. Pass Level} - DF) \times CF$$

where: AF_{SEA} is the variability adjustment factor equal to 0.72 for HC and 0.68 for NO_x.

Max. Pass Level is equal to 1.35 for HC and 1.75 for NO_x.

DF is the deterioration factor equal to 0.43 for HC and 0.18 for NO_x.

CF is the conversion factor held constant at 2.82.

The CO basic emission rate is unchanged (as diesel CO emissions are far below applicable standards). The DR's for all three pollutants remain unchanged from pre-1985 estimates.

Table 4-2 shows the California emission factors for HDDT's.

TABLE 4-2

EXHAUST EMISSION RATES FOR
CALIFORNIA
HEAVY DUTY DIESEL POWERED VEHICLES

* BER = ZML + (DR * M)

Pol	Model Years	Zero Mile Emission Level (Grams/Mile)	Deterioration Rate (Gm/Mi/10K Mi)	50,000 Mile Emission Level (Grams/Mile)
HC	Pre-1984	3.49	0.04	3.69
	1984+	2.65	0.04	2.85
CO	Pre-1984	10.91	0.10	11.41
	1984+	10.91	0.10	11.41
NOx	Pre-1977	22.90	0.12	23.50
	1977-1979	19.47	0.12	20.07
	1980-1983	13.74	0.12	14.34
	1984+	10.31	0.12	10.91

* WHERE:
BER = Basic emission rate
ZML = Zero mile level
DR = Deterioration rate
M = Cumulative mileage / 10,000

DATE: MARCH 31, 1981

5. RECOMMENDATIONS FOR IMPROVEMENTS TO HDT EMISSION FACTORS

5.1 OVERVIEW

The review of the methodology used to derive the existing HDGT emission factors makes the shortcomings of these factors obvious. The zero mile levels are derived either from a small sample of engines tested or are based on the emission standards. Deterioration factors are obtained, for the most part, from light-duty truck deterioration factors in proportion to the ratio of light- to heavy-duty truck zero mile emission levels. There is little engineering rationale to support the theory of a multiplicative deterioration rate being constant across all non-catalyst gasoline engines (which forms the basis of the method of proportioning deterioration rates to the zero mile emissions). In fact, the multiplicative approach has been applied primarily to catalyst-equipped vehicles only, none of which are present in the HDT fleet until 1987. Accordingly, alternate measures are suggested by EEA to improve the methodology and accuracy of the emission factor estimate.

5.2 GASOLINE HDT EMISSION FACTORS

The principal problems associated with the estimate of ZM emission levels in gasoline engines appear to be one of sample size and sample representativeness. The ZM levels were based on samples of five 1969 engines, nine 1973 engines and 11 1979 engines. In addition, although sales of gasoline powered HDT's are overwhelmingly in the 6,000-10,000 lb category, most of the engines tested by EPA are typical of those found in trucks over 16,000 lbs GVW. Very few trucks are sold in the 10,000 to 16,000 lb GVW category and are, therefore, unimportant for analysis.

The 6,000 to 10,000 lb category of trucks is counted as a single class of trucks by the industry (Class II). In 1979, this category was split into two with the 6,000 to 8,500 lb (IIa) category moving to the light-duty truck category similar to vehicles in Class I, and the 8,500 to 10,000 lb (IIb) category remaining in the HDT classification. However, trucks sold in classes IIa and IIb were nearly identical in shape, design and technology prior to 1979. In fact, little data exists to even break out the II(a) and II(b) populations and the distinction is even more difficult in real life. The CARB collects data on the 6,000 to 8,500 lb category of trucks through their surveillance programs. EEA recommends utilizing data generated from these programs to estimate emission factors for the 8,500 to 10,000 lb category of HDGT's. Since approximately 80 percent of all HDGT's fall within this category, the overall accuracy of the emission factor of gasoline trucks should improve enormously. Such a move would, however, require that the CARB's air quality model be able to treat HDGT's as two separate populations. EEA recommends that the cut-point between the two populations be placed at 14,000 lbs GVW. EPA's recent emission regulations (see Section 6) have utilized this cutpoint to separate the two classes, and different emission regulations will apply to each class in the post-1987 time frame.

For gasoline trucks over 16,000 lbs, there are no alternatives currently available to the small sample of EPA test data to estimate zero mile emission. However, even here, EEA recommends the use of the newly derived GVW class specific conversion factors that can be utilized after sales weighting the factors according to the distribution of actual gasoline truck sales by GVW class in California.

Deterioration factors for gasoline powered trucks over 16,000 lbs GVW have, in the past, been assessed from light-duty truck deterioration factors. However, EEA believes that this may lead to a potential over-statement of the HDGT deterioration factor. We have arrived at this conclusion by examining the malperformances in HDGT engines. The potential malperformances include:

- Choke systems
- Spark timing
- Idle-air fuel ratio
- Air pump disconnect/EGR disconnect

Since cold start emissions have not been controlled,, manufacturer specification for the choke setting are likely to be biased in the direction of optimum driveability rather than minimum emissions. Accordingly, maladjustment of the choke appears equally likely in both directions--richer and leaner--than the manufacturer recommended setting. These maladjustments are likely to have offsetting emissions and hence the importance of these maladjustments is not as great as in LDV's.

Similarly, spark timing is set close to the knock limit on HDGT's, which experience a high percentage of full-load operation. Manufacturers are of the opinion that fear of knock in most operators will dissuade them from advancing the timing significantly, while timing retard has generally favorable effects on HC and NO_x emissions. Accordingly, spark timing maladjustments are unlikely to have much impact on the deterioration factor.

Idle air-fuel ratio, however, is likely to be commonly maladjusted. For example, surveys by New York State found trucks with idle CO in excess of 10 percent. In Section 2 of this report, EEA has developed an equation that relates the idle CO percentage to the transient test emissions and we recommend the use of this equation to estimate the influence of idle CO maladjustment on HC, CO and NO_x emissions. Data on average idle CO emissions is a function of odometer and may be available from inspection programs such as the Phoenix I/M program which requires all gasoline vehicles to be inspected for emissions annually. More recently, EPA and the CARB have required that idle mixture adjustments be sealed for trucks starting in MY 1984.

On the rate or effect of EGR and air pump disconnects, however, there is no information available that EEA has been able to procure. We are aware of an EPA program that was recently started to test gasoline HDT's in an as received condition. This program may provide data on the effect of disconnecting the air pump or EGR systems. We recommend that the CARB initiate a survey of HDGT's to obtain information on the rate of EGR and air pump disconnections.

5.3 HD DIESEL EMISSION FACTORS

All emission factors for diesel engines have relied on the 1979 certification data and the EPA "1979 baseline" tests to derive zero mile emission factors for all engines. Conversion of these gm/BHP-hr rates to gm/mile rates has been through a conversion factor of 2.82.

As with gasoline powered HDT's, EEA recommends that vehicles in the 8,500 to 16,000 lb GVW category be treated separately. These vehicles are similar in shape and use to the light-duty truck and feature engines that are all of the 'prechamber" type rather than the "direct-injection" type utilized in most trucks over 16,000 lbs GVW. Unfortunately, diesel engines in such vehicles have become available only recently (1982) and there is no public transient test data available in such engines. Because of their recent introduction, there is no data available on their deterioration under in-use conditions. However, the deterioration factors (additive) should be similar to those obtained for light-duty diesel trucks from recent CARB surveillance testing.

Even in the over 16,000 lb GVW trucks, there appears to be a major division between medium-duty trucks (typically between 16,000 and 50,000 lb GVW) and heavy-duty over-the-road trucks which are typically over 50,000 lbs GVW. Engines in the two categories differ significantly in their useful life and potentially in the deterioration characteristics. EPA has recognized this in their recent rulemaking, and promulgated separate definitions of useful life for the two categories of engines, that have now been adopted by the CARB.

In evaluating the zero-mile emission levels, EEA believes that there are no current alternatives to the EPA method of using sales weighted emission certification data. However, it can be improved by:

- Sales weighting appropriate to California
- Use of the improved regressions (described in Section 2) to convert steady-state emission to transient emissions
- Separate treatment of Cummins engines to reflect their different characteristics

In order to estimate the DR, it was decided that the EPA method of using LDDV rates as a basis was not meaningful as the light-duty automotive diesel has little in common with the large, medium or heavy-duty diesel used in trucks. Since the certification deterioration factors are relatively low, EEA evaluated the significant malperformances possible for diesel engines. They are:

- Disablement of the smoke-puff limiter
- Increased governed speed
- Changed injection timing
- Increased fueling
- Injector clogging

We requested comments from the diesel engine manufacturers on each of these malperformance modes and their comments are summarized.

Smoke Puff Limiter - These devices are used primarily in turbocharged "heavy-heavy duty" engines to control smoke during acceleration. The consensus opinion of the manufacturers was that disconnection of this device is probably common, but there would be little or no impact on gaseous emissions. Visible smoke however would likely increase. EEA believes that particulate and HC emissions may increase by about 10 percent as a result of disconnecting this device. (This is almost within the range of measurement error).

Inc.'eased Governed Speed - As with the smoke puff limiter, engine manufacturers believe that increasing governed engine speed probably occurs in the field but this has little or no impact on brake-specific fuel consumption, since engine output increases as well. EEA concurs with this judgement since many heavy-duty diesels are available at a variety of governed speed settings with no discernable effect of brake-specific emissions.

Injection timing changes are possible but generally difficult to implement in most engines. In engines with unit injectors, the rocker-cover must be removed and each injector retimed. Cummins engines, which do not have unit injectors, have either fixed or two-position timing. Changing timing to other values again requires major effort--removing the camfollower housing and installing new gaskets. However, EEA believes that, since these timings are checked and reset at typically lengthy intervals, some fraction of trucks are likely to see maladjusted injection timing. The adjustments are more likely set towards a more advanced setting than recommended because of improved fuel economy. Higher noise levels however, are likely to inhibit the amount of advance to just a few degrees. Information provided by manufacturers suggest that advanced timing leads to a:

- 10 to 15 percent/degree increase in NO_x
- 2 to 3 percent/degree decrease in HC
- Small decreases in CO and particulate

These changes are appropriate for direct-injection engines; for prechamber engines, HC, CO, smoke and particulate increase with timing advances.

Over fueling has been observed by field personnel of the manufacturers. However, their consensus opinion is that overfueling has little or no impact on brake-specific emissions as horsepower increases at approximately the same rate as emissions. Caterpillar stated that NO_x emissions could decrease slightly with CO emissions increasing as a result of overfueling. Overall, EEA concurs with the manufacturer judgement that overfueling does not contribute significantly to increased brake-specific emissions.

Clogged injectors - In general, manufacturers believed that this is very rare unless there is fuel contamination. Typically, such clogging or injector leakage results in severe performance effects and are immediately noticed by drivers. Injector internal carboning occurs gradually and injector cleaning is recommended (and usually performed) at specific intervals. EEA believes that injector carboning may result in asymmetric fuel spray patterns with resulting modest rise in HC emissions. Part of this effect is captured over the durability test, required for certification.

In conclusion, it appears that there are only two potential causes of increased emissions (over certification levels) and they are timing changes and injector carboning. Even for these malperformances, the range of emissions impact is severely limited for HC, CO and particulate. NO_x emissions can, however, double if injection timing is advanced by 8-10 degrees. No data, however, is available on the rate or extent of injection timing changes on "in-use" diesel engines.

5.4 SUMMARY

The EPA derived emission factors for heavy-duty trucks are based on relatively simplistic methodology and little actual data. Although there is not much additional data available, a number of improvements can be made to the methodology by which these factors are estimated. Another important factor not considered in most models is that the emissions in gm/mile change continuously for each new model year inspite of constant emission standards as truck efficiency improves with time. As a basic recommendation, EEA believes that emission factors should be derived in gm/BHP-hr and converted on a model year specific basis through the use of a conversion factor that varies independently of emission standards*. Other recommendations are:

- Separation of the current heavy-duty class into three sub-classes: light-heavy, medium-heavy and heavy-heavy. (There are not gasoline powered vehicles in the heavy-heavy category).
- Derivation of "light-heavy" truck emission factors (gas and diesel) from data on virtually identical trucks in the California medium-duty category.
- Derivation of historical gasoline zero mile emission factors from "medium-heavy" gasoline trucks from EPA/SWRI data using the improved correlation equations.
- Derivation of historical gasoline deterioration rates for medium-heavy duty gasoline trucks from data on idle CO vs. odometer derived from the Phoenix I/M program (or similar programs).
- Derivation of historical zero mile emission factors for "medium-heavy" and "heavy-heavy" categories of diesel trucks from certification data using actual California sales weighting of the data as well as the EEA derived correlations between transient and steady-state emissions.
- Estimation of deterioration rates for "medium-heavy" and "heavy-heavy" diesels from certification deterioration factors (DF). Since little data is available to support any analysis, EEA recommends doubling the certification DF to obtain an approximate in-use deterioration rate.

---

*EPA has adopted this approach for their new MOBILE3 model.

- Surveying in-use HD trucks to obtain data on the rate of air pump and EGR disconnections in gasoline trucks, and the rate and extent of injection timing changes in heavy-duty diesel engines.

To the extent possible with available data, EEA has utilized these recommendations to derive revised HDT emission factors in Section 6 of this report.

6. EMISSION FACTORS

6.1 INTRODUCTION

The paucity of emissions data from in-use vehicles that span the range of HDT weights is a major problem in deriving adequate in-use emission factors. Technological trends in trucks and newly promulgated emission regulations (introduced partially in recognition of these trends) have also introduced new uncertainties in both historical and future emission factors. An understanding of these trends and new standards is provided below and is useful in the review of emission factors for HDT's.

As described in Section 3 of this report, the broadly defined heavy-duty vehicle class can be divided into three sub-classes that are relatively more homogenous in technological characteristics and use patterns. At the heaviest end are vehicles above 50,000 lb GVW, that are primarily over-the-road tractor-trailers. These vehicles (corresponding to class 8G(2) in Section 3) are used for inter-city transport and have been completely dieselized for the past decade. The second category, spanning the 14,000 lb to 50,000 lb GVW range, are the medium heavy duty vehicles that are used in urban/suburban pickup and delivery routes and also in some short-haul and construction operations. Most of the trucks sold are in the class 6/7 (17,000 to 33,000 lbs GVW) category and diesel penetration is currently over 60 percent. In the third category are vehicles in the 8,500 to 14,000 lb GVW range and are called "light-heavy" duty vehicles. These vehicles are mostly pickups, vans and utility vehicles and, until 1982, were 100 percent gasoline powered. The introduction of the Chevrolet 6.2 L and IH 6.9 L diesel V-8 in 1982 and 1983 respectively has resulted in a 1984 diesel penetration of approximately 15 percent. It should be noted that these diesels are pre-chamber diesels, while direct-injection diesels are used in the medium-duty and heavy-duty truck categories.

EPA has, in 1984, promulgated new useful life provisions for 1985 and later model year trucks as follows.

Category	Gas	Diesel
Light-Heavy	8 years/110,000 miles	8 years/110,000 miles
Medium-Heavy	8 years/110,000 miles	8 years/185,000 miles
Heavy-Heavy	N/A	8 years/290,000 miles

Moreover, EPA has promulgated separate emission standards for light-heavy and medium-heavy gasoline powered HDT's and has accepted an alternate test cycle--called the "MVMA cycle"--that is a smoothed version of the EPA transient cycle. These separate standards for the two sub-classes are as shown below, for the "MVMA cycle", in gm/BHP-hr.

	Pre-1987*	1987+
Light-Heavy	1.9 HC/37.1 CO/10.7 NO_x	1.1 HC/14.4 CO/6.0 NO_x
Medium-Heavy	1.9 HC/37.1 CO/10.7 NO_x	1.9 HC/37.1 CO/6.0 NO_x

California has recently adopted the useful life definitions promulgated by EPA but has retained the steady state test option for gasoline engines only. EEA has learned that CARB staff are considering adopting the same standards promulgated by EPA for HC and CO, while retaining the current more stringent 5.1 g/BHP-hr NO_x standard based on the transient test procedure. These uncertainties in both the standard and test procedure for heavy-duty gasoline powered vehicles makes it difficult to forecast the emission factors. In this section, EEA has provided some forecasts based on reasonable expectations for the future. Our assumptions are documented in this section in detail.

---

*Alternatively, manufacturers can certify on the transient cycle to the 2.5HC/40.0 CO/10.7 NO_x standard.

EPA has recently released an updated HDV emission factor forecast based on numerous (undocumented) assumptions about the behavior of future technologies. Our detailed survey found that the data base on in-use HDV's is very small--approximately 30 diesel vehicles and 10 gasoline vehicles. None of the diesel vehicles are in the "light-heavy" category, and all HDV's were tested using the chassis dynamometer cycle that is equivalent, but not identical, to the engine dynamometer based transient cycle used for certification. Our analysis of in-use data for diesel powered vehicles is summarized in Section 6.2. Section 6.3 summarizes available data on gasoline powered vehicles and Section 6.4 discusses emission factors.

6.2 DIESEL VEHICLES

6.2.1 Data

The in-use data on diesel vehicles was obtained from a relatively small data base of in-use vehicles tested by SWRI. The very limited data base available constrains the analysis of emission factors significantly. The entire data base consists of only 30 vehicles, 7 of which are buses. Since all buses and three additional trucks were tested on No. 1 diesel fuel, their test results are not completely comparable to the tests on other trucks. The 20 vehicles tested on No. 2 diesel fuel had odometers ranging from 8,000 miles to 260,000 miles. Moreover, the emissions test employed by SWRI to generate the data differs from the test procedures used to certify the emissions. Given the inherent random errors in emission measurement and the engine-to-engine variability, it is obvious that a statistically significant deterioration rate in emissions with respect to mileage is impossible to compute from a sample of 20 trucks. This analysis should, therefore, be viewed as one confirming or disproving trends in emission factors developed by the EPA.

6.2.2 **Methodology**

Emissions regulations for HDT's are specified in grams per brake horsepower-hour, whereas the SWRI measurements are in gm/mile. In accordance with EPA regulations, it was decided to convert all gm/mile measurements to an equivalent gm/BHP-hr value. Since no established procedure exists to perform this conversion, we developed a procedure as follows.

Based on engineering considerations, a formula to link the dynamometer settings to the work done over the cycle can be derived. From the laws of motion, it is known that power consumed during acceleration and the power to overcome rolling resistance are both linear functions of the weight (or mass) of a truck. The power consumed in overcoming aerodynamic drag is a function of frontal area and the coefficient of drag. Since the mass is equal to the inertia weight setting and the power consumed to overcome drag is proportional to the dynamometer power absorption setting, we can write:

$$\text{BHP-hr} = A(\text{IW}) + B(\text{DYNOHP})$$

where BHP-hr is the total work over the cycle

IW is the inertia weight setting (in lbs)

DYNOHP is the dynamometer power absorption unit setting in horsepower

A, B are proportionality constants

For the tests conducted by SWRI, the inertia weight setting was equivalent in most cases to 70 percent of the truck's maximum GVW or GCW, while the dynamometer power absorption unit setting was obtained from truck coast down measurements. Note that both variables are related only to the truck's characteristics and are independent of the engine used in the truck.

In contrast, the engine emissions test procedure is specified in terms of the percentage of maximum (or rated) RPM and the percentage of maximum (or rated) torque. All though there is an approximate equivalence, on average, between truck size and engine power, there is also a good correlation with rated RPM and maximum speed. During the chassis transient cycle, all trucks are driven at the same speed, this test is not necessarily equivalent to engine transient cycle. Depending on the engine used, the chassis transient cycle can differ from the engine transient cycle in terms of both power and RPM. A strictly theoretical link between the two tests is, therefore, not possible. SWRI did test three engines on both the EPA engine and chassis test procedures. It was decided to derive the coefficients A and B from the results of the three tests, if the chassis test results and engine test results were comparable. Our assessment of comparability was based on the total mass of fuel consumed over the test.

The total mass of fuel consumed is an indicator of the total energy output (BHP-hr) of the engine, and tests were rated as comparable if the fuel consumption measured over the chassis test was within 5 percent of the fuel consumption measured over the engine test. We used the 5 percent figure as it is equivalent to 2 standard deviations of typical test-to-test differences. A second reason for adopting this comparability criterion is that brake-specific fuel consumption (BSFC) is a non-linear function of power output. The assumption that energy produced by the engine is linearly proportional to the fuel consumed (i.e. BSFC is constant) is valid only for small changes in power output per unit time.

Data utilized to derive the coefficients A and B are shown in Table 6-1. The derivation is from composite emissions data, rather than the individual driving cycles, since the emission factors are for the composite driving cycle. Both hot and cold composite cycle data was used, and the HP-HR and fuel consumption from the engine test (FC_E) is compared to distance and fuel consumption from the chassis test. As can be seen in Table 6-1, Engines (vehicles) No. 202 and 204 are acceptable for the analysis since the fuel consumption varies by less than 5 percent. Values shown are four test averages and their standard deviations. Fuel consumed

TABLE 6-1

COMPARISON OF CHASSIS AND ENGINE DYNAMOMETER TEST RESULTS
(Average of 5 tests)*

Chassis/Engine	Cycle	Engine: HP-HR	Engine: FC_E	Chassis: Distance	Chassis: FC_c
202	Cold Composite	20.66(0.08)	8.96(0.11)	5.35(0.06)	8.80(0.167)
	Hot Composite	21.12(0.036)	8.65(0.08)	5.41(0.08)	8.32(0.159)
203	Cold Composite	22.93(0.20)	10.57(0.08)	5.40(0.02)	9.28(0.16)
	Hot Composite	23.10(0.08)	10.30(0.06)	5.43(0.03)	8.57(0.16)
204	Cold Composite	12.88(0.03)	6.50(0.16)	5.61(0.03)	6.76(0.15)
	Hot Composite	12.80(0.04)	6.25(0.08)	5.65(0.04)	6.28(0.15)

Engine	HP	Test Weight (lb)	Dyno.HP
202	350	54,000	134.5
203	435	54,000	134.5
204	210	29,000	104.6

*Std. Derivation in parantheses.

over the tests for both engine/vehicle 202 and 204 are within two standard deviations (of test-to-test variability). Engine 203, on the other hand, shows substantial differences in fuel consumption between the chassis and engine tests. This can be easily explained, since engine 203 is rated at 435 HP, but is loaded in the chassis test at the same level as engine 202, which is rated at 300 HP. In the engine test, engines are loaded in proportion to their rated power, and thus, agreement between engine and chassis tests is likely only when the loads are approximately matched.

Using the data from engines 202 and 204, the BHP-hr values were adjusted for fuel consumption differences between chassis and engine tests using the proportional relationship described below.

$$\frac{\text{(BHP-hr) engine test}}{\text{(BHP-hr) chassis test}} = \frac{\text{FC engine test}}{\text{FC chassis test}}$$

Where the FC over the chassis test is renormalized to 5.54 miles (the test distance). This is equivalent to assuming a constant BSFC, and is approximately correct for small variation in fuel consumption. Two equations are thus obtained from the hot cycle composite results namely:

$$29{,}000A + 104.6B = 12.61$$

$$54{,}000A + 134.5B = 20.80$$

Which can be solved to give $A = 0.2744 \times 10^{-3}$, $B = 0.0445$

Using the same weight factors used to weight hot and cold emissions over the EPA transient cycle, the weighted values of A and B are:

$A = 0.2693 \times 10^{-3}$ BHP-hr/lb

$B = 0.0467$ BHP-hr/Dyno HP

These values were used to convert inertia weight and dynamometer horsepower settings to BHP-hr.

6.2.3 Emission Factors Derivation

In this analysis, emission factors were derived on two bases, namely:

- A gm/BHP-hr basis, using the method detailed in Section 6.2.2 to convert inertia weight and dynamometer settings to BHP-hr.
- A gm/lb-fuel basis, where mass emissions are normalized by fuel consumption in pounds.

Although the results of both methods are presented in this report, only the emissions in gm/BHP-hr are discussed below, since they are far more useful to the CARB and consistent with emission standards.

At the outset, it was immediately obvious that the emissions (in gm/BHP-hr) were radically different for buses in comparison to trucks, and were typically 2 to 3 times higher on average. Therefore, it was decided to treat to the two emissions separately. On the remaining 23 trucks, inspection revealed that there was a strong tradeoff between HC and NO_X emissions. This tradeoff is well known in engineering circles, and since the emissions requirements specifies only a HC + NO_X standard, manufacturer often set different goals for HC and NO_X. Figure 6-1 shows a plot of HC emissions versus NO_X emissions and the relationship appears to confirm the HC/NO_X tradeoff - all high NO_X emitters ($NO_X > 9$ gm/BHP-hr) have low HC emissions and all high HC emitters ($HC > 1$ gm/BHP-hr) have low NO_X emissions. Only one vehicle, No. 101, had both very high NO_X and very high HC emissions. (This data is not shown in Figure 6-1). As a result of this uncharacteristic behavior, and the fact that it was the very first vehicle tested by SWRI on the chassis procedure, EEA believes that the data is erroneous and has discarded this data for the remainder of the analysis.

The remaining data on 22 trucks were then analyzed to provide emission factors in the form

$$\text{Brake-Specific Emissions} = C + D \times \text{ODOMETER}$$

SAS

14:52 THURSDAY, APRIL 12, 1984

PLOT OF HCHP*NOXHP   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

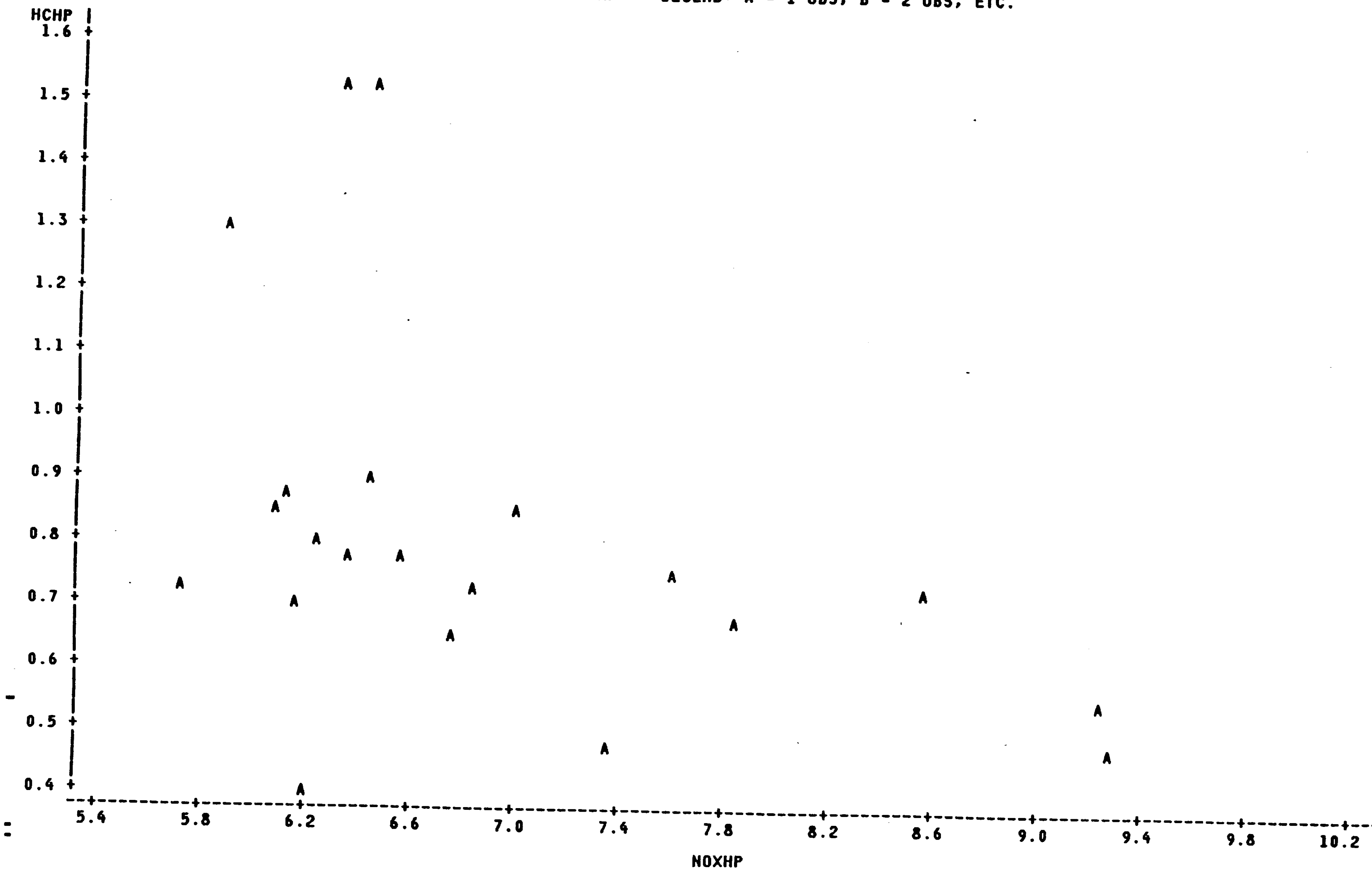


Figure 6-1

HC vs NO_x Emissions

The results for HC, CO, NO_X, particulate and HC + NO_X are summarized in Table 6-2. Using data on the 22 trucks, it can be seen the slope of the emission factor (or deterioration rate) is not statistically significant at the 0.05 level (T-statistic less than 1.96) for HC, NO_X and HC + NO_X emissions.

On the other hand, the slope of the CO emission factor has a T-statistic of 1.83 while the slope of the particulate emissions factor has a T-statistic of 2.40, which are slightly below and above the 1.96 value. (In comparison, T-statistics for HC and NO_X are less than 0.3). Figures 6-2 through 6-6 show the individual truck data plotted against odometer. In each case, emissions appear to be clustered about the mean with the exception of three "outliers". Because of the inverse relationships between HC and NO_X, and a direct relationship between HC emissions and particulate and (to some extent) CO emissions, the "outliers" are different for NO_X emissions, and similar (but not identical) for CO and particulate emissions in comparison to the "outliers" for HC emissions.

The number of Cummins engines tested were the largest of any manufacturer, and were all of the same displacement (855 CID) but had different horsepower ratings. Because of the physical similarity of the engines, EEA was of the opinion that a regression of emissions from these engines against odometer might provide a better indicator of the deterioration factors. Regression analysis of the dta from 12 Cummins engines showed large improvements in the T-statistics for intercept and slope value for all pollutants except the slope for NO_X. The values of the intercept for emissions from Cummins engines did not show any significant differences from those for all trucks; however the deterioration rate for HC emissions was significant at the 0.10 level, while the deterioration rate for CO was significant at the 0.05 level. The T-statistic for particulates increased from 2.40 for all trucks to 3.23 for Cummins engines, in spite of the smaller sample size. As

SAS

12:25 THURSDAY, APRIL 12, 1984

PLOT OF HCHP*ODOM   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

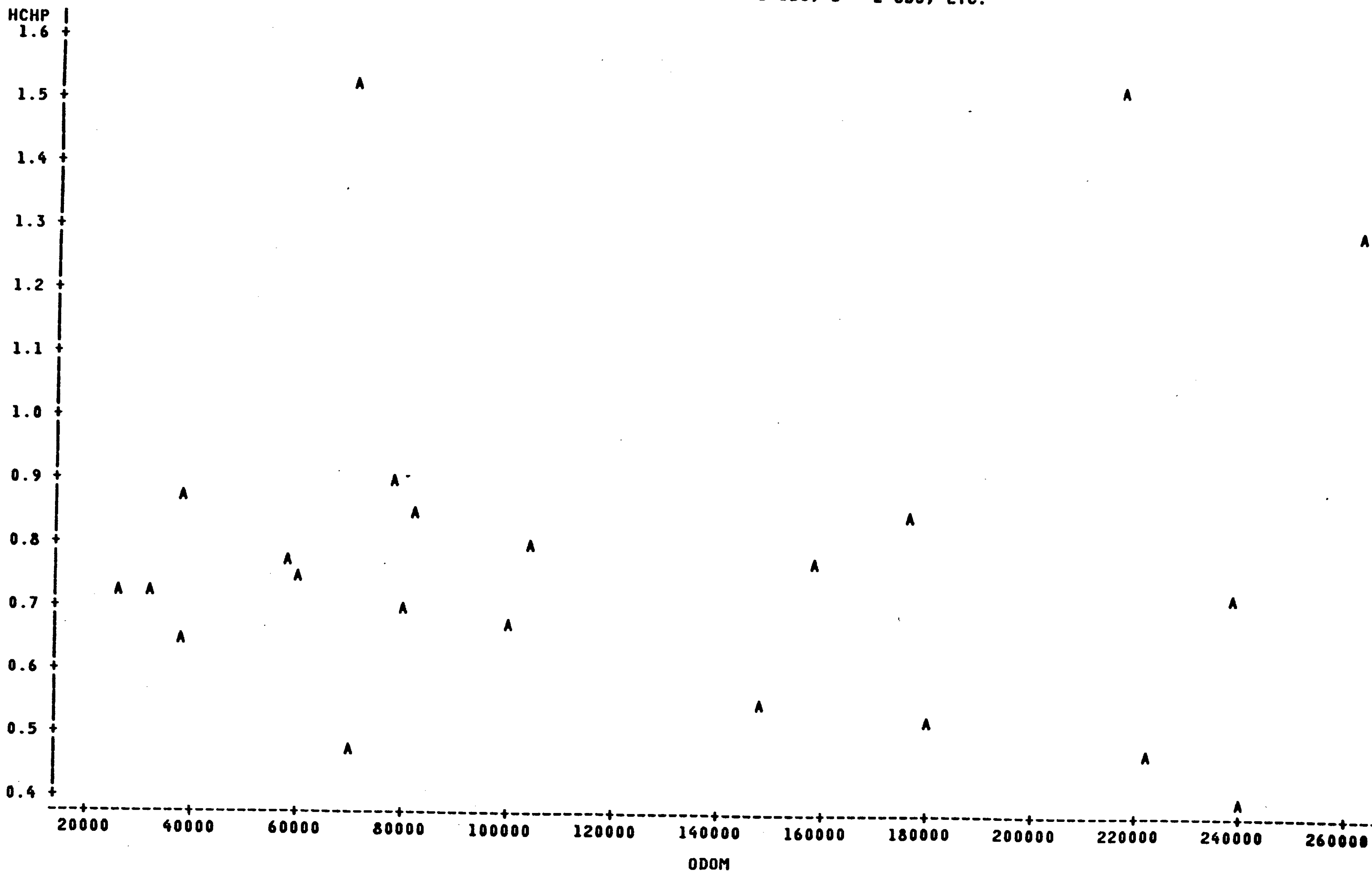


Figure 6-2
Brake Specific Emissions vs. Odometer

SAS 12:25 THURSDAY, APRIL 12, 1984 1

PLOT OF COHP*ODOM LEGEND: A = 1 OBS, B = 2 OBS, ETC.

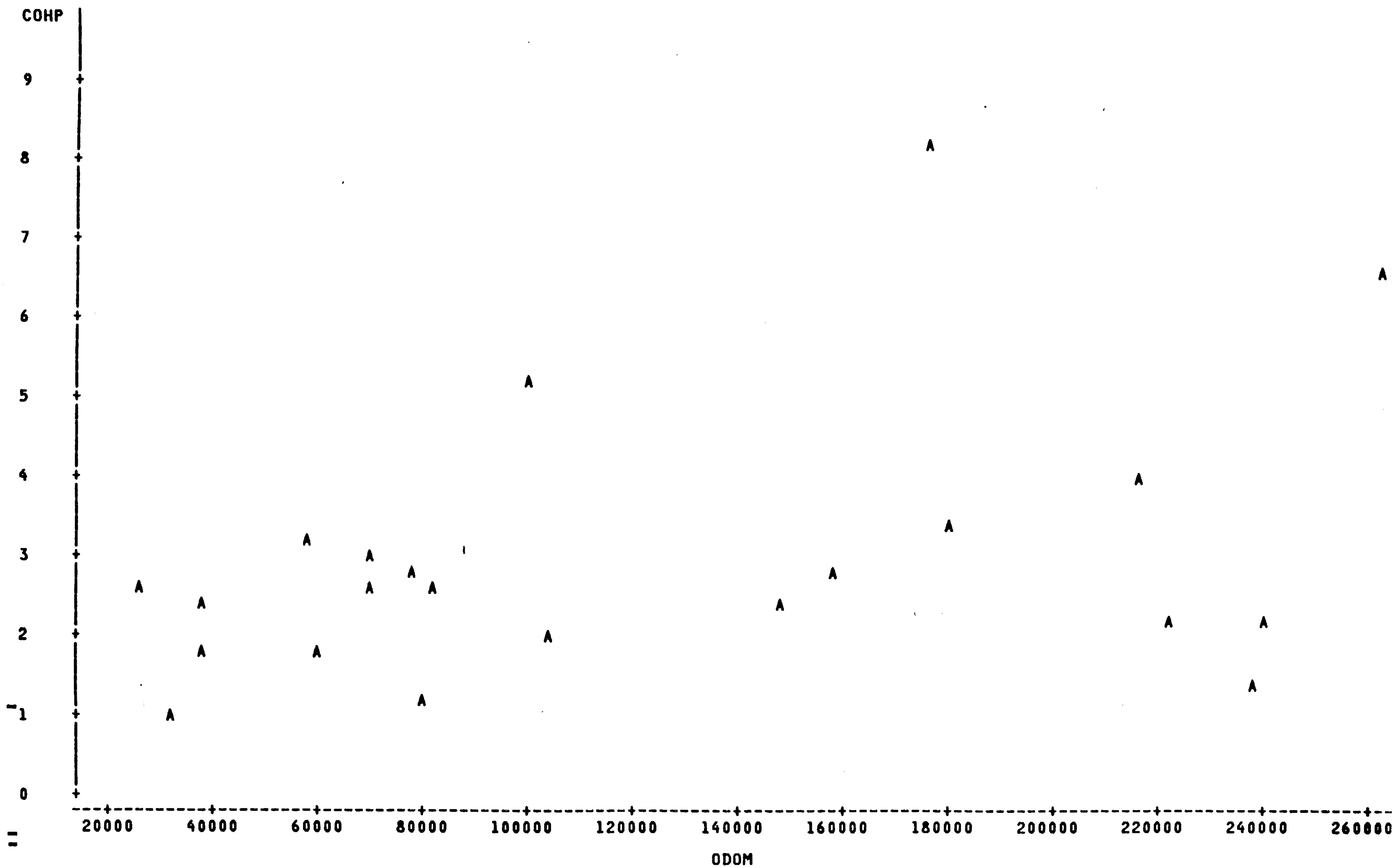


Figure 6-3

ıke ifi Emi...ons .. Odom...

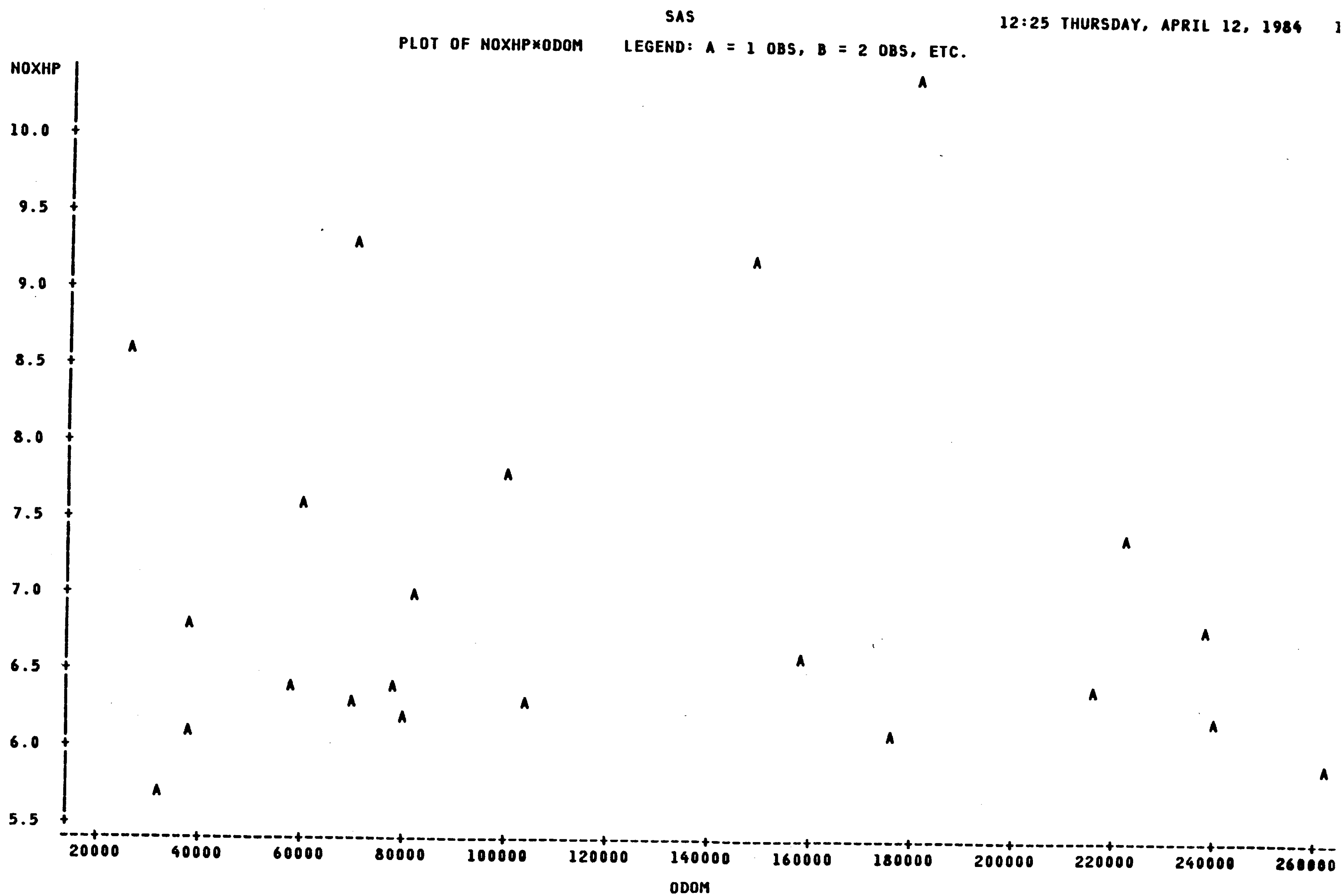


Figure 6-4

Brake Specific NO_x Emissions vs. Odometer

SAS 12:25 THURSDAY, APRIL 12, 1984

PLOT OF PARTHP*ODOM LEGEND: A = 1 OBS, B = 2 OBS, ETC.

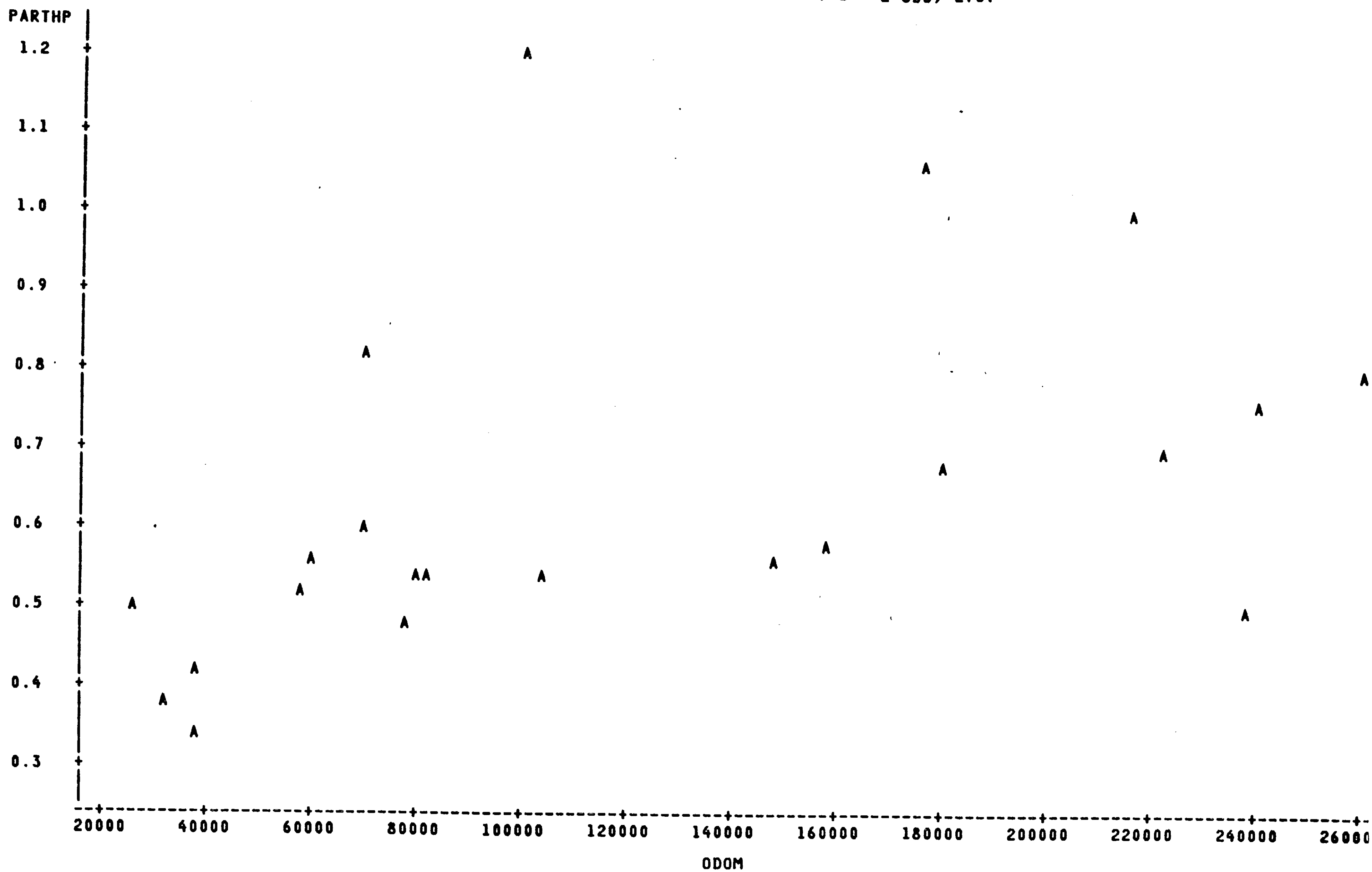


Figure 6-5

Br... Spec... Pa... ula... miss... vs. ...omet...

SAS

12:25 THURSDAY, APRIL 12, 1984

PLOT OF HNP×ODOM   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

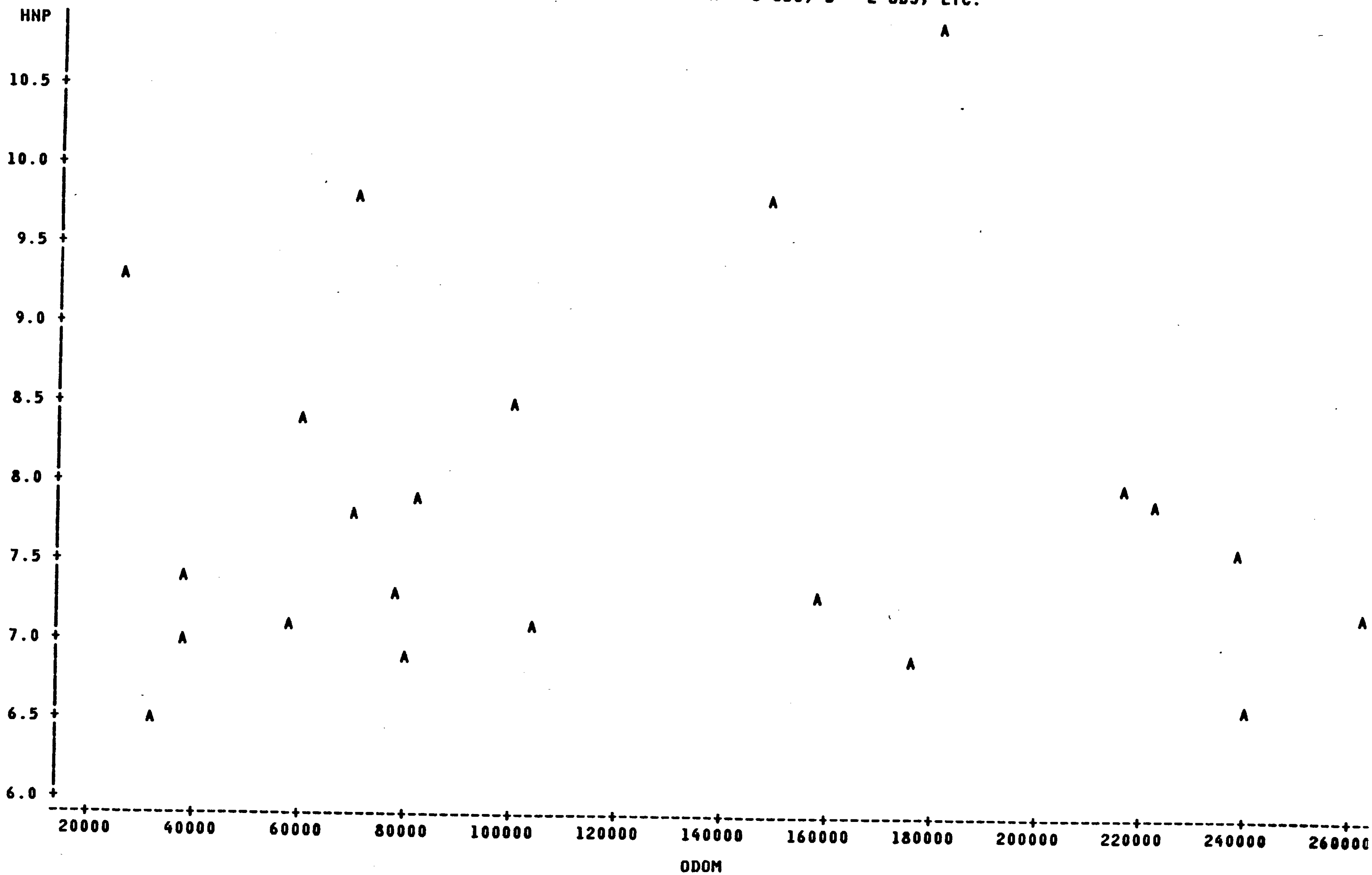


Figure 6-6

Brake Specific HC + NO Emissions vs Odometer expected, regression analysis of the data from all "non-Cummins" engines resulted in loss of significance for all of the deterioration rate estimates. This is because of the wide range of manufacturers and engine sizes in the sample of 10 trucks. The results of the analysis of Cummins and non-Cummins powered vehicles are also shown in Table 6-2.

The analysis was repeated for fuel specific emissions, sometimes called the emission index. Since the brake-specific fuel consumption of most diesel engines are approximately similar, the results of this analysis exhibits the same general trends as the analysis in terms of gm/BHP-hr. The results are detailed in Table 6-3. However, the plots of the individual data points vs. odometer (shown in Appendix B) show greater dispersion than those for brake specific emissions. The results of the fuel specific emissions could be used to convert on-road fuel economy to emissions directly.

The emission estimates from the brake-specific emission analysis was compared with the only other source of equivalent data on heavy-duty diesel emissions. SWRI had previously tested 19 new engines on engine dynamometer tests to provide a 1979 baseline emissions value. The results of those tests are compared with the estimated emission intercepts (as those engines were new) from the chassis test data, in Table 6-4. The comparison shows remarkable agreement between the values for all pollutants, especially considering the differences in test procedure.

Finally, the test data for the buses was analyzed. The data is presented in Table 6-5, and shows that the emissions intercept for all pollutants is considerably higher. Because of the small sample, none of the deterioration rates are statistically significant.

TABLE 6-2

RESULTS OF EMISSION FACTOR ANALYSIS
(Emissions in gm/BHP-hr)

	Intercept	Std. Error	Slope*	Std. Error	Mean
All 22 Trucks					
HC	0.765	0.125	2.73×10^{-3} a/	8.7×10^{-3}	0.798
CO	1.954	0.652	8.35×10^{-2} b/	4.55×10^{-2}	2.971
NO_x	7.131	0.521	-5.59×10^{-3} a/	3.64×10^{-2}	7.064
Particulate	0.475	0.081	1.36×10^{-2}	5.70×10^{-3}	0.640
HC + NO_x	7.897	0.477	-2.86×10^{-3} a/	3.33×10^{-3}	7.862
Cummins Only(12)					
HC	0.732	0.081	1.850×10^{-2} b/	1.22×10^{-6}	0.940
CO	1.555	0.753	1.721×10^{-1}	5.60×10^{-2}	3.492
NO_x	7.146	0.552	-2.950×10^{-2} a/	4.10×10^{-2}	6.814
Particulate	0.397	0.089	2.133×10^{-2}	6.60×10^{-3}	0.637
HC + NO_x	7.878	0.494	-1.102×10^{-2} a/	3.67×10^{-2}	7.754
All Other Trucks(10)					
HC	0.750	0.083	-9.232×10^{-3} a/	5.50×10^{-3}	0.628
CO	2.249	0.825	7.171×10^{-3} a/	5.40×10^{-2}	2.345
NO_x	7.216	1.007	1.106×10^{-2} a/	6.59×10^{-2}	7.363
Particulate	0.577	0.148	5.071×10^{-3} a/	9.70×10^{-3}	0.644
HC + NO_x	7.966	0.972	1.828×10^{-3} a/	6.36×10^{-2}	7.991

* Slope in gm/BHP-hr/10^4 miles

a/ Not significant at the 0.10 level

b/ Significant at the 0.10 level

TABLE 6-3

RESULTS OF EMISSION FACTOR ANALYSIS
(Emission in gm/lb-fuel)

	Intercept	Std. Error	Slope*	Std. Error	Mean
All 22 Trucks					
HC	1.710	0.228	3.795×10^{-3} a/	1.59×10^{-2}	1.756
CO	4.427	1.442	1.808×10^{-1} b/	1.01×10^{-1}	6.[illegible]7
NO_x	15.932	1.187	-1.079×10^{-2} a/	8.29×10^{-2}	15.801
Particulate	1.042	0.166	3.115×10^{-2}	1.16×10^{-2}	1.4[illegible]1
HC + NO_x	17.643	1.045	-6.996×10^{-3} a/	7.30×10^{-2}	17.[illegible]7
Cummins Only(12)					
HC	1.689	0.264	3.313×10^{-2} b/	1.96×10^{-2}	2.[illegible]2
CO	3.799	1.750	3.541×10^{-1}	1.30×10^{-1}	7.784
NO_x	16.587	1.276	-1.167×10^{-1} a/	9.48×10^{-2}	15.[illegible]0
Particulate	0.922	0.152	4.226×10^{-2}	1.13×10^{-2}	1.397
HC + NO_x	18.276	1.063	-8.385×10^{-2} a/	7.90×10^{-2}	11.6[illegible]2
All Others(10)					
HC	1.612	0.155	-1.675×10^{-2} b/	1.01×10^{-2}	1.390
CO	4.734	1.826	3.809×10^{-2} a/	1.196×10^{-1}	5.2[illegible]
NO_x	15.268	2.170	8.810×10^{-2} a/	1.420×10^{-1}	16.438
Particulate	1.202	0.349	1.862×10^{-2} a/	2.280×10^{-2}	1.4[illegible]
HC + NO_x	16.880	2.064	7.135×10^{-2} a/	1.351×10^{-1}	17.828

* Slope in gm/lb-fuel/10^4 miles

a/ Not significant at the 0.10

b/ Significant at the 0.10 level

TABLE 6-4

COMPARISON OF 1979 BASELINE EMISSIONS
WITH INTERCEPT OF EMISSION FACTORS
(gm/BHP-hr)

	Baseline	Intercept
HC	0.83	0.765 ± 0.125
CO	2.28	1.954 ± 0.652
NO_x	7.04	7.131 ± 0.521
Particulate	0.49	0.475 ± 0.081

TABLE 6-5

EMISSION FACTORS FOR BUSES

	Brake Specific Emissions (gm/BHP-hr)				
	Intercept	Std. Error	Slope	Std. Error	Mean
HC	1.421	0.519	1.201×10^{-3} [a/]	3.19×10^{-2}	1.4[illegible]0
CO	40.583 [b/]	25.400	-9.937×10^{-1} [a/]	1.56	25.062
NO_x	13.563	5.190	-3.202×10^{-2} [a/]	3.19×10^{-1}	13.0[illegible]3
Particulate	2.174 [a/]	1.837	-6.076×10^{-3} [a/]	1.13×10^{-2}	2.079
HC + NO_x	14.985	4.994	-3.082×10^{-2} [a/]	3.07×10^{-1}	14.5[illegible]3

	Fuel Specific Emissions (gm/lb-fuel)				
	Intercept	Std. Error	Slope	Std. Error	Mean
HC	1.332	0.493	2.483×10^{-2} [a/]	3.03×10^{-2}	1.7[illegible]
CO	42.319 [b/]	26.898	-8.775×10^{-1} [a/]	1.65	28.610
NO_x	12.651	5.943	1.953×10^{-1} [a/]	3.65×10^{-1}	15.7[illegible]
Particulate	2.309 [a/]	2.070	1.134×10^{-2} [a/]	1.223×10^{-1}	2.486
HC + NO_x	13.984	5.552	2.201×10^{-1} [a/]	3.41×10^{-1}	17.4[illegible]

a/ Not significant at the 0.10 level

b/ Significant at the 0.10 level

6.3 GASOLINE VEHICLES

The data base on in-use gasoline powered HDV's is even smaller than that for diesel HDV's. EEA was able to locate tests on only eight gasoline powered trucks, and the data is shown in Table 6-6. Trucks 1 and 2 were tested by South-West Research, while trucks 3 through 8 were tested by EPA/RTP. Truck No. 4 was noted to have a high oil consumption problem and hence reported abnormally high HC emissions. Truck 6 had a relatively new engine in it (less than 10,000 miles) and the high particulate emission is thought to be related to metal particles from "break-in".

Regression analysis of such a small data base is not meaningful, but some general trends can be observed. Trucks 1 through 7 were Class VI gasoline powered trucks of approximately 22,000 lb GVW and were tested at 70 percent of GVW (inertia weight setting). Trucks 3 through 8 were also tested at an inertia weight setting of equivalent to the empty weight to determine sensitivity to weight. All vehicles were tested on the chassis transient cycle and results are therefore provided in grams per mile.

In order to compare these values against the engine dynamometer tests, a method to convert the g/mi figure to a gm/BHP-hr figure is required. As an approximate measure, EEA utilized the formula

$$C.F = \frac{\text{Fuel Density}}{\text{BSFC x MPG}}$$

as detailed in Section 3 of this report. The Conversion Factor (C.F.) in BHP-hr/mi is then equal to 8.8/MPG, if a constant BSFC of 0.7 is assumed for all engines. The assumption is only approximately correct, and is true only for the test at 70 percent GVW, but for the purposes of this analysis, it is judged reasonable.

The emission test results converted to gm/BHP-hr are shown in Table 6-7. Vehicles 3 and 4 are from model years 1973 and 1975 respectively and

TABLE 6-6

IN-USE HDGT EMISSIONS DATA

No	Make	Odom	IW	Dyno HP	HC (g/mi)	CO (g/mi)	NO_x (g/mi)	Part. (g/mi)	F/E (MPG)
1	'79 Ford V8-370	11,000	16,000	61.2	20.9	129.2	13.3	0.58	4.35
2	'79 IH 345	15,100	16,000	60.9	6.2	103.5	13.7	0.88	4.20
3	'73 IH 345	105,000	15,047	55.4	13.9	233.1	9.4	0.29	4.4
			9,819	47.5	12.1	213.6	7.2	0.22	4.7
4	'75 GMC 350	35,000	16,378	50.4	32.4*	237.4	10.2	0.49	5.1
			11,150	43.6	29.6*	211.1	8.3	0.54	5.2
5	'80 GMC 366	~10,000	15,798	55.4	26.3	113.7	8.3	0.32	4.8
			10.514	48.8	14.1	91.4	7.0	0.32	5.1
6	'79 Ford 370	~10,000	14,560	66.4	22.7	147.6	9.5	2.11*	4.7
			9,920	60.2	15.6	115.5	8.3	1.52*	5.4
7	'79 Ford 370	~10,000	14,560	49.1	20.4	142.4	9.4	0.47	4.6
			9,920	42.9	15.3	78.3	7.3	0.89	5.3
8	'76 Ford 351	91,000	9,215	50.1	10.0	101.9	8.7	0.21	6.9
			6,380	47.5	6.9	73.9	7.9	0.19	7.8

*Unrepresentative values

TABLE 6-7

EQUIVALENT BRAKE-SPECIFIC EMISSIONS FOR IN-USE GASOLINE VEHICLES

No	CF	g/BHP-hr HC	CO	NO_x	Particulate
1	2.02	10.35	64.0	6.58	0.29
2	2.09	2.97	49.5	6.55	0.42
3	2.00	6.95	116.5	4.70	0.14
4	1.72	18.25*	138.0	5.93	0.28
5	1.83	14.37	62.1	4.53	0.17
6	1.87	12.14	78.9	5.08	1.13*
7	1.91	10.68	74.5	4.92	0.25
8	1.275	7.85	79.9	6.80	0.16

*Unreliable values

show relatively high CO emissions in comparison to the CO emissions from the 1979 and later engines. NO_x emissions show little variation ranging from 4.5 to 6.8 g/BHP-hr, but HC emissions vary widely from 3 to 14 g/BHP-hr (excluding emissions from vehicles No. 4). Particulate emissions vary from 0.14 to 0.42 g/BHP-hr, excluding emissions from vehicle No. 6.

EEA compared these values against values obtained from engine dynamometer tests conducted on 1972-1973 engines at SWRI and from tests on 1979 engines detailed in Section 2 of this report. These tests reported an average emissions of 6 g/BHP-hr HC emissions, 103 g/BHP-hr CO emissions and 5.9 g/BHP-hr NO_x emissions and then values are approximately consistent with the values observed for the two 1973-1975 vehicles in the sample. However the tests on 14 1979 engines provided the following results

- 3.32 g/BHP-hr HC
- 77.41 g/BHP-hr CO
- 6.70 g/BHP-hr NO_x

Results from the tests of in-use vehicles No. 1, 2, 5, 6, 7, 8 are in good agreement with the engine test results for NO_x and CO. However, average HC emissions from the chassis tests are at 9.7 g/BHP-hr, approximately 300 percent higher than the values obtained from the engine tests. The reasons for this large difference is not clear, especially since CO emissions are similar. EPA is currently testing a sample of HDGV in-use engines on the engine dyno test, but the results are not yet publicly available. EEA has learned that test results indicate that HC emissions are approximately at the 5 g/BHP-hr level, but this is based on a very small sample.

A separate but related issue is the representativeness of the current transient emissions cycle. EPA has recently agreed to the "MVMA" cycle which is nearly identical to the transient cycle but removes some of the high frequency transients. EPA/RTP staff studied the differences between the transient cycle and on-road driving and also concluded that the high frequency components in the transient cycle are unrepresentative of real-world driving. Their testing indicated that using the "smoothed" transient cycle resulted in reductions of HC and CO by 16 percent from the values measured in the transient cycle.

6.4 EMISSION FACTOR RECOMMENDATIONS

6.4.1 Diesel Vehicles

The analysis of malperformances and the analysis of in-use emission data indicates that diesel emission deterioration rates are likely to be quite low, and that certification values are likely to be representative of actual in-use diesel emissions. Additionally, we recommend that emissions factors be specified in gm/BHP-hr and converted to gm/mile by multiplying by the appropriate conversion factor shown in Section 3 of this report.

For diesel engines, emissions prior to 1977 were roughly at uncontrolled levels, equivalent to pre-1979 Federal vehicles. EPA has in their new MOBILE3 emission model, assumed these levels to be (in gm/BHP-hr)

$$HC = 1.23 + 0.02M$$
$$CO = 3.59 + 0.05M$$
$$NO_x = 8.00 + 0.06M$$

EEA believes these values to be approximately correct except for the NO_x deterioration factor, which (for reasons explained below) is likely to be negative.

The California standards for 1977 to 1979 were equivalent to the 1979-1984 Federal standards, as the more stringent NO_x standard was partially offset by the lack of any requirement for end-of-line testing and audit. EEA disagrees with the EPA emission factors for that period, as data shown in Section 6.2 agrees with EPA's own baseline data but not with their assumed emission factors. Based on the data presented in Section 6.2, the recommended emission factors are (in gm/BHP-hr):

$$HC = 0.765 + 0.003$$

$$CO = 1.96 + 0.085$$

$$NO_x = 7.13$$

The results from the in-use vehicles indicate that NO_x deterioration is negative and this is consistent with the fact that there is an inverse relationship between HC and NO_x; as HC emissions rise, NO_x emissions should decline. A zero deterioration factor is chosen as a conservative assumption.

For the 1980-1983 period, California reduced the NO_x standard to 6.0 g/BHP-hr. Most manufacturers met this standard though a combination of injection timing retard and limiting maximum fuel (with slight reduction in horsepower). Because the standard was based on the steady state test procedure, the average certification level of 5.7 g/BHP-hr is equivalent to a transient test NO_x level of 6.1 g/BHP-hr, representing a 15 percent decrease in NO_x levels from the previous period. We have therefore increased HC emissions by a proportional amount to account for HC/NO_x tradeoff. The recommended factors are (in gm/BHP-hr)

$$HC = 0.88 + 0.003M$$

$$CO = 2.00 + 0.1M$$

$$NO_x = 6.1$$

For 1984 and later model years, the CARB has introduced the more stringent 4.5 g/BHP-hr steady-state NO_x standard, with the 5.1 g/BHP-hr transient standards optional. In 1985 and later model years, transient testing is required; moreover, a new set of useful life requirements have also been imposed.

The regulations have resulted in several manufacturers introducing new technologies--for example, Cummins has introduced mechanically variable timing on their high volume engine line. (Cummins accounts for nearly 70 percent of the heavy-heavy duty diesel fleet). These new technologies have reduced NO_x emissions without significantly impacting HC emissions--in some cases, both NO_x and HC have been reduced from pre-1984 levels. Based on limited data EEA recommends the following factors (in gm/BHP-hr)

$$HC = 0.80 + 0.01M$$
$$CO = 2.00 + 0.1M$$
$$NO_x = 4.80 + 0.02M$$

All of the above emission factors are relevant only for medium-heavy and heavy-heavy categories. No diesels were available in light-heavy duty vehicles till 1982 when the GM 6.2 L and the IH 6.9 L were introduced. Based on 1985 certification data the average emissions of these two engines are

$$HC = 0.65 + 0.01M$$
$$CO = 2.65 + 0.1M$$
$$NO_x = 4.00 + 0.02M$$

The emissions from these engines can be expected to constant until such time as more stringent NO_x standards are imposed. Although the light-heavy diesels emission factors are shown separately, a sales-weighted average or a urban VMT weighted average for all heavy-duty diesel can be used. Relevant national sales figures and urban VMT fractions are provided in Section 3 of this report, and the same relative mix of vehicles can be assumed for California as an approximation.

Our recommendation for diesel emission factors are summarized in Table 6-8.

6.4.2 Gasoline Vehicles

The data base on in-use gasoline vehicles is so small that its only use is to provide an approximate confirmation of emission factors derived from other methods. EPA has recently derived a set of emission factors using the available data and assumptions similar to those used for

TABLE 6-8

RECOMMENDED HD DIESEL EMISSION FACTORS
(g/BHP-hr)

Pollutant	Period	Zero Mile	Deterioration Factor
	Medium and Heavy-Heavy (>14,000 lb)		
HC	pre-77	1.230	0.002
	77 - 79	0.765	0.003
	80 - 83	0.880	0.003
	1984+	0.80	0.010
CO	all years	2.00	0.1
NO_x	pre-77	8.00	0
	77 - 79	7.13	0
	80 - 83	6.10	0
	1984+	4.80	0.02
	Light-Heavy (8,500 to 14,000 lb)		
HC	1982+	0.65	0.01
CO	1982+	2.65	0.1
NO_x	1982+	4.00	0.02

Note - Light-heavy diesel and medium- and heavy-heavy diesel factors should be averaged (sales-weighted average) before these factors are multiplied by the conversion factor to provide gm/mile emission estimates.

deriving the MOBILE2 factors (summarized in Section 4 of this report). Given the lack of any new or independent California specific data, our only recourse has been to modify the EPA MOBILE3 emission factors as described below. The new MOBILE3 factors are derived in gm/BHP-hr and converted to gm/mi using the conversion factors detailed in Section 3 of this report. EEA had additionally suggested (in Section 5) that idle CO/HC readings from in-use trucks could be obtained from I/M programs and used to estimate deterioration factors. EEA attempted this approach but found it nearly impossible to obtain good data from either Portland or Phoenix, two cities where heavy-duty gasoline trucks are included in the I/M programs. Accordingly, our current estimates are based solely on the data presented in Section 6.3 and engineering analysis.

For the pre-1969 time frame, it is believed that EPA emissions factors based on the limited testing of such engines is an adequate estimate. The estimates in gm/BHP-hr are

$$HC = 12.74 + 0.24M$$
$$CO = 155.18 + 3.72M$$
$$NO_x = 6.08$$

For the 1969-1972 period, the estimates should be equivalent to the reduced estimates for 1970-73. They are

$$HC = 6.76 + 0.18M$$
$$CO = 115.40 + 4.69M$$
$$NO_x = 5.00 + 0.06M$$

For 1975-1976, the steady state CO emissions standard was reduced from 40 to 30 g/BHP-hr and HC + NO_x standard reduced from 16 to 10 gm/BHP-hr. If one assumes (based on the correlation equations developed in Section 2 of this report) that approximately 50 percent of transient emissions are independent of steady-state emissions, then transient CO reduction due to standards would $\frac{30}{40} \times 0.5 = 0.125$. It is likely that no reduction NO_x emission occurred, but HC emissions are likely to have been reduced by an amount equivalent to the CO reduction. The recommended factors are

$$HC = 5.91 + 0.18M$$
$$CO = 101.00 + 4.70M$$
$$NO_x = 5.00 + 0.06M$$

For the 1977 - 1983 period, we expect that California emission factors are equivalent to the Federal 1979-1984 emission factors. Although the California NO_x standard was more stringent in this period than the Federal NO_x standard, we note that gasoline engine NO_x emissions were already well below applicable standards and are not likely to be effected by the lower California NO_x standard. The recommended factors are (in gm/BHP-hr)

$$HC = 3.00 + 0.18M$$
$$CO = 80.00 + 4.69M$$
$$NO_x = 5.00 + 0.06M$$

These factors are equivalent to the MOBILE3 factors, except for the zero mile CO emission rate, which we believe should be lower based on the observed emissions from such engines.

Finally, for the 1986+ period for California, it is difficult to estimate the emission factors from available data as the standards are unique and other regulations such as the anti-tampering regulations and revised useful life requirements have been imposed. Conversations with manufacturers lead us to believe that HC emissions are likely to be around 2.0 gm/BHP-hr for certification engines while CO emissions are likely to be 60 g/BHP-hr and NO_x emissions around 4.0 g/BHP-hr. EPA has estimated deterioration factors based on the anti-tampering and revised useful life regulation and these are recommended for 1985 and later years. Accordingly, recommended emission factors are (in gm/BHP-hr)

$$HC\ (1984) = 2.5 + 0.18M$$
$$HC\ (1985+) = 2.5 + 0.13M$$

$$CO\ (1984) = 60 + 4.69M$$
$$CO\ (1985+) = 60 + 2.06M$$
$$NO_x\ (1984) = 4.4 + 0.06M$$
$$NO_x\ (1985+) = 4.4 + 0.06M$$

Our estimates are summarized in Table 6-9.

6.5 OTHER RELATED FACTORS

The CARB has also requested that we provide particulate and sulfate emission factors. EEA also recommends that diesel city bus emission factors be considered separately from truck emission factors because city buses operate on a completely different cycle and have different engines.

The recommended particulate emission factors for all diesels is placed at 0.475 + 0.014M gm/BHP-hr. This is lower than the EPA assumed value of 0.7 gm/BHP-hr.

The recommended particulate emission factors for all gasoline trucks is 0.30 gm/BHP-hr. (This should be reduced if lead is phased out of gasoline or catalysts are introduced; the emission factor is derived for non-catalyst vehicles using gasoline with 1.1g/gallon Pb).

Based on EPA data, we recommend a sulfate emission factor of 5.0mg/BHP-hr for gasoline (non-catalyst) trucks and a factor of 30 mg/BHP-hr for diesel trucks.

For bus emission factors, our recommendations are based on the values shown in Table 6-5, i.e.,

$$HC = 1.44$$
$$CO = 25.1$$
$$NO_x = 13.06$$
$$\text{Particulate} = 2.08$$

All the above values are in gm/BHP-hr.

7. SPEED CORRECTION FACTORS

7.1 Overview

Speed correction factors for emissions are specified in EPA's MOBILE 2 and MOBILE 3 models as multipliers to basic emission rates, so that they predict emissions at speeds other than the speed for which the basic emission rate is derived. This can be expressed as

Emissions at speed, S = Correction Factors (S) X Basic Emission Rate.

If the basic emission rate is valid for a particular speed, S_1, it is obvious that

$$\text{Correction Factor } (S_1) = 1.$$

Speed correction factors are decoupled from the effects of cold start by considering only hot start data. Thus all of the data used to derive speed correction factors are from the "hot" cycles only.

As described in Section 2, the EPA transient cycle for heavy-duty trucks is comprised of four segments, two of which are identical. They are the Los Angeles Freeway and Los Angeles Non-Freeway (2 LANF and 3 LANF) as well as two New York Non-Freeway segments, one from a hot start (1NYNF) and one following the 3 LAF segment (4NYNF). Since the first New York Non Freeway (1NYNF) cycle includes emissions from the "hot start" phase, only the 4NYNF cycle was considered for the speed correction factor derivation. Each of the three cycles used to derive the speed correction factors have unique speeds and they are as follows:

- 2 LANF has a speed of 16.82 MPH
- 3 LAF has a speed of 46.91 MPH
- 4 NYNF has a speed of 7.31 MPH

Data for HC, CO and NO_x are available on a cycle specific basis, but such data is not available for particulate emissions.

Importantly, the composite cycle which has an average speed of 18.79 MPH is not a separate cycle but an average of the cycles described above. Emissions for the composite cycle, which are used to derive the basic emission rate represents a distance weighted average of the four cycles described above. In comparison, the basic emission rate for light duty vehicles is derived from an actual cycle whose speed corresponds to the speed for the basic emission rate. This has important ramifications for the speed correction for heavy-duty vehicles, as discussed in this section.

7.2 Methodology

The speed correction factor for emissions is generally expressed as a polynamial of speed in MPH. Since there are only three speeds at which emission data is available, a maximum of three constants can be solved for, restricting the polynamial in speed to a second-order polynamial. It is well known that emissions per unit distance rise steeply at low speeds - in fact, it is infinite at idle, but the speed correction factor is not used at idle - and therefore, exponential forms of the equations are generally used. The two forms tried

$$E/Eo = \exp (A_1 + B_1 S)$$

$$E/Eo = \exp (A_2 + B_2 S + C_2 S^2)$$

where E is the emission rate of HC, CO, or NO_x at speed, S
Eo is the basic emission rate for the pollutant
A, B and C are regression constants.

This form of the equation allows the speed correction factor to be used as a multiplier to the base emission rate. An advantage of this form is that emission rates for each speed are normalized by the composite emission rate, and hence vehicle specific effects are removed. A non-exponential form was also tried of the form

$$E/Eo = A_3 + B_3 S + C_3/S$$

This form uses the $1/_S$ term to model the rapid increase in emission rates at low speeds.

7.3 Results

The approach used to determine the regression constants was by fitting the equations, by pollutant, for each vehicle and then averaging the constants over all vehicles. As for the emission factor analysis, the buses were removed from consideration because of their unique behavior. Models were selected for each pollutant depending on their relative accuracy as measured by the variance of the estimated values for each coefficient, as well as their ability to behave correctly outside the range of speeds for which there is data. Correct behavior is defined based on engineering analysis of directional trends for emissions at speeds higher than the range encountered in the data.

The following values* were determined for the speed correction factors, using the first model $E/Eo = \exp(A_1 + B_1 S)$ or conversely,

$$\ln E/Eo = A_1 + B_1 S$$

$$\ln HC/HC_o = 0.9450\ (\pm\ 0.2134) - 0.0351\ (\pm\ 0.0096)S$$

$$\ln CO/CO_o = 0.6594\ (\pm\ 0.1403) - 0.0244\ (\pm\ 0.0056)S$$

$$\ln NO_x/NO_{xo} = 0.1859\ (\pm\ 0.1247) - 0.0063\ (\pm\ 0.0039)S$$

The second for $\ln E/E_o = A_2 + B_2 S + C_2 S^2$ were found to give

$$\ln HC/HC_o = 1.1709\ (\pm\ 0.4226) - 0.0610\ (\pm\ 0.0358)\ S + 4.585\times10^{-4}(\pm\ 5.21\times10^{-4})S^2$$

$$\ln CO/CO_o = 1.2023\ (\pm\ 0.3128) - 0.0867\ (\pm\ 0.0337)\ S + 0.0011\ (\pm\ 0.0006)\ S^2$$

$$\ln NO_x/NO_{xo} = 0.6426\ (\pm\ 0.1215) - 0.0586\ (\pm\ 0.0119)\ S + 9.269\times10^{-4}(\pm\ 2.417\times10^{-4})S^2$$

Examination of the equations show that the S^2 term is not significant in the HC Equation at 0.10 level, but is significant for the CO and NO_x equations. The positive sign of the S^2 term in the equations indicate that emissions begin to increase beyond a certain speed, and the speed at which this occurs (i.e., the speed of minimum emissions) was calculated from the above

*Std. errors in parantheses.

data to be 66.52 mph for HC, 39.40 mph for CO and 31.61 for NO_x. Engineering considerations show that both HC and CO should decrease at higher speeds and the available data confirms this hypotheses, showing that the significant coefficient found for the S^2 term is simply an artifact of the model used. On the other hand, engineering analysis shows that NO_x emissions should rise at higher speeds due to the higher engine loads experienced at higher speed, and hence the S^2 term is required.

Analysis of this equation for NO_x emissions shows that the speed correction factor increases rapidly beyond 50 mph. At 50 mph its value is 1.03, but at 70 mph the factor rises to 2.95. In order to determine if such an increase is realistic, EEA examined records of steady-state test data for HD diesel engines. If we assume that the intermediate RPM, 75 percent load point corresponds to 50 MPH and rated speed, rated load point corresponds to 70 MPH (these assumptions are approximately correct), than we found that, on a gm/BHP-hr basis, NO_x emissions decrease between the 50 mph and 70 MPH points. Engineering analysis shows that BHP-hr, or work, should increase at approximately the square of the speeds, indicating that the correction factor should increase by $(\frac{70}{50})^2$, or 1.96. Emissions should increase by less than this factor, indicating that the exponential model with an S^2 term may be overestimating NO_x emissions at higher speeds. Accordingly, the alternative model using a polynomial in S (1/S, S^0, S was used. The polynomial form for NO_x emissions was found to be

$$NO_x/NO_{xo} = 0.4437\ (\pm\ 0.2297) + \frac{5.8851}{S}\ (\pm\ 1.3309) + 0.00778\ (\pm\ 0.00567)S$$

This model however, predicts hardly any increase in NO_x emissions between 50 and 70 MPH, giving values of 0.9504 and 1.072 for the two speeds respectively. The coefficients are also less significant (i.e. they have large variance) than these for the exponential equations. Accordingly, EEA recommends the following equations for speed correction factor:

$$\ln (HC/HC_o) = 0.945 - 0.0351 \pm S$$

$$\ln (CO/CO_o) = 0.659 - 0.0244 \pm S$$

$$\ln (NO_x/NO_{xo}) = 0.6426 - 0.0587 \pm S + 0.000927 \pm S^2$$

It must be recognized that engineering analysis show that NO_x may be over-predicted for speeds above 50 MPH, with the form of exponential employed. Figure 7-1 to 7-3 shows the plot of predicted vs. actual correction factors for HC, CO and NO_x .

A problem with the form of the equation is that the correction factor is not equal to 1 at the composite cycle average speed, 18.79 MPH. That is because the composite cycle takes a linear distance weighted average whereas all of the equations used for the correction factors are non-linear. Thus, there can be no correspondence between average speed and average emissions. Note that there is no actual data at 18.79 MPH for heavy duty trucks that is derived independently from the other data. As a result, the values of the correction factor at 18.79 MPH are 1.33 for HC, 1.22 for CO and 0.875 for NO_x. Two alternatives are possible.

- Accept the fact that transient cycle emissions are average of highway and city cycles, and therefore not representative of emissions at 18.79 MPH. Actual emissions for a cycle at 18.79 MPH would be represented by the values predicted by the speed correction factor.
- Modify the factors to make them predict a correction factor of one at 18.79 MPH.

If the second approach is followed, it can be accomplished as an "offset" to the existing factors. The resulting equations are:

$$\ln HC/HC_o = 0.6595 - 0.0351 S$$

$$\ln CO/CO_o = 0.4585 - 0.0244 S$$

$$\ln NO_x/NO_{xo} = 0.7756 - 0.0587 S + 0.000927 S^2$$

A1 14:19 THURSDAY, APRIL 19, 1984 10

PLOT OF PRHCN*RHCN LEGEND: A = 1 OBS, B = 2 OBS, ETC.

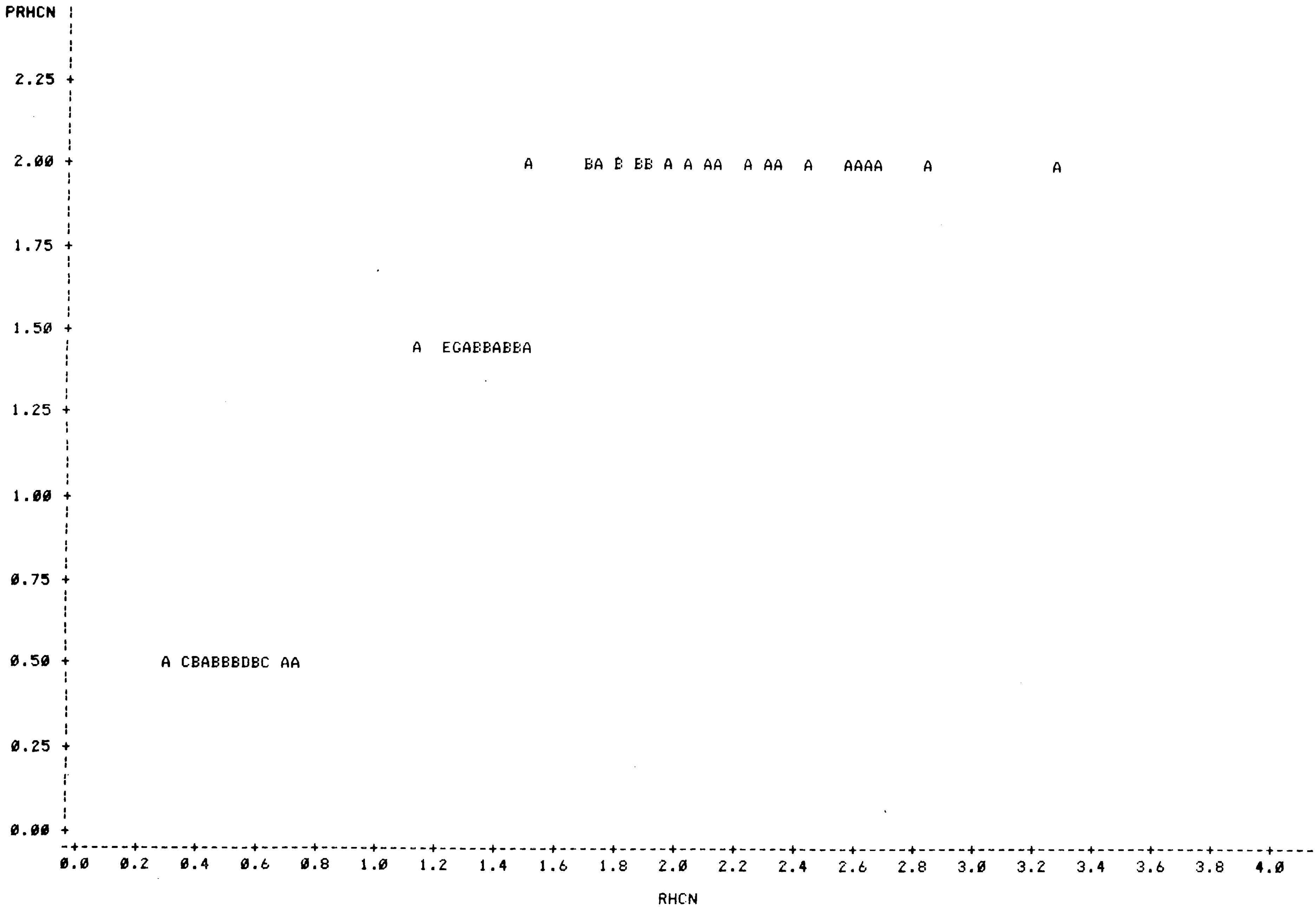


Figure 7-1

Predicted vs. Actual HC Speed Correction Factor

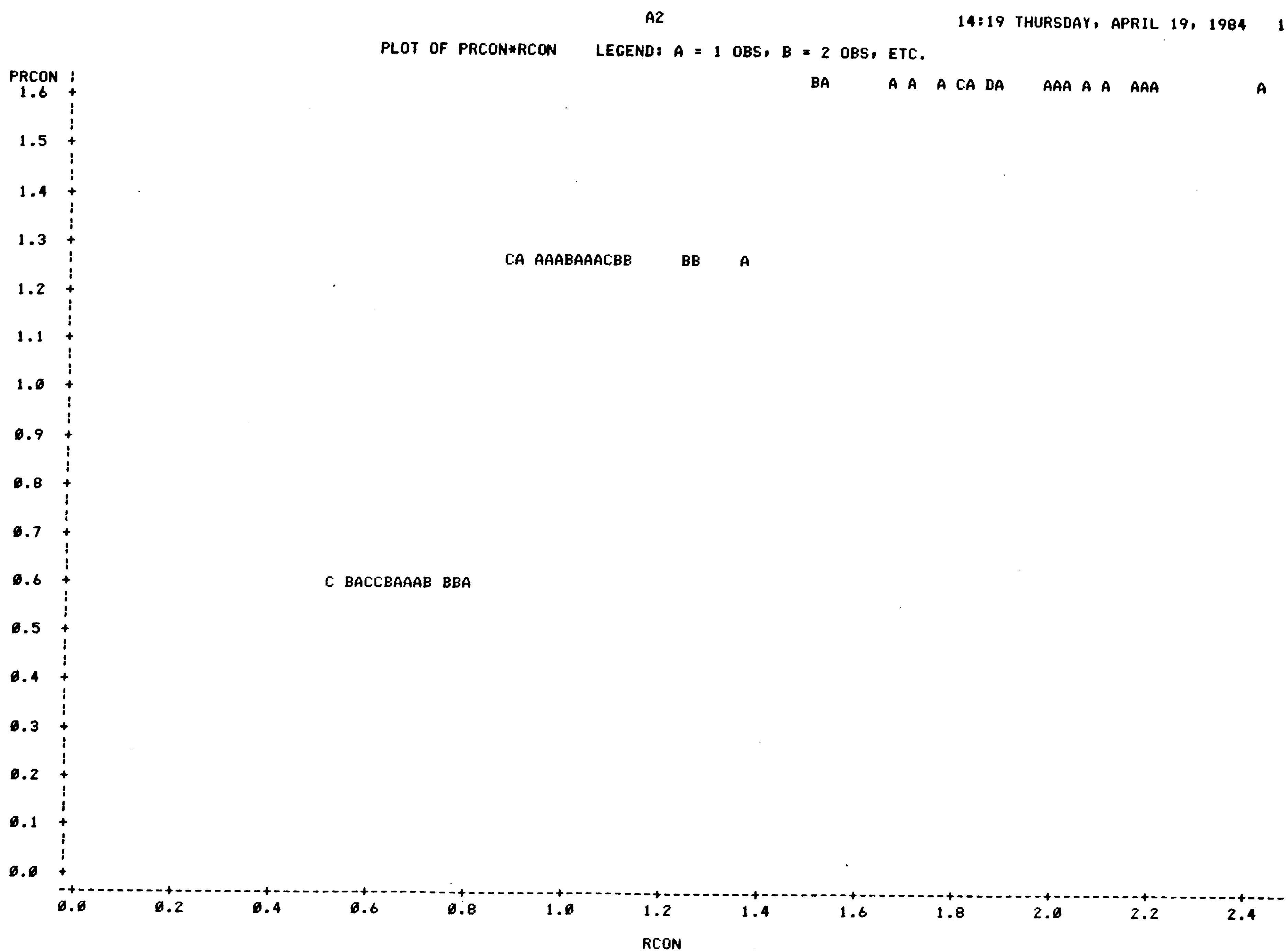


Figure 7-2

Predicted vs Actual CO Speed Correction Factor

B3 14:19 THURSDAY, APRIL 19, 1984 15

PLOT OF PRNOXN*RNOXN LEGEND: A = 1 OBS, B = 2 OBS, ETC.

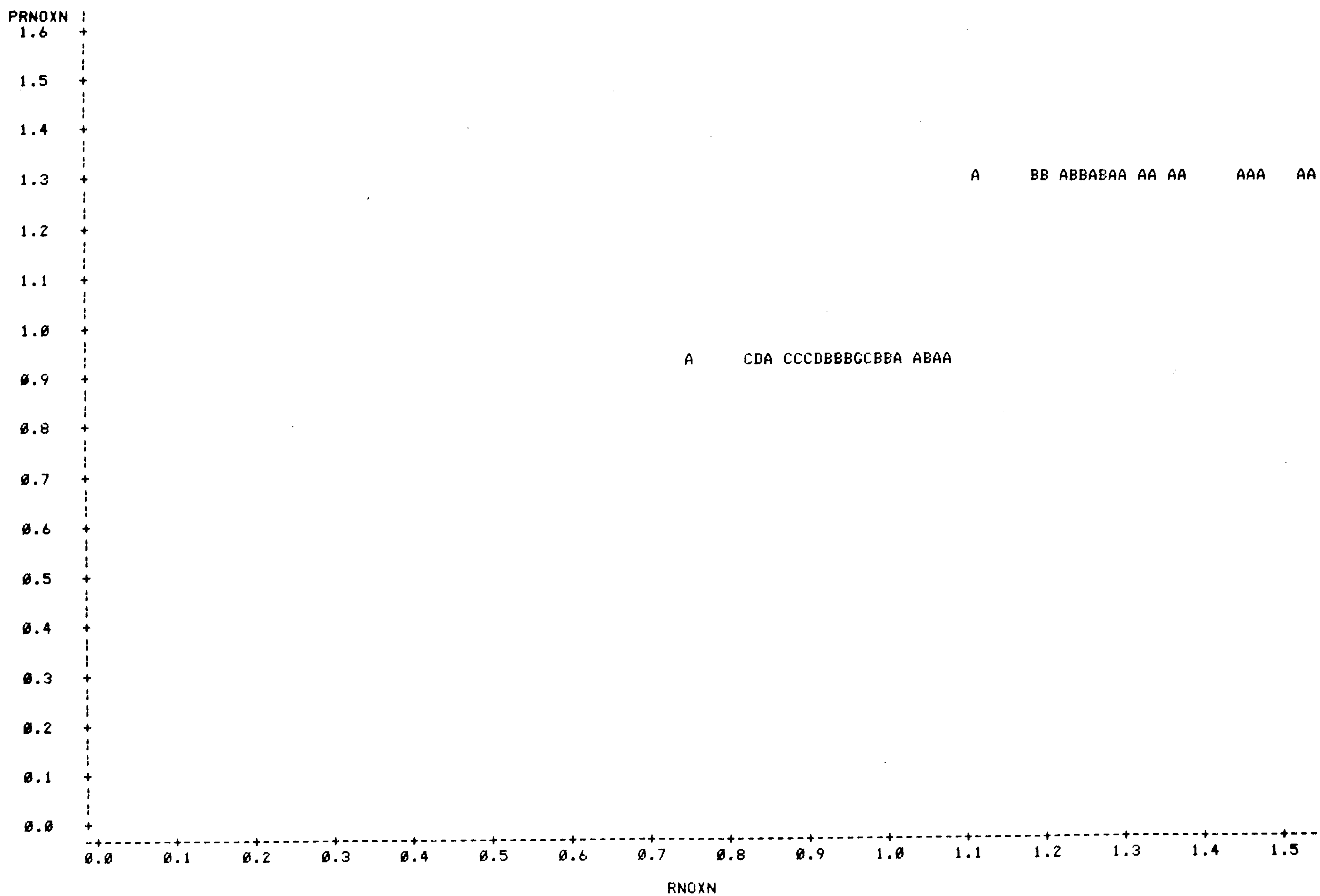


Figure 7-3
Predicted vs. Actual NO_x Speed Correction Factor

This, of course, changes the values of the factor at the observed cycle speeds, and provides a poorer fit of the data. Yet another approach to the normalization problem is to attempt to fit the regressions through 18.79 as an additional data point, but this introduces an unnatural shape to the speed correction curve. EEA did not attempt, nor does it recommend, such an approach.

APPENDIX A

MANUFACTURERS RESPONSES TO QUESTIONS REGADING IN-USE MALPERFORMANCES

Cummins Engine Company, Inc.
Columbus, Indiana
47201

May 12, 1983

Mr. K. G. Duleep
Energy and Environmental Analysis, Inc.
1111 North 19th Street
Arlington, VA 22209

Dear Mr. Duleep:

In response to your inquiry regarding California in-use malperformance analysis, I offer the following information relative to the specific questions as outlined in your letter of April 7, 1983.

Malperformance, as you know, is a relatively subjective term when evaluating in-use heavy-duty engines, however, we have interpreted the term, as used in the context of your questions, to mean a malperformance which would cause a significant and measurable increase in gaseous emissions. It is Cummins opinion that a change of ±.75 grams/HP-HR NO_x and ±.3 grams/HP-HR HC or ±1.0 grams HC + NO_x are within measurement error and are not significant.

Based on our own durability test results, Cummins contends that properly maintained heavy-duty diesel engines do not deteriorate or change emission levels above the limits of our ability to measure these emissions. In other words, the average emissions rate of a heavy-duty Cummins engine over its life time is essentially constant.

Malperformance then must be assumed to be the result of improper or unperformed maintenance, improper operations, or tampering, i.e. replacement by incorrect parts, omission of parts, misadjustment of systems and/or components.

The four categories listed in your April 7, 1983, letter would probably be appropriate when considering the entire North American heavy-duty diesel engine population. We would recommend that restricted or dirty air cleaners be added to your list of parts having an adverse impact on performance and emissions.

Phone: 812 372 7211

The emissions impact of these, relative to Cummins heavy-duty engines, are as follows:

Clogged Injectors - This is extremely rare on Cummins' engines unless contaminated fuel is encountered, and in these cases, mechanical or performance problems arise which preclude the use of bad fuel for a sustained period. We conclude that the impact of such conditions on emissions or air quality is insignificant, if any at all.

Injector Timing Adjustment - Cummins' engines have either fixed or two-position timing. On fixed timed engines, the timing is fixed during major component assembly and requires major effort (camfollower housings must be removed and new gaskets installed) and expense to change. Thus, we would conclude that on fixed timed engines, this condition would be too cost prohibitive and therefore should be ruled out.

On two-position variable timed engines (if tampered with so as to operate in as fixed timing in either position) there are noticeable performance and durability penalties which can result if the system does not operate in the correct position i.e. if locked into the retard mode excessive acceleration smoke would result with possible slight increase in horsepower. If locked into the advance mode, smoke would not be adversely affected, however, there would be an increase in NO_x emissions (possibly in the range of 30 to 40 percent) as well as increased noise levels. Because of increased cylinder pressures, a sustained operation would ultimately result in severe durability problems. The operator may perceive a light increase in horsepower because of increased noise levels, however, horsepower would be actually be decreased. Operators will be knowledgeable of these penalties and would normally seek prompt repair.

Disabling The Smoke Puff Limiter - Historical demonstrations have proven that without these devices being incorporated into the engine design, an experienced operator can achieve optimum acceleration performance and still control smoke; however, some drivers do not always opt to use this ability. On Cummins' engines, the "smoke puff limiter" is referred to as the Air Fuel Control (AFC) and is an integral part of the fuel pump and is sealed; if disconnected the result is severe power loss. There is limited capability for misadjustment. However, recent tests on transient emission tests indicate that for this limited range of misadjustment, these acceleration puffs are not significant to the total exhaust particulate measurement. Misadjusting the smoke puff limiter (AFC) does not effect the gaseous emission as measured on the 13-mode or transient cycles.

Maladjustment of Fuel Pump - Replacing fuel pump or increasing fuel rate has been observed by our field maintenance personnel on engines at overhaul and/or rebuild. Increasing the fuel rate (within the limits that engine damage will not occur, i.e. 10%) has little or no effect on brake specific emissions as the brake specific horsepower increases in approximately the same rate as the total emissions. Raising the power on the engine may give the driver a perception of increased control or improved driveability, but would have little or no effect on brake specific emissions emitted during the mission. Continued operation with gross overfueling will result in severe mechanical and thermal loads on an engine with subsequent severe and costly damage to the engine. In general, these comments apply to an overgoverning condition of the engine.

Restricted Air Cleaners - Improper maintenance can and often does result in high air cleaner restriction resulting in dense smoke and loss of power. Again, the transient test results indicate that restriction that does not result in prohibitive power loss, has not shown to have significant effects on gaseous emissions on the transient test.

Admittedly there are engines in operation which have malperformance due to maladjustments, abuse or tampering. The percentage of occurrence would be small and relatively insignificant; considering the total heavy-duty diesel engine population, probably immeasurable. It would be less than the effect of a change in ambient relative humidity from 20% to 80%, i.e., this humidity change would result in a 8% change in NO_x.

We have no means to quantify the amount of field maladjustments. Furthermore, we are reluctant to make projections relevant to actual instances of in-use malperformance because Cummins warranty records would not reflect any of the above stated malperformance categories since they are operator responsibility. If they would occur as a result of faulty material or workmanship by Cummins or Cummins authorized service representatives then they would promptly be corrected under commercial warranty.

It is worth noting that more stringently imposed NO_x control will result in more performance and fuel economy penalties. It will become more difficult to design engines which would deter tampering, because technology may be pushed to it's limits. Application of EGR, a likely NO_x control system, to turbocharged diesel engines is much more complicated than on gasoline engines and, therefore, may be less prone to be subjected to disconnection or bypassing. The final details of such control systems are unknown and renders comments on the possible effects or probable operator actions very speculative.

I hope the above response meets with your needs. Please direct any comments and/or questions relating to this document to me.

Regards,

J. L. Hendricks/jvk

Environmental Specialist
Product Environmental Management

JLH105L

Environmental Activities Staff
General Motors Corporation
General Motors Technical Center
Warren, Michigan 48090

October 20, 1983

Mr. K.G. Duleep
Energy and Environmental Analysis, Inc.
1111 North 19th Street
Arlington, Virginia 22209

Dear Mr. Duleep,

This letter is in response to your April 7, 1983 request for information about heavy-duty truck malperformance and maladjustment under in-use conditions. There are no surveys conducted by General Motors specifically aimed at determining the incidence of malperformance or maladjustment in the field. Two high-mileage study summaries submitted by the Engine Manufacturers Association (EMA) to EPA as part of Public Docket A-81-11 indicate that regular maintenance and adjustment to factory specifications is occurring on heavy duty fleet trucks which suggests that malperformance and maladjustment is not widespread in the field in fleet trucks. However, since we are unable to draw a reliable conclusion about the extent of malperformance and maladjustment from these studies, we will limit our comments in this letter to judgements based upon our understanding of heavy-duty engine usage in trucks by vehicle operators along with our knowledge of the design features of these engines.

In general, we believe that your preliminary research of malperformance is probably inaccurate when applied to GM heavy-duty **diesel engines** with the possible exception of raised governed engine speed and adjustment or disconnection of the smoke puff limiter. These, however, have an insignificant effect upon regulated gaseous emissions.

Clogged diesel injectors account for only a very small percentage of in-use operating problems. Impurities in the fuel have been identified as the only cause for clogging in cases we have investigated in more detail from the few that have occurred. Two impurities found were zinc and barrium which precipitated out of the fuel, deposited on the spray tip assembly, and resulted in increased smoke and power loss. It does not appear that clogged injectors from impurities in diesel fuel is a significant field problem.

Injection timing maladjustment probably is not widespread on most GM heavy-duty diesel engines because access is very difficult. The rocker covers must be removed and each individual unit injector retimed on all but the 6.2 liter engine. For the 6.2 liter engine, injection timing tends to be at the optimum setting at the factory specification because advancing it results in noticibly more noise and retarding it causes significant losses in fuel economy, so the incentive to maladjust is not strong.

The emission impact of a timing maladjustment is generally dependent upon individual engine calibrations. At current California calibrations, we would expect an injection timing change on all but the 6.2 liter GM engines to cause about an 8% change in BSNOx for each degree of change in all injectors and a negligible change in BSHC and BSCO. This same group of engines will emit more particulates with **retarded** injection timing in contrast to the 6.2 liter engine which has increased particulates emissions with **advanced** injection timing, chiefly because it has indirect fuel injection and all of our other engines have direct fuel injection. The other gaseous emissions vary with changes in injection timing according to the approximate rates shown on the following table for the 6.2 liter engine:

RETARD TIMING

.13 g/bhp-hr/deg	HC increase
.35 g/bhp-hr/deg	NOx decrease
.15 g/bhp-hr/deg	CO increase
Particulate	No change
Smoke	No change

ADVANCE TIMING

.04 g/bhp-hr/deg	HC decrease
1.3 g/bhp-hr/deg	NOx increase
.11 g/bhp-hr/deg	Particulate increase
.20 g/bhp-hr/deg	CO increase
1.0 %/deg	Smoke increase

Maladjustment or replacement of the fuel metering pump to increase fueling is also unlikely on all but the 6.2 liter GM heavy-duty diesel engines because individual injectors would have to be replaced to accomplish the equivalent fueling change. Maladjustment of fuel metering on the 6.2 liter engine is deterred because the adjusting screw is covered with a plug to render it relatively inaccessible. You should be aware that our production engines(other than the 6.2 liter engine) have several different emission certified injectors with different outputs in the same basic engine. Thus, a change of injectors from original production would not cause excessive emission output if an authorized injector were used. Even a replacement with a non-certified, higher-output injector probably would not affect gaseous emissions significantly; the primary emission effect would be on smoke level. On the 6.2 liter engine, there is no effect upon gaseous emissions up to a ten percent increase in the maximum fuel rate; the primary effect, again, is upon the smoke level.

An increase in the governed engine speed above the certified speed may be encountered with in-use vehicles, however, this only causes a loss of fuel economy and has little effect upon either brake specific emission levels or the smoke level. In some of our engine families, we certify a range of speeds for different applications so you should be aware of this condition when reviewing any data about in-use governed engine speed maladjustments.

Adjustment or disconnection of the smoke puff limiter may be occurring on GM engines other than the 6.2 and 8.2 liter engines since an improvement in vehicle acceleration response could result. Such an adjustment or disconnection will exhibit increased levels of visible smoke, but on accelerations only. Regulated gaseous emissions are unaffected. Our 6.2 and 8.2 liter engines are not equipped with a smoke puff limiter.

The only new technology affecting adjustments and anticipated by General Motors for introduction into heavy-duty diesel engines with the emission limits currently being proposed is electronic controls. If this technology were introduced, we would expect any observations of maladjustment to decrease because some of the current adjustments are likely to be eliminated. EGR for diesel engines is not being considered and particulate traps are neither cost-beneficial nor technologically feasible.

With respect to **gasoline engines**, we are able to make some judgements about heavy-duty in-use parameter adjustments by drawing parallel conclusions from EPA's investigation a few years ago of light-duty gasoline vehicle in-use parameter adjustments. The results of this study showed that idle air fuel mixture was being adjusted in a predominantly rich direction from the nominally specified setting. In contrast, the other three parameters studied (choke, spark timing, and idle speed) were being adjusted in both directions in an even distribution pattern around the nominally specified setting. Since our data indicates that this even distribution of adjustments tends to produce offsetting emission results, General Motors has concluded that only the idle air fuel mixture adjustments found in EPA's study could be expected to generate an adverse air quality impact. We believe the same conclusion applies to heavy-duty gasoline engines because the same type of adjustments studied by EPA for light-duty gasoline vehicles are also found on heavy-duty gasoline engines. The idle air fuel mixture screw on both light and heavy duty GM engines is covered with a hardened steel plug to discourage improper adjustment.

Of course, the air pump can be disconnected on heavy-duty gasoline engines, but we believe little benefit is realized from this alteration and, therefore, little incentive exists to make the modification. General Motors has no data on the occurance of such an alteration.

I hope this information is helpful to you in your analyses. I would appreciate a copy of your final report and look forward to your findings. Please call me if you require clarification on any of the information in this letter.

Sincerely yours,

David Keenan

for - C. J. Elder, Manager
Heavy-Duty Activities

INTERNATIONAL HARVESTER

May 5, 1983

Mr. K. G. Duleep
Consultant
Energy & Environmental Analysis Inc.
1111 North 19th Street
Arlington, Virginia 22200

SUBJECT: Heavy-Duty Truck In-Use Emission Factors

Dear Mr. Duleep:

Reference is made to your letter of April 6, 1983 to Mr. Farrel Krall of International Harvester Company. Your letter was forwarded to me so that I might answer your questions concerning heavy-duty engines. It is my understanding that your truck related questions will be handled by Mr. R. W. Glotzbach of our Truck Group. The following discussion represents the Engine Division's responses to your questions.

- Does your knowledge of the malperformance types show that our understanding of malperformance is erroneous or incomplete?

  Your list for diesel and gasoline engines appears to be fairly complete in terms of the most important components or parameters that might be maladjusted. The only other major emission control component which sometimes is either poorly maintained or blocked is the exhaust gas recirculation system (EGR). (Your subsequent questions cover this.)

- Can you provide the typical emission impact (or range of impact) as a result of the presence of a malperformance?

  A question similar to the above was recently asked by EPA. It concerned the effect of fuel injection timing upon the emission performance and fuel economy of our most popular California diesel engine model. This model is rated at 210 bhp and features direct injection, turbocharging, and intercooling. In other words, it is our most fuel efficient, emission controlled, heavy-duty engine. The following table relates the percentage changes in emissions and fuel economy as the injection timing was varied (advanced by 11 crank degrees).

Item	Approximate Change
Fuel Economy Improvement (Average of Rated & Peak Torque)	10%
NOx Increase	120%
Particulate Decrease	15%

- Does your field warranty or service data provide any indication of the rates of occurance of the malperformance?

  These records do not necessarily provide a good indication of malperformance since maladjustment by the customer or improper maintenance may occur without an increase in warranty claims. However, the Manager of our Service Department from the observation of both he and his staff believe that there is very little tampering or improper maintenance in terms of our medium and light-heavy duty diesel engines. Our Manager attributes this to the fact that diesel engine technology is not well understood by the majority of our customers now switching to diesel power and for this reason they are hesitant to tamper with the factory settings or extend maintenance periods.

- Do you expect future emission control technology (other than particulate traps) to change the relationships described above? In particular, if EGR is likely to be adopted for California diesel engines, is there any way to estimate EGR disconnection rates?

  Certainly the employment of EGR systems or the use of particulate traps would lead to tampering. These systems are not intergal to the engine and their malperformance will not adversely effect the performance of the vehicle. Therefore, disconnection or removal will probably be widespread in IH's opinion. However, to date IH has not made use of either of these emission control systems and hence, has no experience and only an opinion to express.

- Expected percentage increase in diesel fuel economy over the decade.

  IH, in conjunction with our various fuel injection component supplies, have conducted parametric studies to determine the effect of electronic fuel injection control on both emissions and fuel economy. As a result of these studies, IH made the following response to EPA in our last submission on this subject.

"Electronic Fuel Injection Systems

While IH and other manufacturers have used alteration in injection timing (i.e. retarded injection timing) as one method of reducing NOx emissions, this control strategy has the disadvantage of increasing fuel consumption, particulate emissions, and hydrocarbons. The ideal fuel injection system would be capable of controlling timing over the entire range of engine loads and speeds. While mechanical injection systems have become more and more sophisticated, there is a limit to the amount of control they can achieve over fuel economy losses. The National Academy of Science (NAS) report previously cited mentions (P. 24) that technicians developing electronic fuel injection systems for light-duty diesel engines claim to be able to achieve fuel economy improvements of 10 to 15% over the best mechanical injection systems. So far, however, IH is unaware of the development of any electronic fuel injection systems that would produce this degree of fuel economy improvement in IH heavy-duty diesels, and we doubt such systems will become available to us until the late 1980's at the earliest.

The information in the previous statements has been worded in a fashion which makes its disclosure of a non-sensitive nature to IH, therefore, you are free to use it in any manner you see fit. If I can be of any further assistance, please feel free to call me at (312) 865-4200.

Yours sincerely,

Charles R. Hudson
Manager, Environmental Staff
Engine Division Component Group

CRH:ch

CATERPILLAR TRACTOR CO.

Peoria, Illinois 61629

April 29, 1983

Mr. K. G. Duleep
Consultant, Transportation Technology
Energy and Environmental Analysis, Inc.
1111 North 19th Street
Arlington, VA 22209

Dear Mr. Duleep:

We have reviewed your April 6, 1983 request for information on the in-use emissions performance of our heavy-duty highway truck engines and have prepared responses to your questions. Some of our responses, as you can well understand, are sensitive to our commercial business so we must request that our comments be held confidential by your organization and only be released, as you suggested, on an industry-wide aggregate level and not be specific to any make or model.

We would agree that your understanding of in-use malperformances for HD diesel engines is in general correct from a generic point of view. Design characteristics of HD diesel engines vary among manufacturers but those items affecting emissions are pretty well identified by your list. For Caterpillar engines, the engine adjustments that affect emissions and/or engine performance are primarily:

1. Timing changes
2. Rating changes (fuel rate and governed speed)
3. Air-fuel ratio (puff limiter) settings
4. EGR system made inoperative.

These changes are generally made to improve vehicle performance for either fuel consumption and response or both. Truck drivers, and particularly those who operate long haul trucks, are very critical of a vehicle's acceleration characteristics, lugging capability, speed and fuel consumption and have been known to change our factory settings. Changes to the items listed above would affect emissions as described below:

1. Timing - Advancing the timing improves fuel consumption and smoke but increases NO_x. HC and CO may improve slightly. An attached graph shows some trends of smoke, NO_x and BSFC plotted against injection timing. This data is fairly typical of our large heavy duty diesel engines.

2. Rating changes - Increasing the power of an engine usually decreases NO_x on a brake specific basis but could increase CO and smoke.

3. Air-fuel ratio setting - Loosening the limiter setting will increase acceleration and peak smoke. We question, at least on Caterpillar engines, if this smoke control device is disconnected, because we believe that operators recognize that some smoke control must be maintained on highly turbocharged engines to avoid smoke citations from local and state authorities.

4. EGR system - Disconnecting the EGR system would increase NO_x and HC but reduce CO and smoke. Caterpillar currently has an engine with an EGR system that is required for trucks sold in California.

Our field warranty and service data system does not define in detail whether an emission malperformance occurred, a part failed or if a part was misadjusted. In other words, we can only quantify the number of incidents that have been reported through our data system but not the cause of the incidents. Fuel nozzles are a good example of a component that has a high number of incidents reported but in our evaluation of so-called defective nozzles, we find that almost 90% of them are good and should not have been replaced. Replacement of nozzles and other fuel system incidents reported to us result from our dealers trying to resolve a driver's perception of a performance problem and they often replace and adjust unnecessarily in an effort to solve an elusive and unquantifiable problem. We communicate to our dealers, the need to maintain our specifications for engines so we would like to believe that there is no deliberate attempt by our dealers to create malperformance situations through either adjustment or disconnect. We cannot speak for individual owner actions.

As for future emission control technologies, we would not expect them to change the relationships previously described.

Future fuel economy improvements on our large heavy-duty engines of up to 6% are expected assuming that 1984-1985 emission standards remain in effect. This is over and above the almost 15% gain that we have made on this type of engine since the mid seventies. Any tightening of NO_x standards will cancel some fuel consumption gains and if NO_x levels are reduced sharply, all of the fuel consumption gains expected could be more than negated. We currently have programs underway to improve the fuel economy of our mid-range truck engines which are primarily used in pickup and delivery operations. We expect improvements ranging from 8 to 20% depending upon application and drive train matching.

In response to your request about non-engine related technologies, we are not in a position to comment since we are only an engine manufacturer and do not design and build highway trucks. However, I am enclosing several articles from a recent issue from the "Diesel Equipment Superintendent" which you may find of interest. As these articles point out, fleets are very cognizant of fuel consumption and have become very innovative in their search for improvements.

From an engine supplier's viewpoint, we have seen in the past several years a definite shift in the market toward fuel economy engines. Fuel economy is now the No. 1 sales feature of diesel engines and every manufacturer including Caterpillar is very intent upon making further improvements. Sales to truck fleets trend to the lower engine speeds in order to maximize fuel economy. Sales to owner-operator long haul trucks still favor the high horsepower and highest rated speed. A sales brochure is enclosed to provide you with additional details on the variety of ratings that we offer to our customers.

If there are any questions, please call.

Sincerely,

DC Dowdall

Engine Emissions Manager
Product Safety & Environmental
Control G.O.

D. C. Dowdall
AB6A
Ph: (309) 675-5362
glb (3160y-D)

Encls.

MACK TRUCKS, INC.

One of the Signal Companies

1999 Pennsylvania Avenue, Hagerstown, Maryland 21740

Area Code (301) 733-8300

June 24, 1983

Mr. K. G. Duleep
Energy and Environmental Analysis, Inc.
1111 North 19th Street
Arlington, Virginia 22209

Dear Mr. Duleep:

This letter responds as best we can to the questions raised in your correspondence of April 6, 1983, to Mr. Frank Pekar. Those questions addressed heavy-duty truck "in-use" emission conditions.

You should know that Mack manufactures only Class 8 heavy-duty trucks, which are those over 33,000 lbs. GVW. All of our trucks are powered by heavy-duty diesel engines, 90% of which are our own design and manufacture. All Mack engines are turbocharged.

Heavy-duty engine manufacturers, through a joint EMA/EPA program, are now initiating a program to help us better understand in-use emission performance. However, that program is in the very early stages and no data is available.

We agree that in-use malperformances do exist with our engines. Those we know about are as follows:

- Clogged Injection Nozzles - These are normally caught at regular maintenance intervals. However, the operator would notice as a condition of deteriorating performance.

- Over Fueling - Operators do this maybe as much as 15% of the time to increase power.

- Disconnection of Puff Limiter - We know this does occur, but have no idea how often. However, the extreme cases are very obvious, you see a puff of black smoke at start.

We do not have any estimates of the impact of non-engine related technologies on fuel economy, nor do we have any estimates of fuel economy gains as a result of market shifts towards more fuel efficient trucks.

From our 1982 production figures we can see that 11% of our forty-nine state engines and 41% of our California engines were the high torque rise lower speed engines. It should also be noted that our California engine sales represented only 1.5% of our total domestic sales in 1982.

With respect to increases in diesel fuel economy over the decade, we can only compare the fuel economy of our engines to the level of the NOx standard. This is shown on the attachments for two of our California engine models. Attachment "A" shows our 237 HP engine that was produced from 1966 through 1979. You can notice the change in BSFC each time the NOx emission regulations were changed. Finally in 1980 we could no longer offer this model in California because of the feasibility of meeting the 6.0 g/bhp-h HC+NOx standard.

Attachment "B" also shows the trend for our 285 HP engine that was introduced with the 7.5 g/bhp-h NOx standard and the impact of the 6.0 g/BHP-h HC+NOx standard. This engine is not going to be offered in 1984.

Sorry, we are so late in responding to your request, but I gather that you can still use this input for your study.

Should you have any questions concerning any of the contents, please advise.

Very truly yours,

MACK TRUCKS, INC.

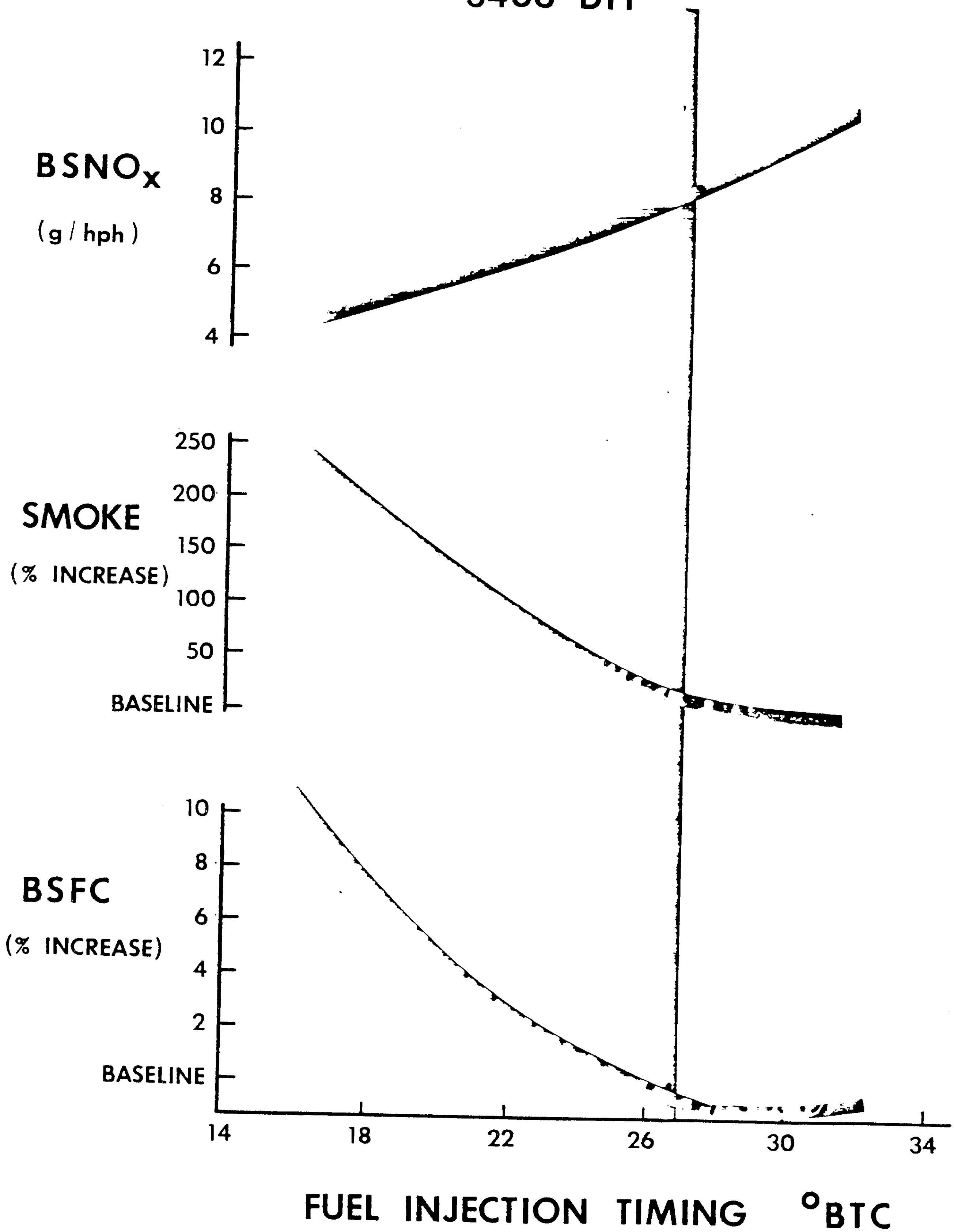
R. E. Kendall

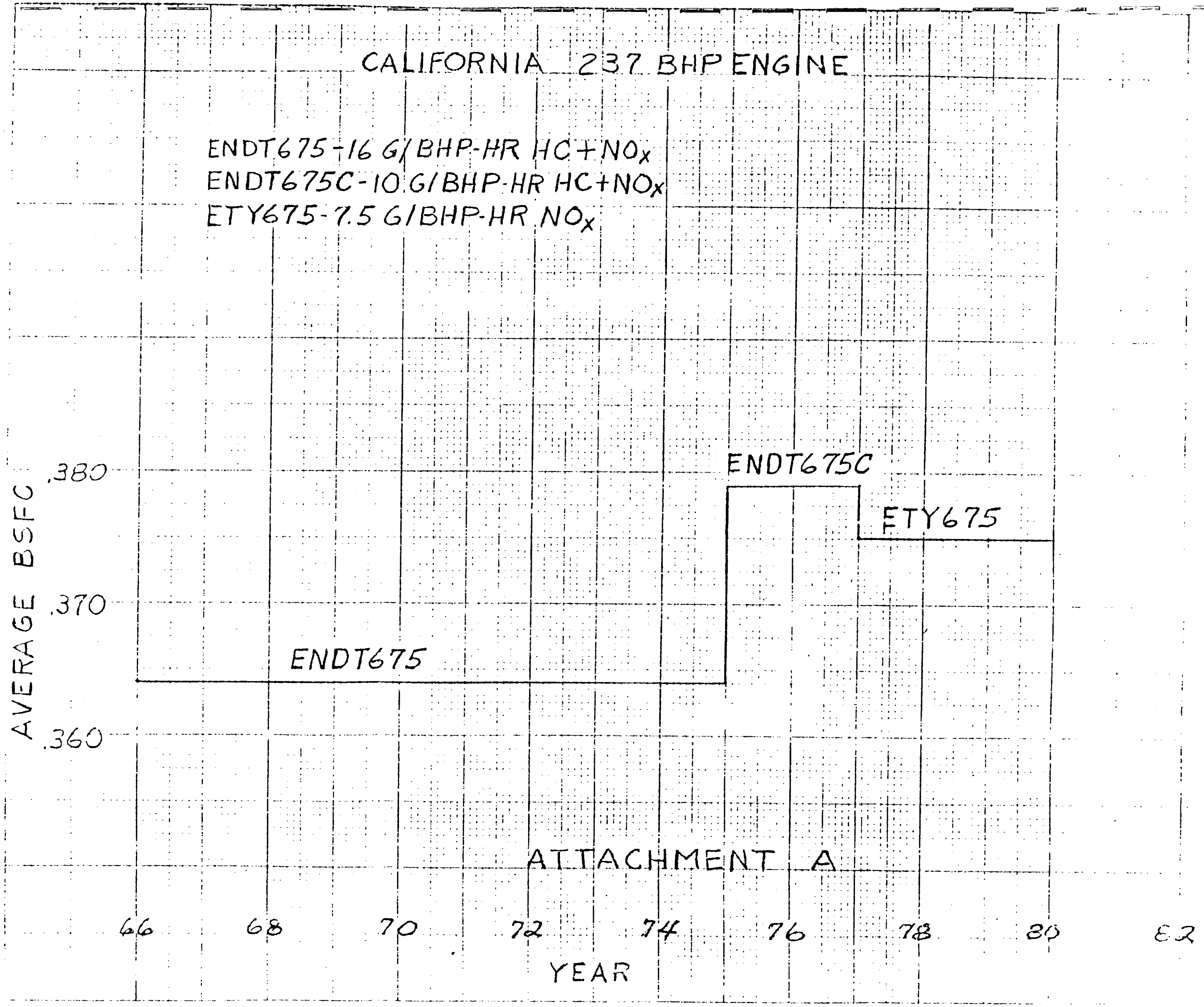
R. E. Kendall
Sr. Project Engineer
Engine Certification

nk

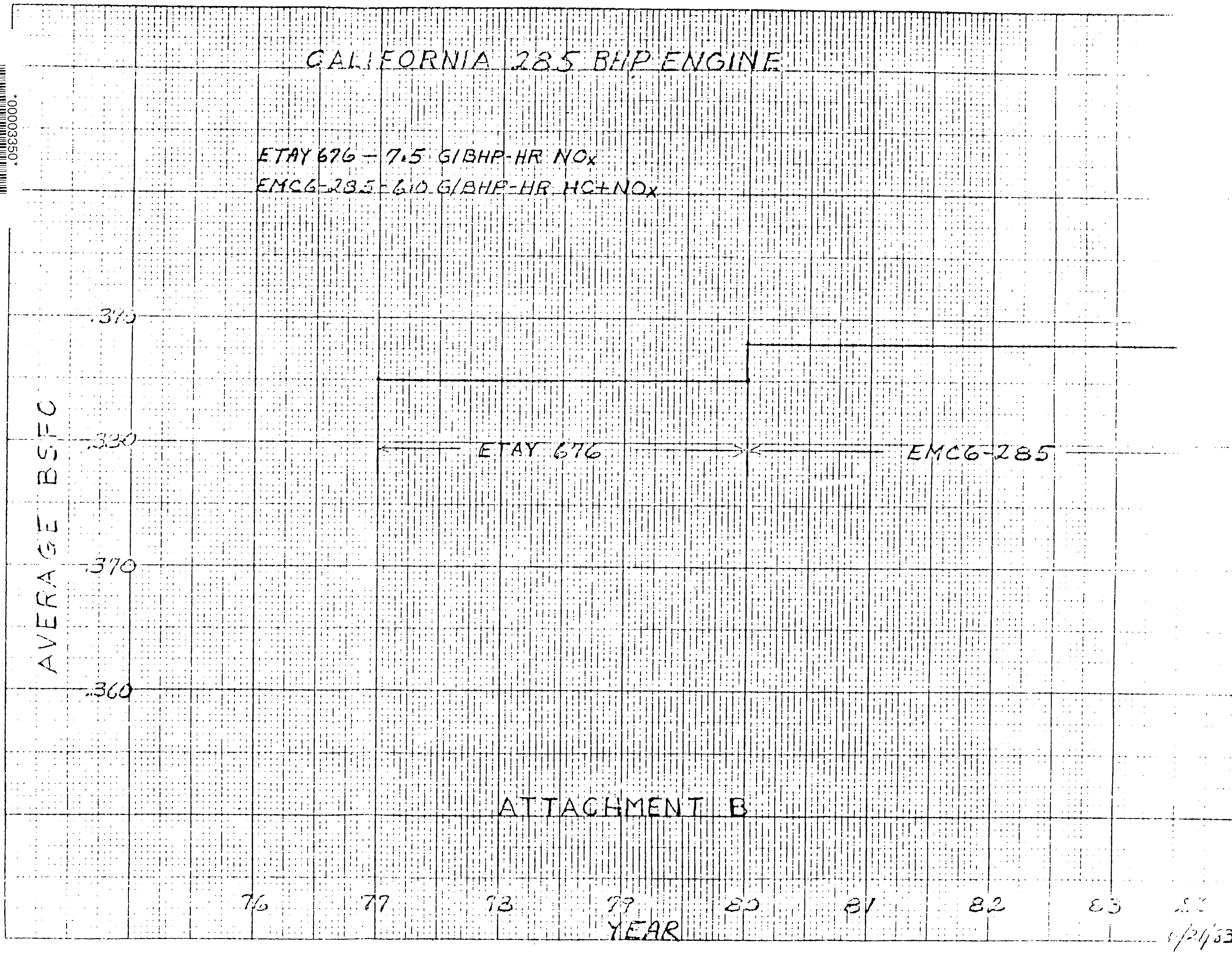
Attachments

EMISSIONS & FUEL CONS. vs TIMING
3406 DIT





ATTACHMENT A


CALIFORNIA 285 BHP ENGINE
ETAY 676 – 7.5 G/BHP-HR NOx
EMC6-285 – 6.0 G/BHP-HR HC+NOx
AVERAGE BSFC
.390
.380
.370
.360
ETAY 676
EMC6-285
ATTACHMENT B
76
77
78
79
80
81
82
83
YEAR