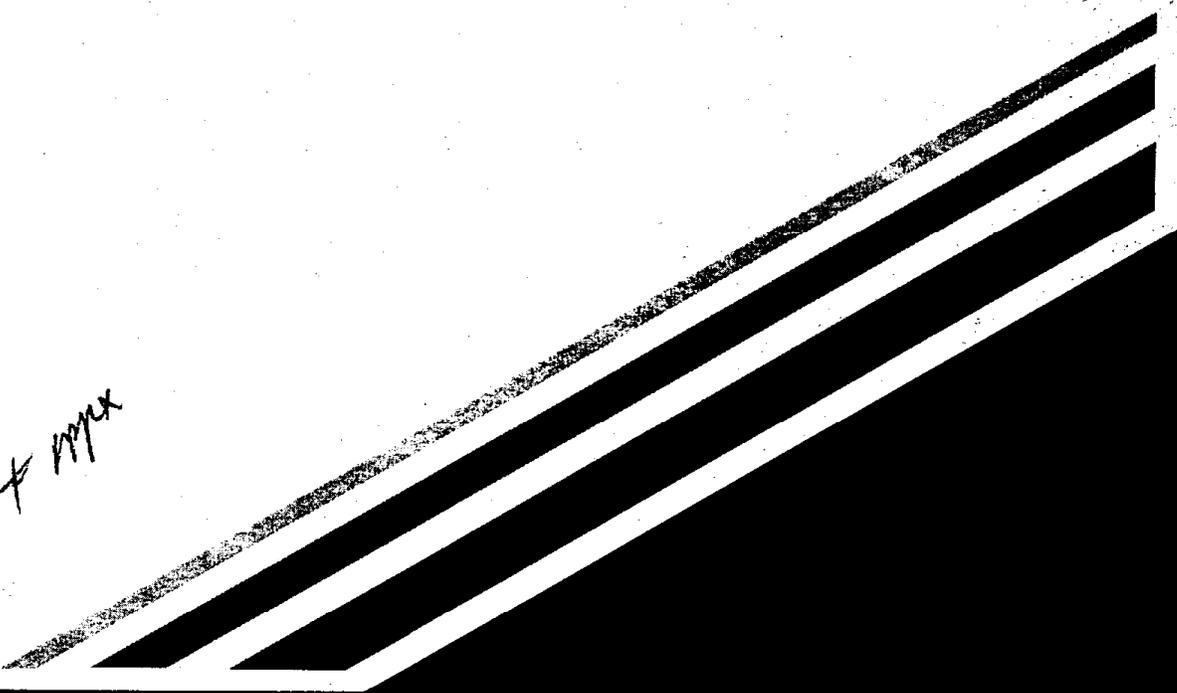




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FINAL REPORT
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Effect of Use of Low Oxygenate Gasoline Blends upon Emissions from California Vehicles

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CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY



AIR RESOURCES BOARD
Research Division

Effect of Use of Low Oxygenate Gasoline Blends upon Emissions from California Vehicles

Final Report

Contract No. A932-159

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ARB--The initial Program Manager was Manjit Ahuja who, near the completion of vehicle testing in the Summer of 1992, was replaced in this capacity by Hector Maldonado. Mike Carter was the initial Technical Manager, beginning with the RFP, and continued in this capacity through most of the vehicle testing. Jack Kitowski replaced Mr. Carter, continuing through the end of the program. David Parker provided the key technical advisory function through most of the vehicle testing phase after which Joseph DeVita briefly held that position. Annette Hebert was the key technical advisor from the vehicle retesting phase through the end of the program. Others who assisted in a technical advisory capacity were John Courtis, Shelley Sabate, Dilip Patel, Nelson Chan and Richard Vincent.

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The data analysis was performed under subcontract to ATL by Timothy DeFries with the assistance of Sandeep Kishan, both of Radian Corporation, Austin Texas.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this study was to determine the effects of oxygenated fuels on regulated emissions (hydrocarbons, HCs; carbon monoxide, CO; and oxides of nitrogen, NO_x) and unregulated emissions (speciated HCs, carbonyl compounds, and alcohols) from California vehicles under summer and winter conditions. Both exhaust and evaporative test sequences were included using a fleet of in-use, California emissions-certified vehicles drawn from a wide range of emission control technologies. The test results obtained were examined statistically to address six specific questions concerning the use of oxygenated fuels:

1. Do slight increases in NO_x emissions offset the benefit of HC and CO reductions attributable to the oxygenate?¹
2. Do different vehicle technologies respond differently to the oxygenates?
3. How do the oxygenated fuel effects change with the driving cycle?
4. What is the emission impact of splash blending of ethanol versus RVP match blending of ethanol?
5. Do increased emissions of toxic materials due to the oxygenates offset reductions in the regulated pollutants?¹
6. What are the temperature and fuel blend season effects on emissions from the oxygenated fuels?²

B. SCOPE

1. *Vehicles.* The thirteen California-certified vehicles used in the emission tests were all obtained in California and met criteria specified by the ARB concerning odometer mileage and condition of emission control equipment. To the maximum extent possible, the condition of the vehicles represented actual in-use expectations. Key specifications of the vehicles are given in Table 1. Additional information on the vehicles can be found in Appendix A.

2. *Fuels.* Summer (RVP 7.6 psi) and Winter (RVP 9.8 psi) sets of fuels were tested. Each set consisted of a hydrocarbon base fuel plus four oxygenated blends. The oxygenates used were: MTBE, ETBE, ethanol blended to match the target RVP, and splash-blended ethanol. The oxygenate levels were 2.0 wt.% for Summer Fuels and 2.7 wt.% for Winter Fuels. In the discussions below, the fuel variable (i.e., the type of oxygenate) in the testing matrix is referred to as the "blend type". Similarly, "blend season" refers collectively to the Summer or Winter Fuel Sets. Due to an RVP problem in the Original Winter Base, a new Winter Base was prepared. ATL performed extensive chemical and vehicle testing in an attempt to verify that these fuels were

¹ The intent of this question is not to assess whether or not any increase in one pollutant is acceptable in view of a decrease in another pollutant.

² Fuel "blend season" means the difference between adding oxygen to summer gasoline and adding oxygen to winter gasoline.

Table 1. Key Specifications for the Vehicle Fleet

Veh. No.	Year. Make. Model	Miles (1,000s)	Engine cyl./disp. ^(a)	Catalyst ^(b)	Fuel System ^(c)
1	'90 Oldsmobile, Calais	16	4/2.3	TWC	PFI
2	'85 Chevrolet, Blazer/S10	56	6/2.8	TWC	carburetor
3	'73 Oldsmobile, Cutlass	132	8/350	none	carburetor
4	'90 Mercury, Cougar	19	6/3.8	TWC	PFI
5	'90 Honda, Accord	9	4/2.2	TWC	PFI
6	'90 Dodge, Dynasty	27	6/3.0	TWC	PFI
7	'83 Plymouth, Reliant	86	4/2.2	TWC	carburetor
8	'87 Ford, Escort	65	4/1.9	TWC	PFI
9	'86 Chevrolet, Cavalier	76	4/2.0	TWC	TBI
10	'76 Ford, Granada	78	8/351	oxy.	carburetor
11	'84 Chrysler, New Yorker	101	8/318	TWC	carburetor
12	'78 Toyota, Celica	156	4/2.2	oxy.	carburetor
13	'91 Ford, Taurus	5	6/3.0	TWC	PFI/FFV

(a) Number of cylinders/displacement in liters (except for vehicles 3, 10 and 11 which are in cubic inches)

(b) TWC: three-way catalyst; oxy.: oxidation catalyst

(c) PFI: port fuel injection; TBI: throttle body injection; both types of injection use adaptive learn-type systems. None of the carbureted vehicles had adaptive learn systems. FFV: flexible fuel vehicle capable of operating on gasoline containing 0% to 85% methanol.

similar in composition and emissions effects. The new fuel was used only in the 50°F test matrix. Fuel inspection data for all of the fuels are given in Table 3-1.

While considerable effort was made before vehicle testing to ensure that the Fuel Y (New Base) had composition and emissions performance similar to the Fuel N (Original Base), statistical analysis of the results of vehicle testing at 50°F indicates that exhaust emissions were significantly different between Fuel Y and Fuel N for CO, HC, NO_x, benzene and acetaldehyde but were not significantly different for estimated ozone production, formaldehyde and 1,3-butadiene. No significant difference in the eight emission types could be found between Fuel X (Low RVP Base) and Fuel N.

3. *Exhaust Emissions Test Matrix.* The data collected for the exhaust portion of the testing included regulated mass emissions (HCs, CO and NO_x), and unregulated speciated emissions (HCs, alcohols, and aldehydes including specific toxic species). Speciated emissions were measured on a sub-set of seven of the thirteen test vehicles. The driving cycles used were the Federal Test Procedure (FTP), the Federal Highway Fuel Economy Test (HFET), and the New York City Cycle (NYCC). The Winter Fuels were tested at 50°F and 75°F and the Summer fuels were tested at 75°F and 95°F.

4. *Evaporative Emissions Test Matrix.* For the evaporative emissions portion, diurnal breathing loss and hot soak evaporative emissions tests were performed for the summer fuels at 75°F and 95°F and for the winter fuels at 75°F. HC speciation was performed for the same seven vehicles for which exhaust speciation was performed. Alcohol speciation of the evaporative emissions was included for the ethanol-containing fuels only. In addition, running loss tests with hydrocarbon and alcohol (where applicable) speciation analysis were performed on six of the thirteen vehicles using the summer fuels and a 95°F testing temperature.

5. *Data Analysis Approach.* The effects on the emission rates of the test design parameters, including blend type, were determined by regression. The exhaust emissions data analyzed in these regressions were the regulated mass emissions (HCs, CO and NO_x) plus four specific toxic species from the speciation analyses (formaldehyde, acetaldehyde, 1,3-butadiene, and benzene). Emissions of about 120 other speciated HCs plus 7 carbonyl compounds and two alcohols (methanol and ethanol) were not analyzed as individual species from the data analysis. However, the speciation results were used to compute ozone forming potentials which were analyzed by regression. Similarly for the evaporative emissions, the data included for regression analyses were the total HC value, the ozone forming potential computed from the HC speciation data, and the HC speciation data for benzene.

The major challenge of the data set analysis was to detect and estimate, with statistical significance, oxygenate effects on the order of 20% when the emissions for the entire fleet ranged across three orders of magnitude. This analysis was accomplished by modeling all effects with class, also known as categorical, regression. Uncertainties were estimated by assigning three-factor and higher order interactions, as well as main effects and two-factor interactions that were shown to be not statistically significant, to error since true replicates were not available in the data set.

For each emission type, an appropriate transformation of the measured values was chosen based on an examination of residuals from a preliminary regression. Apparent outliers were identified and investigated. The few that were confirmed as outliers were dropped from subsequent regressions. A regression model was developed to fit the emissions response of individual vehicles taken as a group. The best individual vehicle regression model statement included significant main effects and two-factor interactions and typically described the measured values with an r^2 of 0.95. To generalize the behavior of individual vehicles and to find the best vehicle technology descriptor, alternative vehicle technology models were evaluated by successively substituting technology descriptors into the best individual vehicle model. The model with the best fit of the measured values was chosen as the best technological model. The size and statistical significance of the effects of varying each parameter were examined to answer the objectives of the study.

Effects have been deemed statistically significant if they are significant at the 95% confidence level (i.e., there is a 5% chance that the actual effect of changing the parameter in question is zero), which is the significance criterion used here. However, the reader must realize that the particular levels of significance found in this study for the 13 vehicles tested does not imply the same level of significance for corresponding effects in the real-world fleet. Nevertheless, it is likely that the effects found significant at the 95% confidence level in this study may have significance at *some* non-trivial level in the real-world fleet, and that the qualitative conclusions probably can, with only a few exceptions, be cautiously extended to the real-world fleet.

6. *Limitations of the Study.* Because this study addressed such a broad scope of experimental parameters, it was inevitable that some of the limitations that had to be imposed on its experimental design might result in some limitations in the breadth and strength of the conclusions that can be made from the resulting data. The main limitation, of course, was the size of the vehicle fleet. A substantially larger vehicle fleet would have resulted in more vehicles within each emission technology control group and, consequently, a more definitive statistical interpretation of the data. For instance, the vehicle fleet contains only one non-catalyst vehicle, only two oxidation catalyst vehicles, and only one throttle body injection vehicle. An additional limitation was that chemical speciation of emissions was performed on only 7 of the 13 vehicles, and this subset contained only one vehicle each in three of the four exhaust emission control technology groups (3-way catalyst without adaptive learn, oxidation catalyst and non-catalyst). A limitation in the fuel matrix design was that the two oxygenate levels, 2.0 and 2.7 wt.% oxygen, were associated with summer and winter fuel, respectively, as were the two fuel volatilities, 7.6 psi for summer and 9.8 psi for winter. Thus, the effects of oxygen content and fuel volatility cannot be separated in the data obtained. The separate discussion here of these limitations is not intended to imply that this study is in any way flawed. These limitations were necessary both to conform to budgetary constraints as well as to define a practical size and scope for the study--thereby, insuring that the results would be available in a reasonable amount of time. In the discussions that follow, effects of these limitations in scope are noted where they impact the statistical significance issue.

C. RESULTS

For clarity and brevity, the discussion of test results is mostly restricted to the Summer Fuel Set in this *Executive Summary* section. The data analysis clearly showed that there was essentially no interaction between blend season and blend type, so no information is lost in focusing here on the Summer Fuel Set results only. The absence of this interaction means that the emissions response of the different oxygenate types was essentially the same at the different oxygen levels and vapor pressure levels used in the test program. The only two study parameter differences between the blend seasons are vapor pressure and oxygen level. The fuels in the Winter Set have a vapor pressure 2.2 psi greater than the Summer Set and a higher oxygen content at 2.7 wt.% oxygen for winter versus 2.0 wt.% for summer. The reader is directed to the full report for details concerning the Winter Fuel Set test results.

The emissions were affected by several parameters; however, vehicle technology clearly had the largest effect on emissions. The vehicle technology can be described by the vehicle's exhaust emission control technology, fuel induction type, engine displacement and canister bottom design. Large variability of emissions among vehicles from the same technology category still remained due to the idiosyncrasies of the individual vehicles.

1. *Summary of Exhaust Emission Results.* Measurement of the response of the exhaust emissions of different technology vehicles to changes in oxygenate type was one of the goals of this study. Exhaust emission control technology was found to be the most important technology descriptor of exhaust emissions. Driving cycle and ambient temperature had significant effects on emissions, but the type of oxygenate was found (within experimental and analysis uncertainty) to have an influence on emissions that was independent of driving cycle, ambient temperature, and blend season. Because of this independence, Table 2 has been designed to show the summary of

Table 2. Fuel Effects on Mass Emissions by Vehicle Technology Groups

Vehicle Technology	No. of Vehicles	Percent Change in Exhaust Emissions Levels versus Non-oxygenated Base, Summer Fuel Set (2.0 wt % Oxygen)						Ethanol/SB					
		ETBE		MTBE		Ethanol		Ethanol		Ethanol/SB		Ethanol/SB	
		H/C	CO	NOx	H/C	CO	NOx	H/C	CO	NOx	H/C	CO	NOx
TWC/AL	7	-7	-3	-5	-5	-2	-10	1	-2	-1	-1	0	5
TWC/NAI	3	-15	-19	-3	-13	-14	1	-9	-16	9	-2	-8	2
Oxidation Catalyst	2	5	-10	13	6	-2	5	4	-3	17	12	6	6
No Catalyst	1	-4	-34	-9	-7	-40	-7	-14	-43	-10	-10	-37	-7

Percent changes for exhaust NOx are relative to 1 g/mi for the base fuel (see text)

Enlarged and bold face type indicates significance at the 95% or higher level.

TWC: three-way catalyst; AL: adaptive learn system; NAI: no adaptive learn system.

the size and significance of the oxygenate effect on HC, CO, and NO_x emissions in terms of the four different types of exhaust emission control technology in this study: 3-way catalyst with adaptive learning (TWC/AL, includes all fuel injected vehicles), 3-way catalyst without adaptive learning, (TWC/NAL, includes all TWC vehicles with carburetors), oxy-catalyst, and non-catalyst. Note that only the TWC/AL category has more than 5 vehicles in the group. The other three technology groups have only a few vehicles per group.

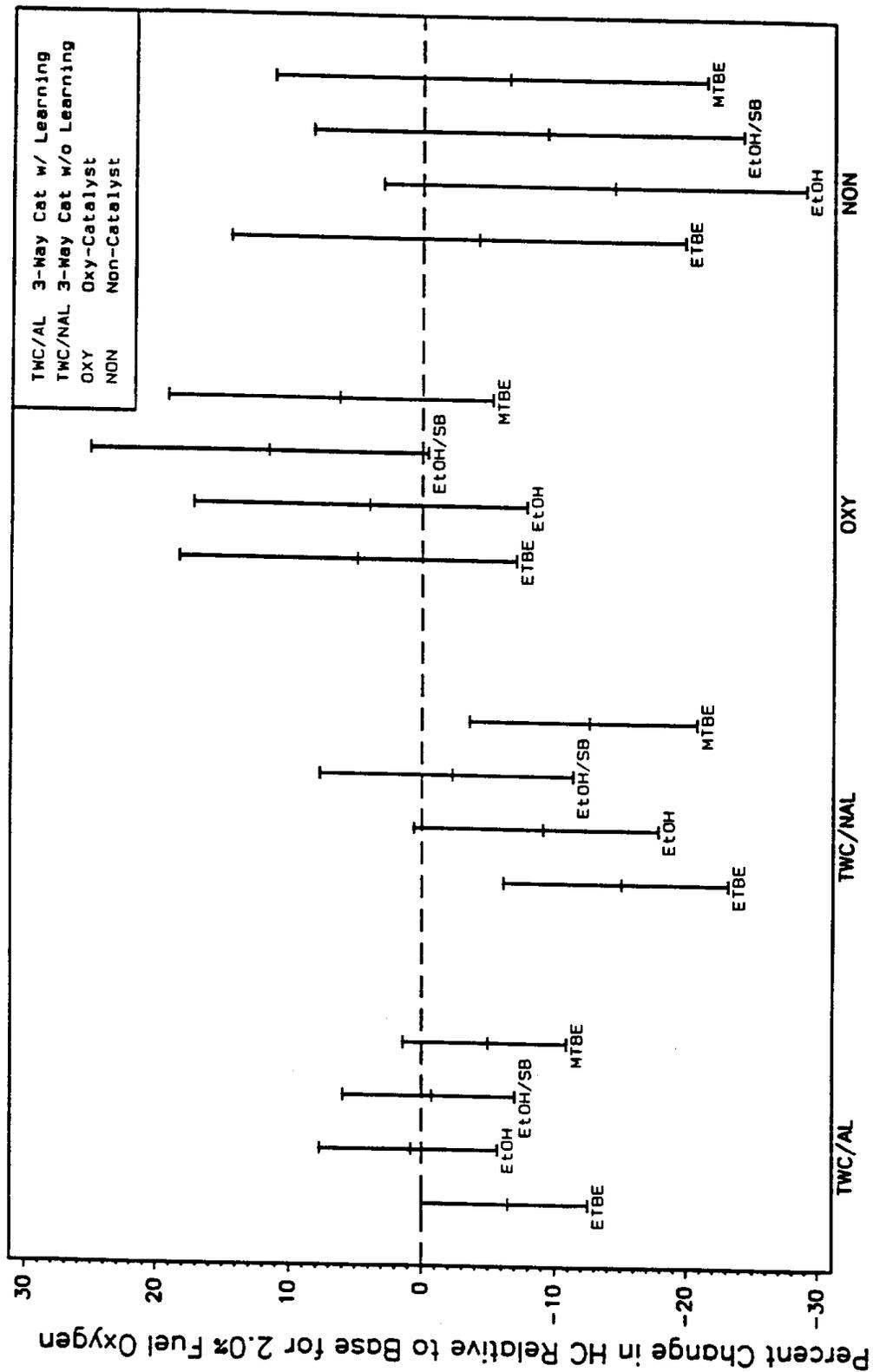
Table 2 shows the estimated effect of adding 2.0% oxygen as ETBE, MTBE, EtOH (matched RVP), and EtOH/SB (splash blend) to the base non-oxygenated gasoline as the percent change in emissions. If the change was found to be statistically significant at the 95% confidence level, the value is in bold-face type in a larger size. Percents not in the large bold type are the measured values with lower levels of confidence. Note that the NO_x changes are relative to a base (non-oxygenated) fuel emission rate of 1.0 g/mi. The direction of the changes in Table 2 for NO_x are independent of the size of the assumed baseline value, but the magnitude of the change *is* dependent on the baseline value. Specifically, the percent changes in NO_x for smaller baseline emission values will be slightly larger depending on the baseline value. For an example of the use of baseline emission values of NO_x in this way, see the final paragraph under part 8 of Section C ("Specific Analysis Example for NO_x") of the Results and Discussion section. The percent changes in HC and CO are independent of baseline emission values.

Figures 1, 2, and 3 provide a means of comparing the exhaust emissions responses for HC, CO, and NO_x of different oxygenates with each other, as well as with the base blend. These plots show, for each combination of technology and blend type, the estimated effect relative to the base blend plus or minus two standard errors of the mean. These error bars can be used to determine if one oxygenated blend has a significantly different emissions response from a second blend, but when making a comparison, only one set of error bars should be used. For example, if the average value of the second falls outside of the error bars for the first, then the emissions response of the two blends are significantly different at the 95% confidence level.

Table 3 shows exhaust results for toxic compounds and the ozone forming potential of hydrocarbons based on 1991 Carter reactivity factors. Note that the last three technologies are represented by a single vehicle because the sub-set of seven speciated vehicles included only one vehicle for each of them. Also, note that the percent changes for acetaldehyde and 1,3-butadiene are based on a 10 mg/mi baseline value; the percent changes for other baseline values will be slightly different.

2. *Summary of Evaporative Emissions Results.* Evaporative emission results for the Summer Fuel Set are shown in Table 4. Measurement of the response of the evaporative emissions of different technology vehicles to changes in oxygenate type was one of the goals of this study. The fuel induction system technology was found to be the most important technology descriptor to evaporative emissions. This apparent dependency on fuel system technology is probably mostly related to vehicle age effects on the canister. Older vehicles always have reduced evaporative canister capacity versus their new condition as well as rubber fuel system components that may have become more permeable to fuel components with age. However, some of the emission rate differences are logically attributable to the technology type since carburetor float bowls are an inherently "open" design. Volatility and ambient temperature also had significant effects on emissions.

Figure 1. Effect of Blend Type on HC Emissions.



Exhaust Emission Control Technology

Figure 2. Effect of Blend Type on CO Emissions.

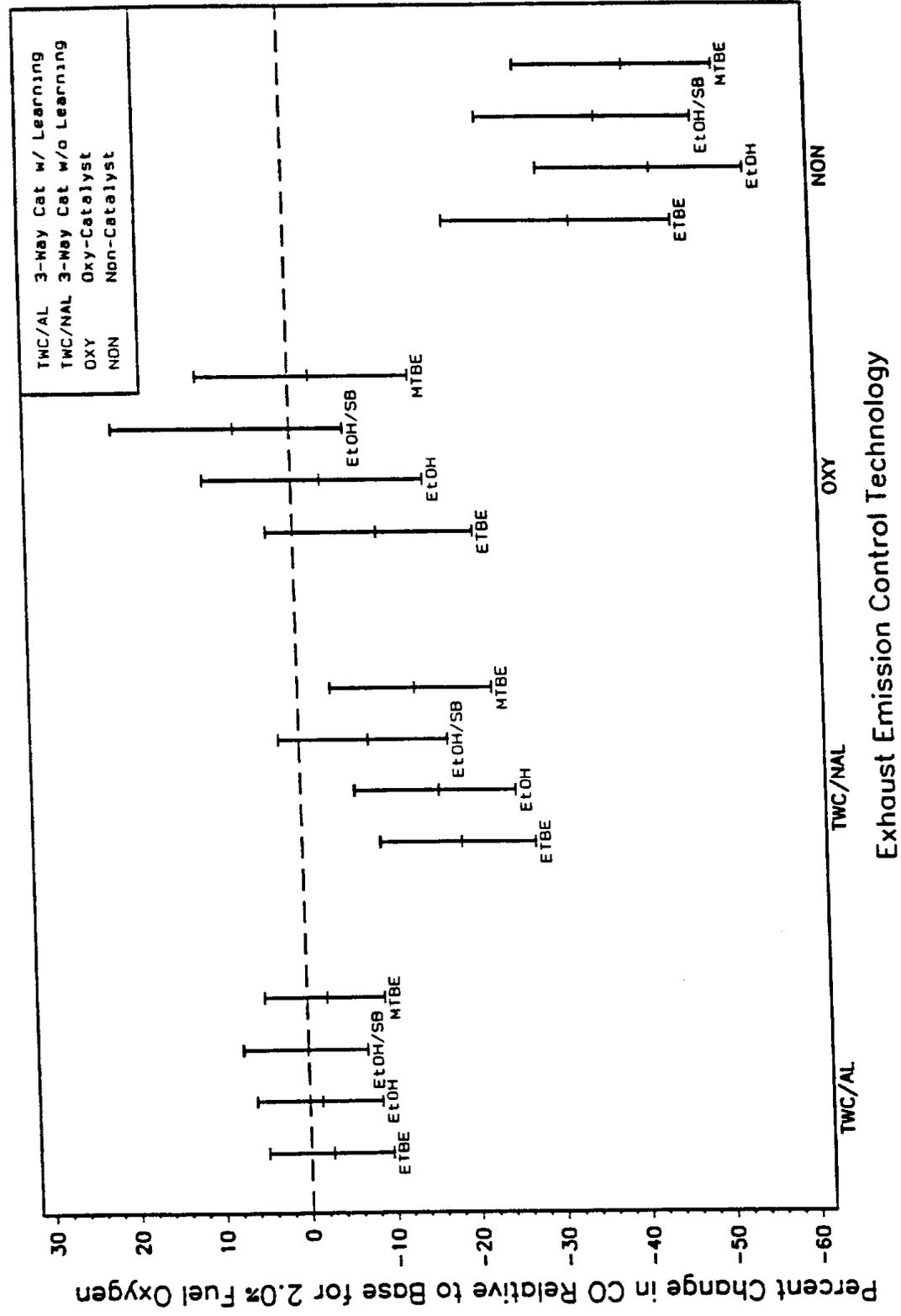
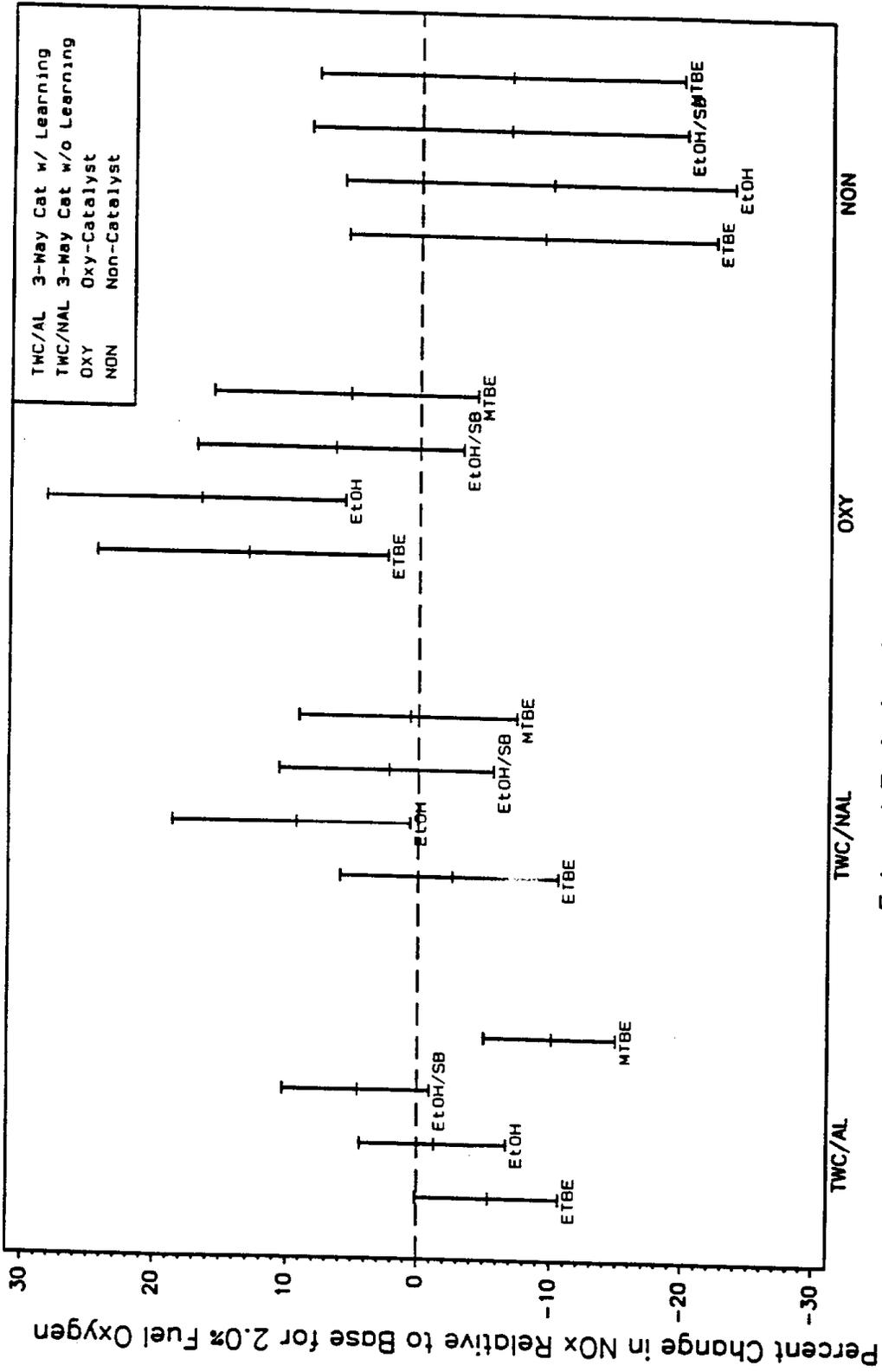


Figure 3. Effect of Blend Type on NOx Emissions.



Exhaust Emission Control Technology

Table 3. Fuel Effects on Ozone and Toxics by Vehicle Technology Groups

Vehicle Technology Emission Type	No. of Vehicles	Percent Change in Exhaust Toxic Emissions Levels versus Non-oxygenated Base, Summer Fuel Set (20 wt % Oxygen)			
		ETBE	MTBE	Ethanol	Ethanol S/B
THC/AL					
Ozone	4	-20	-9	5	-8
Benzene	4	-28	-12	4	-10
Formaldehyde	4	29	8	-3	-1
Acetaldehyde (rel. to 10 mg/mi)	4	21	8	29	25
1,3-Butadiene (rel. to 10 mg/mi)	1	-14	-10	-5	-3
THC/NAI					
Ozone	1	-22	-22	-11	-13
Benzene	1	-26	-23	-6	-15
Formaldehyde	1	-8	21	-7	-11
Acetaldehyde (rel. to 10 mg/mi)	1	82	-15	73	62
1,3-Butadiene (rel. to 10 mg/mi)	1	-38	-36	-5	-17
Oxidation Catalyst					
Ozone	1	10	21	12	26
Benzene	1	-2	20	16	34
Formaldehyde	1	21	25	11	17
Acetaldehyde (rel. to 10 mg/mi)	1	84	4	56	74
1,3-Butadiene (rel. to 10 mg/mi)	1	-2	11	12	22
No Catalyst					
Ozone	1	-8	-4	-17	-11
Benzene	1	-28	-25	-28	-21
Formaldehyde	1	10	16	1	-8
Acetaldehyde (rel. to 10 mg/mi)	1	85	10	81	52
1,3-Butadiene (rel. to 10 mg/mi)	1	-33	-23	-27	-20

Enlarged and bold face type indicates significance at the 95% or higher level.
 THC: three-way catalyst; AL: adaptive learn system; NAI: no adaptive learn system.

Table 4. Fuel Effects on Evaporative Emissions by Fuel System Type.

Emission Test	Percent Change in Evaporative Emissions versus Non-oxygenated Base, Summer Fuel Set (2.0 wt.% Oxygen)							
	Carburetted Fuel Induction Systems			Fuel-Injected Fuel Induction Systems				
Emission Type	ETBE	Ethanol	Ethanol/SB	MTBE	ETBE	Ethanol	Ethanol/SB	MTBE
<i>Diurnal</i>								
Total Hydrocarbons	-32	-5	9	-8	-18	-33	6	-19
Ozone Forming Potential	-47	-18	-13	-33	-7	-16	17	-16
Benzene	-19	14	9	3	10	4	16	2
<i>Hot Soak</i>								
Total Hydrocarbons	-5	20	24	9	10	9	5	-7
Ozone Forming Potential	-7	24	33	2	-3	4	-9	-25
Benzene	-15	24	25	-3	3	15	9	-12
<i>Running Loss</i>								
Total Hydrocarbons	8	53	122	33	29	20	32	75
Ozone Forming Potential	30	124	na	114	48	52	28	-5
Benzene	136	223	na	191	65	71	36	-30

na: Not available; hydrocarbon speciation data are not available for this fuel and technology type.

Enlarged and bold face type indicates significance at the 95% or higher level.

The type of oxygenate was found (within experimental and analysis uncertainty) to have an influence on emissions that was independent of blend season and ambient temperature. Because of this independence, Table 4 groups the effects of the oxygenates on the nine types of evaporative emissions by the type of fuel induction system technology: carburetor and fuel-injected. Note that the single throttle body vehicle was grouped with the multi-port vehicles and considered as fuel-injected technology. Just as for Tables 2 and 3, Table 4 shows the estimated effect in percent change in emissions of adding 2.0% oxygen (the Summer Fuel Set) as ETBE, MTBE, EtOH (matched RVP), and EtOH/SB (splash blend) to the base non-oxygenated gasoline.

D. CONCLUSIONS

The conclusions related to the specific questions listed above in the sub-section, *Objectives*, are the following:

Do slight increases in NO_x emissions offset the benefit of HC and CO reductions attributable to the oxygenate? Although the word offset was originally used in the proposal, this study was not designed or intended to be viewed as a trade-off of one emissions factor for another. Such an evaluation implies an ability to quantify the air quality detriment of NO_x versus HC and CO, and this type of evaluation was not within the present scope. The relationship found in this work between the exhaust NO_x levels and the presence of oxygenates in the fuel is somewhat in disagreement with the commonly held view that decreased HC and CO emissions with oxygenated fuel are accompanied by an increase in NO_x emissions. The present data, in most cases, show that the oxygenates produced no significant change in NO_x versus the non-oxygenated base fuel. The only significant NO_x emission rate changes versus the non-oxygenated fuel were vehicle technology dependent, and some of these differences were increases while others were decreases. As shown in Table 2 and Figure 3, MTBE produced a significant NO_x reduction of 10 percent (for 2.0% oxygen) for the TWC/AL technology. EtOH produced a significant NO_x increase of 9 percent (for 2.0% oxygen) for TWC/NAL technology. ETBE and EtOH blends gave 13 and 17 percent NO_x increases (for 2.0% oxygen) for the oxy-catalyst technology. Other than these cases of small but statistically significant effects, oxygenates did not produce significant changes in NO_x emission rates.

Do different vehicle technologies respond differently to the oxygenates? For TWC/AL and TWC/NAL vehicles, ETBE and MTBE blends had a consistent, noticeable, and sometimes statistically significant tendency to produce lower exhaust emission levels than EtOH and EtOH/SB blends for HC, CO, NO_x, estimated ozone production, benzene, acetaldehyde, and 1,3-butadiene emissions. Significance was greater for the TWC vehicles with and without adaptive learning possibly because a large number of vehicles were in those categories. For exhaust formaldehyde emissions, the trend with blend type was the opposite; that is, ETBE and MTBE produced higher formaldehyde levels than EtOH and EtOH/SB blends. Thus, this study seems to indicate that vehicles do not respond to just the oxygen content of a blend, but the molecular structure of the oxygenate also has an effect.

How do the oxygenated fuel effects change with the driving cycle? An important finding with respect to the driving cycles was the absence of a significant driving cycle/blend type interaction. In other words, the effect of the oxygenated blends was independent of the driving cycle which was used to test the vehicle; the percent change in emissions produced by a given oxygenated

blend was about the same for the FTP as for the other driving cycles in this study (NYCC, HFET). Since the study did not use any of the recently proposed high load driving cycles, the conclusion that the effects of blend type are independent of driving cycle may or may not apply to high severity cycles or real-world driving behavior.

What is the emission impact of splash blending of ethanol versus RVP match blending of ethanol? For the exhaust HC, CO, and NO_x emissions, Figures 1, 2, and 3 show that the ethanol RVP matched blends usually gave lower emissions than the ethanol splash blends, but the differences were usually not statistically different. In the one case where the difference was significant, for the TWC/AL group, the NO_x from the splash blended fuel was about 6 percent higher than the RVP matched blend (referenced to the 1.0 g/mi baseline level). Also, HC and CO emission rate differences for vehicles with TWC/NAL were nearly significant at the 95% level with the splash blend giving higher emission rates than the RVP matched blend. For evaporative emissions on vehicles with fuel-injection, most blend-type effects were not significant. In one that was, the splash blend gave 39% higher diurnal emissions than the RVP matched blend. For carbureted fuel induction systems, evaporative emissions for the RVP matched blend were lower than for the splash blend, as expected, but the differences were not significant at the 95% level.

Do increased emissions of toxic materials due to the oxygenates offset reductions in the regulated pollutants? Similarly, as above for the NO_x increase issue, a quantitative treatment of the "offsetting" issue was outside the scope of this work. However, the blend type and vehicle technology impact on toxics emissions can be discussed here.

For all exhaust system technology groups except the oxidation catalyst, either three of the four or all four of the oxygenated fuels gave significantly reduced exhaust benzene emissions, ranging from 10% to 28%, versus the non-oxygenated fuel. ETBE produced the largest reduction of benzene emissions. Surprisingly, the oxidation catalyst vehicle produced increased benzene levels for both the splash blend ethanol and for MTBE.

The only significant effect on formaldehyde emissions was found for the TWC/AL vehicles for ETBE (29% increase) and for the single oxidation catalyst vehicle on MTBE (25% increase). Both ETBE and MTBE tended to produce higher formaldehyde emissions than did the two ethanol blends.

As expected, significantly increased acetaldehyde emissions were produced by ETBE, ethanol and the ethanol splash blend for all four vehicle technology groups. However, the TWC/AL technology showed increases of only about 25% (relative to a base level of 10 mg/mi), while the other three technologies showed increases of acetaldehyde from 52 to 85% (relative to a base level of 10 mg/mi). In contrast, MTBE did not produce a significant change in acetaldehyde. These results are probably due to the presence of the ethoxy group in ETBE and EtOH and its absence in MTBE.

The results of the 1,3-butadiene analysis are based on only one vehicle for each technology. Three of the four speciated vehicles in the TWC/AL group gave 1,3-butadiene emission rates of 0.0000 g/mi (the method detection limit is about 0.0003 g/mi) for all test conditions except the FTP cold starts. All three of these vehicles were equipped with multi-port fuel injection. The fourth vehicle in the group (which gave non-zero 1,3-butadiene emissions) had throttle body injection. This vehicle showed significant 1,3-butadiene reductions of about 12 percent for ETBE and MTBE, but the EtOH and EtOH/SB reductions were not significant. The oxy-catalyst

vehicle showed a significant increase in 1,3-butadiene of 22% for EtOH/SB; other blends did not show significant differences from the base blend.

What are the temperature and fuel blend season effects on emissions from the oxygenated fuels? In general, under the ambient temperatures and vehicle technologies investigated in this study, the following observations can be made:

- Exhaust emissions responded only weakly to seasonal blending parameters (blending stock and volatility). Summer blends gave significantly lower CO, HC, estimated ozone production, formaldehyde and 1,3-butadiene emissions than the winter blends, with decreases on the order of 8 to 14 percent. NO_x, benzene, and acetaldehyde were not significantly affected by the combined effect of these two blending parameters.
- Evaporative emissions for fuel-injected vehicles did not seem to be affected significantly by oxygenated components relative to the base fuels. Ambient temperature had large effects on evaporative emissions for these vehicles. A drop from 95 to 75°F caused diurnal and hot-soak emissions to decrease by 30 to 60 percent. The seasonal blending parameter (blending stock and volatility) did not seem to greatly affect evaporative emissions for these vehicles.
- Evaporative emissions for carbureted vehicles were affected significantly relative to the base fuels by oxygenated blend type, ambient temperature, and blending parameters (blending stock and volatility). Ambient temperature had large effects on evaporative emissions for these vehicles. A drop from 95 to 75°F caused diurnal and hot-soak emissions to decrease from 20 to 75 percent. Summer blends had significantly lower diurnal and hot-soak emissions than winter blends with decreases on the order of 25 to 57 percent for summer versus winter fuels of the same oxygenate type.

E. RECOMMENDATIONS

The results of the study indicated that only two parameters, individual vehicle characteristics and vehicle technology type, influenced the changes in exhaust emission rates as a function of the blend types (ETBE, MTBE, EtOH, and EtOH/SB). The cycles tested (FTP, FTP Bag1, FTP Bag 2, FTP Bag 3, NYCC, and HFET) did not interact significantly with the effect of blend type. Thus, any one cycle of these is sufficient to test the effect of blend type. Other parameters which did not give strong interactions with the blend type are the test temperature and the blend season. Thus, the first recommendation is that future work to refine the data base on the effects of these oxygenates on vehicle emissions should focus on the two parameters which did strongly interact with blend type: individual vehicle characteristics and vehicle technology type. This type of experimental design would emphasize using a substantially greater number of in-use vehicles with a minimum of five vehicles for each technology group and a limited set of testing conditions. In addition, the small differences seen for blend season (Summer versus Winter which differed by both RVP and wt.% oxygen) indicated that if future work needs to quantify the effect of small variations in oxygen content for the same oxygenate, an even larger number of test vehicles may be needed to achieve definitive conclusions from the data. The recommended test plan would also include a partial replication scheme which would greatly assist in the statistical interpretation of the data. Such a test design would result in data that is more representative of the vehicle popu-

lation so that comparisons of blend type effects with the base fuel would be more reliable.

A second recommendation concerns extending the examination of the effect of fuel blend types to driving cycles that are more severe than the ones used in this work. High load operation such as that encountered during heavy acceleration or during driving up a grade usually puts engines into a fuel enrichment mode which gives substantially different exhaust emissions results. For example, recent work by General Motors (N.A. Kelly and P.J. Groblicki, "Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles," General Motors Research Publication GMR-7858 EV-403, Warren, Michigan, 6 December 1992) indicates that CO emission rates for the vehicle tested were 2500 times higher and that HC emission rates were 40 times higher during enrichment operation than during non-enrichment operation. While the occurrence of real-world high load operation is low, an enrichment:non-enrichment emission rate ratio for CO of 2500:1 for the fleet would mean that the mobile source CO emission inventory has been substantially underestimated by current inventory models which are based on data taken with non-enrichment cycles such as the FTP cycle (S. Kishan, T.H. DeFries, and C.G. Weyn, "A Study of Light-Duty Driving Behavior: Application to Real-World Emission Inventories," SAE 932659, SAE Fuels and Lubricants Meeting, 18-21 October 1993). EPA has recently released study results from its *FTP Review Project* in which these concerns regarding the impact on mobile emissions modeling of severe driving cycles is a central focus ("EPA's Survey of In-Use Driving Patterns: Implications for Mobile Source Emissions Inventories", P. Enns, J. German and J. Markey, U.S. EPA Office of Mobile Sources, Certification Division, Ann Arbor, Michigan, released November, 1993).

Thus, because the effects of oxygenates on exhaust emissions during enriched operation may be quite different from the effects observed in this work, we recommend testing with severe driving cycles to give enriched mode emissions. Temperature and blend season (RVP and percent oxygen) should be included in the test program since their effects are unknown for enriched operation.

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1. INTRODUCTION

The addition of oxygenates and other modifications in fuel chemistry has emerged in recent years as an apparently attractive option for air quality planners to promote reductions in hydrocarbon (HC) and carbon monoxide (CO) emissions from in-use vehicles. Existing data indicates statistically significant reductions in HC and CO are achieved with the use of oxygenated fuels on some vehicles. A number of questions remain, however, with regard to this option particularly as applied to the specialized California vehicle population and climatic environment. These questions include:

- Do slight increases in oxides of nitrogen (NO_x) emissions offset the benefits of HC and CO reductions attributable to the oxygenate?
- Does a "splash" blend of ethanol with a higher RVP have greater emissions values than a matched blend of ethanol in either a summer or winter environment?
- Does vehicle technology respond the same with the addition of different oxygenates and other modifications in fuel chemistry?
- Are toxics generated by the use of oxygenates to an extent which offsets observed reductions in regulated pollutants?
- What effects are noted over a wide range of vehicles at the moderate wintertime and elevated summertime temperatures typical of Southern California?
- What impact do driving patterns other than those represented by the FTP have on emissions?

The California Air Resources Board (ARB) initiated a study on the effect of the use of low-oxygenate gasoline blends on emissions from California vehicles. In support of this effort, the Automotive Testing Laboratories (ATL), Inc. was contracted by ARB to measure the tailpipe and evaporative emissions of a fleet of vehicles from the State of California. The objective of this study was to determine the effects of oxygenated fuels on regulated emissions (HCs, CO and NO_x) and unregulated emissions (speciated HCs, carbonyl compounds, and alcohols). The driving cycles used were the high speed Federal Highway Fuel Economy Test (HFET), the moderate speed Federal Test Procedure (FTP-city Cycle), and the low speed New York City Cycle (NYCC). Both Running Loss and one hour Diurnal and Hot Soak evaporative emissions were measured. HC speciation was performed to determine relative reactivity of both exhaust and evaporative emissions. The test results obtained were examined statistically to address six specific questions described above.

The vehicles tested included a cross section of past, current, and expected future emissions control technologies. A flex-fuel vehicle was also included in the test vehicle sample. The base test fuel was designed to represent a thorough cross section of the specifications anticipated for future commercial availability in California in the winter and summer seasons. Ethanol, MTBE, and ETBE oxygenates were added to these base stocks to produce additional test fuels.

The RFP for this study was released by the ARB on December, 1989. The vehicle testing was performed at ATL's Ohio Lab (East Liberty, Ohio) except for the running loss tests which were

performed at ATL's Indiana Lab (New Carlisle, IN). Vehicle testing was completed in October, 1992. The data analysis was performed under subcontract by Radian Corp. (Austin, TX), and was completed in the spring of 1993.

2. TEST VEHICLES

A. VEHICLE DESCRIPTION

Twelve vehicles representing General Motors, Ford, Chrysler and two Japanese manufacturers were procured for this program. In addition, one flexible-fuel vehicle (FFV) was included. The thirteen vehicles can be grouped in four emissions control technologies:

1. Seven vehicles with three-way catalyst and fuel injected adaptive learning-type management systems; this vehicle technology group is designated TWC/AL.
2. Three vehicles with three-way catalyst but without adaptive learning systems, designated TWC/NAL.
3. Two vehicles with oxidation catalyst.
4. One vehicle without a catalyst.

Six of these thirteen vehicles were equipped with multi-port fuel injection, one had throttle-body injection, and six were carburetted. All vehicles except the FFV (supplied by ARB through Ford) were purchased by ATL in California and verified as being California emissions certified. The vehicles had between 5000 and 155,000 miles on the odometer and were in varying degrees of mechanical worthiness. A complete description of each vehicle can be found in Appendix A.

B. VEHICLE MAINTENANCE

Care was taken over the course of this project to maintain the vehicle "as received" emissions status. No maintenance was performed on the vehicles unless safety issues or marked emissions changes were discovered. The only interruption in the vehicle testing activity was an 8 week period between the completion of the 50°F test program and the start of the 75°F program. To eliminate any layoff problems in the fleet, the entire fleet was subjected to mileage accumulation prior to resumption of testing. Each week for eight weeks the vehicles were driven 10 miles. Just prior to resumption of the testing, each vehicle was driven 50 miles at 55 miles per hour on the Transportation Research Center (TRC) test track.

3. TEST FUELS

A. SPECIFICATIONS

The ten test fuels were obtained from the Phillips 66 Company, Borger, Texas. The five winter fuels were blended from a common "winter base", and the five summer fuels were blended from a separate, common "summer base". The specifications for these two base fuels were the following:

Parameter	Winter Base	Summer Base
Aromatics, vol.%	34	39
RVP, psi	9.8 ± 0.2	7.6 ± 0.2
Olefins, vol.%	7.0	6.5
Octane, (R+M)/2	87 to 90	87 to 90
Distillation, °F		
10%	110	127
50%	214	223
90%	334	335

From each of these base fuels, four additional oxygenated fuels were blended to produce 2.0 wt.% oxygen in the summer fuel set and 2.7 wt.% oxygen in the winter fuel set:

1. MTBE at 11 vol.% (summer) and 15 vol.% (winter)
2. ETBE at 12.7 vol.% (summer) and 17.2 vol.% (winter)
3. Ethanol at 5.7 vol.% (summer) and 7.75 vol.% (winter), match blended to the base blend RVP specification
4. Ethanol as No. 3, but splash blended into the base fuel (already adjusted to RVP specification) with up to 1.0 psi RVP increase allowed.

The aromatic and olefin content and distillation characteristics were allowed to fluctuate from the respective base fuels with the oxygenate additions. The ethanol RVP match blend fuels required that the base fuel blending stock be prepared below the target volatility so that the ethanol addition would not overshoot the respective RVP specifications. Thus, most of the fuels required a final butane adjustment to achieve the target RVP. A summary of the fuel inspections provided by Phillips is given in Table 3-1. The complete fuel inspection sheet for all fuels, as supplied by Phillips, can be found in Appendix B. There are three winter base fuels shown in Table 3-1. Fuel X and fuel N are identical except for the amount of butane and they reflect the identical hydrocarbon stocks used for the winter oxygenated fuels. Fuel Y was prepared later in an attempt to re-create fuel N. Details concerning these multiple winter base fuels are found in the following sections.

Table 3-1. Fuel Inspection Results for the Test Fuels.

Property	Summer Fuels										Winter Fuels																
	M		S		O		Q		U		X		N		Y		T		P		R		V		A		
	Base	EtOH	EtOH	MTBE	MTBE	ETBE	ETBE	EtOH	EtOH	Splash	Low RVP	Base	Original	Base	New	Base	EtOH	EtOH	MTBE	MTBE	ETBE	ETBE	Splash	EtOH	EtOH	RFA	(Ind. Avg)
Oxygenate, vol. % (1)	---	5.7	11	12.8	5.7	---	---	---	---	---	---	---	---	---	---	---	7.75	15	17.2	7.75	---	---	---	---	---	---	---
Oxygen, wt. % (1)	0.0	2.0	2.0	2.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	0.0
RVP, psi	7.7	7.6	7.7	7.5	8.5	9.0 (2)	9.6	9.6	9.6	9.6	9.0 (2)	9.6	9.6	9.5	9.6	9.6	0.748	0.789	0.740	0.744	0.744	0.744	0.744	0.744	0.744	0.744	---
Specific Gravity	0.753	0.757	0.752	0.753	0.756	0.739	0.739	0.739	0.739	0.739	0.739	0.739	0.739	0.739	0.739	0.739	83.4	83.3	83.1	83.6	83.6	83.6	83.6	83.6	83.6	83.6	86.7
Carbon, wt. %	87.0	84.2	84.9	84.2	84.5	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.8	86.9	86.8	86.8	13.1	14.0	14.2	13.7	13.2	13.2	13.2	13.2	13.2	13.2	13.2
Hydrogen, wt. %	12.8	13.8	13.1	13.8	13.6	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.1	13.0	13.0	95.6	97.2	96.6	95.5	92.0	92.0	92.0	92.0	92.0	92.0	92.0
RON	93.6	95.3	96.0	96.4	95.4	93.1	93.1	93.1	93.1	93.1	93.1	93.1	93.1	94.5	95.6	97.2	85.1	86.8	87.4	85.1	82.6	82.6	82.6	82.6	82.6	82.6	82.6
MON	84.5	85.1	86.6	86.8	85.1	84.6	84.6	84.6	84.6	84.6	84.6	84.6	84.6	85.2	85.1	86.8	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Sulfur, ppm (3)	55.0	55.0	55.0	55.0	55.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	85.0	58.0	58.0	70.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	339.0
Distillation, °F																											
IBP	98	100	94	99	96	89	89	89	89	89	89	89	89	88	88	89	94	93	89	89	89	89	89	89	89	89	91
10%	132	128	132	139	125	115	115	115	115	115	115	115	115	113	113	114	117	118	123	114	114	114	114	114	114	114	128
20%	148	136	145	154	134	129	129	129	129	129	129	129	129	128	128	123	126	128	136	123	123	123	123	123	123	123	151
30%	168	146	158	167	143	144	144	144	143	143	144	144	144	146	146	133	135	138	149	133	133	133	133	133	133	133	174
40%	189	174	174	182	172	170	170	170	172	172	170	170	170	176	176	168	146	151	168	145	145	145	145	145	145	145	196
50%	218	206	194	199	203	210	210	210	203	203	210	210	210	218	218	174	170	174	191	171	171	171	171	171	171	171	218
60%	247	237	227	223	235	244	244	244	235	235	244	244	244	248	248	208	226	208	215	226	226	226	226	226	226	226	243
70%	277	269	264	258	267	270	270	270	267	267	270	270	270	274	274	250	258	250	246	257	257	257	257	257	257	257	267
80%	303	297	294	293	296	298	298	298	296	296	298	298	298	302	302	285	290	285	285	291	291	291	291	291	291	291	295
90%	332	328	325	325	327	329	329	329	327	327	329	329	329	332	332	320	326	320	322	329	329	329	329	329	329	329	330
EP	420	411	413	413	408	419	419	419	408	408	419	419	419	422	422	415	415	415	412	418	418	418	418	418	418	418	415
Loss %	1.0	1.5	1.4	1.6	1.5	1.4	1.4	1.4	1.5	1.5	1.4	1.4	1.4	1.6	1.6	1.4	0.6	1.4	1.8	1.4	1.4	1.4	1.4	1.4	1.4	0.2	
HC Type, vol. %																											
Aromatics	38.5	36.3	34.3	33.6	36.4	33.2	33.2	33.2	36.4	36.4	33.2	33.2	33.2	34.5	34.5	28.1	30.7	28.1	27.5	30.6	30.6	30.6	30.6	30.6	30.6	30.6	32.0
Olefins	7.0	6.6	6.2	6.1	6.6	5.1	5.1	5.1	6.6	6.6	5.1	5.1	5.0	8.7	8.7	4.3	4.7	4.3	4.2	4.7	4.7	4.7	4.7	4.7	4.7	4.7	9.2
Saturates	54.5	51.4	48.5	47.5	51.6	61.7	61.7	61.7	51.6	51.6	61.7	61.7	62.2	56.8	56.8	52.3	57.0	52.3	51.0	56.9	56.9	56.9	56.9	56.9	56.9	56.9	58.8
Oxygenate	0.0	5.7	11.0	12.8	5.4	0.0	0.0	0.0	5.4	5.4	0.0	0.0	0.0	0.0	0.0	15.3	7.6	15.3	17.3	7.7	7.7	7.7	7.7	7.7	7.7	7.7	0.0

(1) Specification value. All other values are results of inspections performed by the supplier, Phillips 66 Co.

(2) The supplier reported the RVP at 9.6 psi, but data from ATL was 9.0 psi.

(3) The sulfur content of the summer fuels are estimates; the winter fuels are actual.

B. FUEL STORAGE AND RVP MONITORING

All fuels were stored in and dispensed from an indoor facility maintained at 50°F. Drums of fuel were either put on-line in the fuel storage building through a metering dispenser in the fueling bay or were hand-pumped in the fuel storage building into containers for carrying to the vehicle.

Each drum of fuel was sampled for RVP determination when it was first opened and again at the end of its use. The RVP was determined using a Grabner Model CCA-VPS vapor pressure instrument using the ASTM D5191-91 method of sequential cooling to 0°C (in ice), venting, and shaking to fully saturate the sample with air prior to RVP measurement. The equation used to calculate RVP in psi units was:

$$\text{RVP(Equivalent)} = (0.965 \times P_{\text{(total)}}) - 0.55$$

which is the one specified in Method D5191-91. The vapor pressures found for the fuel drum monitoring are given in Table 3-2. It can be seen in Table 3-2 that the RVP of the Winter Base fuel was about 0.6 psi below specification for the first four drums and initially for the fifth drum. Results from the tests using this "low RVP" winter base are designated as fuel X, Table 3-1. This below-specification RVP problem was discovered at the point of partial completion of the 75°F tests. Butane was added to drums 5 through 8 to achieve an RVP of 9.7 psi, and the resulting fuel was designated fuel N. All 75°F tests performed with the low (9.1 psi) winter base fuel X were repeated with the RVP-adjusted fuel N. However, insufficient Winter Base fuel remained to repeat all of the 50°F tests on that fuel, and the decision was made with the ARB to have the supplier prepare a new Winter Base fuel for use in repeating the 50°F tests. This new winter base fuel is designated fuel Y.

C. SPECIATION OF FUELS

The imperfection in the Winter Base RVP led the ARB to question whether the summer and winter fuel sets were, indeed, blended from respective common bases. To settle this issue, ATL performed a GC speciation of all 10 fuels, and the results are tabulated in Table 3-3. In order to show most clearly the commonality of the blending bases, the relative amounts of the species in Table 3-3 are expressed as percents of the *non-butane/non-oxygenate subtotal* for each fuel. The butane and MTBE/ETBE relative amounts are given as percents of the *grand total* for all species. Ethanol speciation is not amenable to the hydrocarbon speciation method, and, therefore is not listed in Table 3-3. These fuel speciation results clearly show that the winter and summer sets of fuels did, indeed, come from respective common bases and, also, that fuel X, the "as received" low RVP winter base, had a low RVP because the supplier had simply omitted the butane addition for this fuel. The Table 3-3 speciation results are tabulated in terms of percent of total peak height values. These values, because they are based on peak height rather than peak area, should not be taken as a reflection of the percent of total carbon in the fuel represented by each species. However, because the Table 3-3 data were all obtained on the same GC instrument over a 2-day period, the data are completely appropriate for evaluating whether each fuel of a given set is, indeed, derived from a common base.

Table 3-2 RVP Records for Fuel Drums

Fuel	RVP Spec.	Sampled At	RVP for the Given Drum Number, psi									Avg.
			1	2	3	4	5	6	7	8	9	
Summer Base	7.60	Start	7.64	-	7.64	7.64	7.79	7.73	7.76	7.72	-	7.70
		End	-	7.28	7.47	7.25	7.56	7.47	7.50	-	-	7.42
Winter Base	9.60	Start	9.02	9.05	9.01	9.20	9.08	9.76	9.67	9.78	-	9.32
		End	8.89	9.01	9.06	-	9.38	9.30	9.62	9.35	-	9.21
Summer/MTBE	7.60	Start	7.86	7.89	7.85	7.85	7.93	8.18	7.92	7.69	7.77	7.88
		End	7.80	7.66	7.77	-	7.69	7.79	7.56	7.37	-	7.66
Winter/MTBE	9.60	Start	9.34	9.21	9.34	9.27	9.24	9.33	9.27	9.24	-	9.28
		End	9.05	8.72	9.24	9.25	9.20	9.09	8.82	8.96	-	9.04
Summer/ETBE	7.60	Start	7.06	7.11	6.96	7.11	7.45	7.40	7.41	7.47	7.39	7.26
		End	7.09	6.98	6.86	6.67	7.30	6.72	7.03	7.08	-	6.97
Winter/ETBE	9.70	Start	9.59	9.63	9.63	9.56	9.62	9.43	-	-	-	9.58
		End	9.50	9.50	9.49	9.14	9.33	9.44	-	-	-	9.40
Summer/EtOH RVP match	7.60	Start	7.80	7.89	7.88	7.88	7.73	7.86	7.95	7.73	7.22	7.77
		End	7.86	7.74	7.25	7.61	7.80	7.90	7.80	7.73	7.15	7.65
Winter/EtOH RVP match	9.60	Start	9.95	10.02	10.02	9.98	10.07	9.98	-	-	-	10.00
		End	9.83	9.83	10.02	9.85	9.89	9.53	-	-	-	9.83
Summer/EtOH Splash	8.80	Start	8.41	8.41	8.38	-	8.37	8.73	-	8.28	8.24	8.40
		End	7.93	8.30	7.90	8.12	8.27	-	-	8.09	8.15	8.11
Winter/EtOH Splash	10.70	Start	10.47	10.57	10.44	10.57	10.56	-	10.62	10.78	-	10.57
		End	10.47	10.47	10.38	10.51	10.02	10.14	9.60	-	-	10.23
RFA	8.70	Start	8.44	8.69	8.69	8.50	8.31	8.60	8.66	8.46	8.41	8.53
		End	7.93	7.99	8.41	7.73	7.79	8.03	-	8.44	-	8.05

"-" indicates that either the drum was not sampled or the data is not available.

Table 3-3. Speciation Summary for Fuels

Species (0.5% of Total or Greater)	Percent of Total GC Peak Height (Omitting Butane and Oxygenates*)									
	Summer Fuels					Winter Fuels				
	MTBE	ETBE	EtOH	EtOH/S	Base	Base	MTBE	ETBE	EtOH	EtOH/S
n-Butane (1)	2.48	2.11	0.92	1.79	2.57	0.68	0.84	3.01	1.77	2.04
2-Methylbutane (Isopentane)	13.30	12.52	12.04	12.14	15.31	33.22	29.91	32.09	28.02	29.70
n-Pentane	2.28	2.20	2.13	2.28	2.21	2.69	2.46	2.58	2.81	2.98
t-2-Pentene	0.56	0.55	0.48	0.54	0.66	0.70	0.60	0.69	0.82	0.87
2-Methyl-2-butene	0.97	0.94	0.85	0.91	1.12	1.17	1.00	1.13	1.35	1.38
2,2-Dimethylbutane	3.01	2.97	2.81	2.82	2.30	0.14	0.12	0.13	0.17	0.16
MTBE (1)	10.02	0.00	0.00	0.00	0.00	0.00	(2)	0.00	0.00	0.00
2,3-Dimethylbutane	0.00	3.01	2.94	2.94	2.46	0.45	(2)	0.46	0.53	0.52
2-MePentane & 4-Me-c-2-Pentene	9.92	9.89	9.66	9.49	8.19	2.18	(2)	2.20	2.52	2.56
3-Methylpentane	4.96	4.87	4.67	4.76	4.18	1.49	1.48	1.51	1.69	1.69
2-Methyl-1-pentene & 1-Hexene	2.43	2.34	2.35	2.36	1.93	0.27	0.27	0.27	0.29	0.30
n-Hexane	1.73	1.67	1.77	1.72	1.61	1.11	1.06	1.13	1.27	1.27
ETBE (1)	0.00	10.15	0.00	0.00	0.00	0.00	10.58	0.00	0.00	0.00
Methylcyclopentane	0.73	0.70	0.78	0.70	0.80	0.81	0.76	0.78	0.93	0.93
Benzene	1.79	1.77	1.74	1.74	1.70	1.59	1.50	1.60	1.86	1.84
2-Methylhexane	2.59	2.52	2.52	2.49	2.43	2.64	2.50	2.65	3.08	3.03
2,3-Dimethylpentane	0.83	0.80	0.94	0.91	0.78	0.88	0.85	0.88	1.00	0.99
3-Methylhexane & cyclohexene	2.98	2.96	2.90	2.86	2.79	2.94	2.84	2.99	3.54	3.51
n-Heptane	2.06	1.98	2.04	2.01	1.87	2.00	1.91	3.23	2.49	2.34
Toluene & 2,3,3-Trimethylpentane	9.24	9.21	9.00	8.99	8.72	6.94	6.43	6.85	7.60	7.67
2-Methylheptane	0.69	0.68	0.69	0.67	0.70	0.62	0.58	0.60	0.71	0.68
3-Methylheptane	0.82	0.79	0.81	0.79	0.81	0.71	0.68	0.71	0.80	0.77
n-Octane	0.58	0.55	0.56	0.56	0.56	0.47	0.44	0.47	0.53	0.52
Ethylbenzene	3.73	3.66	3.70	3.63	3.48	2.57	2.48	2.60	2.86	2.86
meta- & para-Xylenes	5.65	5.52	5.64	5.60	5.44	4.22	4.10	4.23	4.64	4.52
ortho-Xylene	3.00	2.95	3.11	3.00	2.92	2.33	2.30	2.38	2.46	2.40
n-Propylbenzene	0.90	0.86	0.91	0.89	0.86	0.72	0.72	0.75	0.71	0.72
1-Methyl-3-Ethylbenzene	2.43	2.38	2.47	2.45	2.35	1.97	1.94	2.02	2.03	2.03
1-Methyl-4-Ethylbenzene	1.10	1.08	1.08	1.08	1.05	0.88	0.84	0.87	0.90	0.89
1,3,5-Trimethylbenzene	1.11	1.04	1.13	1.11	1.06	0.90	0.88	0.93	0.94	0.93
1-Ethyl-2-Methylbenzene	0.82	0.80	0.78	0.79	0.75	0.67	0.61	0.64	0.69	0.66
1,2,4-TriMeBenz & tert-Butylbenz	3.19	3.07	3.13	3.22	3.13	2.68	2.58	2.59	2.76	2.63
1,2,3-Trimethylbenzene	0.63	0.60	0.64	0.62	0.61	0.52	0.52	0.53	0.54	0.52
1-Methyl-3-Propylbenzene	0.52	0.50	0.50	0.52	0.51	0.45	0.43	0.42	0.45	0.44
1,4-Diethylbenzene	0.57	0.56	0.60	0.60	0.59	0.52	0.52	0.50	0.52	0.51
Total (omit butane, oxy. cpds.)	85	86	85	85	84	81	73	81	82	83

(1) The percent carbon values given for butane, MTBE and ETBE refer to the total of all species (except ethanol).

(2) Data not available due to peak tailing of the MTBE peak.

D. VALIDATION OF THE SECOND BLEND OF WINTER BASE FUEL

A new Winter Base, Fuel Y, was blended by Phillips to enable the re-testing at 50°F of all vehicles. The goal for this new Winter Base blend was not only to meet all the specifications of the original Winter Base, but to duplicate the original Winter Base fuel as exactly as possible, species by species. Therefore, ATL worked closely with Phillips by performing speciation analysis on several potential blending stocks as well as several intermediate trial blends. The fourth trial blend matched the main speciation characteristics closely and, after some fine tuning, the new Winter Base was blended from that formulation. A speciation comparison of the original Winter Base, Fuel X, and the new Winter Base, Fuel Y, is given in Table 3-4.

In addition to the chemical verification of the duplicate Winter Base fuel, a vehicle-based comparison was also conducted. Original formulation Winter ETBE fuel in previously unopened drums was used for this purpose. Reagent ETBE was obtained from Phillips and blended with the new Winter Base fuel at 17.2 vol.% to produce a comparison "new" Winter ETBE fuel. The ETBE Winter Fuel was chosen for two reasons: 1). It remained in adequate supply as the original Winter Base type, and 2). The addition of ETBE has almost no effect on the RVP of a normal gasoline, so the "old" and "new" Winter ETBE fuels would be identical in regard to RVP. These two "old base" and "new base" fuels were used with two of the more "stable" (with regard to tailpipe emissions) vehicles in triplicate FTP tests (non-speciated) to assess whether the "new" Winter Base was equivalent to the original Winter Base with respect to the exhaust mass emissions obtained. The exhaust emission results for this comparison test series are shown in Table 3-5. While triplicate tests do not enable a definitive statistical comparison, the variances (standard deviations) found do give some indication of whether observed differences are real. We do not believe that there are any significant differences in the emissions values between those of the new Winter Base and those that would have been obtained from the original Winter Base with the correct RVP.

Table 3-4. Speciation Comparison of Original (Fuel X) versus New (Fuel Y) Winter Base

Species Name (a)	Percent of		Ratio	Species Name (a)	Percent of		Ratio
	Fuel Y	Fuel X			Fuel Y	Fuel X	
n-Butane (b)	1.63	0.96	1.69	2-Methylheptane	0.57	0.65	0.87
2-Methylbutane (Isopentane)	21.59	19.69	1.10	1-MeCyfHexene & 4-MeHeptane	0.34	0.32	1.05
2-Methyl-1-butene	0.29	0.27	1.06	3-Methylheptane	0.73	0.80	0.91
n-Pentane	1.81	1.64	1.11	n-Octane	0.61	0.54	1.13
1-2-Pentene	0.45	0.46	0.97	Ethylbenzene	3.48	3.05	1.14
c-2-Pentene	0.26	0.27	0.97	meta- & para-Xylenes	7.12	6.67	1.07
2-Methyl-2-butene	0.67	0.77	0.87	4-Methylheptane	0.38	0.47	0.80
2,3-Dimethylbutane	0.33	0.47	0.70	3-Methylheptane	0.30	0.39	0.76
2-MePentane & 4-Me-c-2-Pentene	1.30	1.86	0.70	ortho-Xylene	3.14	2.78	1.13
3-Methylpentane	0.86	1.17	0.73	Isopropylbenzene	0.29	0.21	1.37
2-Methyl-1-pentene & 1-Hexene	0.28	0.29	0.98	n-Propylbenzene	1.01	0.90	1.12
n-Hexane	0.92	0.91	1.01	1-Methyl-3-Ethylbenzene	2.55	2.43	1.05
1-2-Hexene	0.30	0.29	1.05	1-Methyl-4-Ethylbenzene	1.18	1.13	1.04
3-Methyl-1-2-pentene	0.27	0.30	0.91	1,3,5-Trimethylbenzene	1.14	1.21	0.94
2-Methyl-2-pentene	0.26	0.27	0.99	1-Ethyl-2-Methylbenzene	1.00	0.93	1.08
c-2-Hexene & 3-Methyl-c-pentene	0.21	0.19	1.12	1,2,4-TriMeBenz. & t-Butylbenz.	3.41	3.35	1.02
3-Methyl-c-2-pentene	0.28	0.38	0.75	1,2,3-Trimethylbenzene	0.74	0.69	1.07
Methylcyclopentane	0.43	0.66	0.65	Indan	0.39	0.41	0.93
2,4-Dimethylpentane	0.43	0.54	0.80	1,3-Diethylbenzene	0.31	0.27	1.12
1-Methylcyclopentene	0.30	0.21	1.44	1-Methyl-3-Propylbenzene	0.64	0.58	1.11
Benzene	1.69	1.44	1.18	1,4-Diethylbenzene	1.17	1.06	1.10
2-Methylhexane	2.11	2.41	0.87	1,4-Dimethyl-2-Ethylbenzene	0.42	0.38	1.10
2,3-Dimethylpentane	0.96	0.98	0.98	1,3-Dimethyl-4-Ethylbenzene	0.33	0.29	1.16
Cyclohexene & 3-Methylhexane	2.53	2.68	0.94	1,2-Dimethyl-4-Ethylbenzene	0.60	0.54	1.11
1-1,2-Dimethylcyclopentane	0.50	0.57	0.87	1,2,4,5-Tetramethylbenzene	0.33	0.31	1.05
IsoOctane	0.85	1.04	0.82	1,2,3,5-Tetramethylbenzene	0.47	0.46	1.03
n-Heptane	1.62	1.91	0.85	Methylindan	0.36	0.38	0.95
2-Methyl-2-Hexene & c-3-Heptene	0.40	0.36	1.09	1,3-Diisopropylbenzene	0.41	0.42	0.99
2,4-Dimethylhexane	0.41	0.54	0.76	Naphthalene	0.53	0.52	1.01
2,3,4-Trimethylpentane	0.40	0.81	0.49				
2,3,3-Trimethylpentane	0.40	0.81	0.49				
Toluene	8.23	7.26	1.13				
				Total in This List:	86.9	84.5	
				Total Identified but Omitted from List:	7.1	9.6	
				Total with unknown identity:	6.0	5.8	

(a) The species listed are those at the highest levels in the New Winter Base; species below about 0.25% of the total are omitted.

(b) The butane amount shown for the original Winter Base (Fuel X) reflects the incorrect, low RVP fuel, so matching the butane level was not a goal for Fuel Y.

Table 3-5. Comparison of 75°F Mass Emissions Using ETBE Fuel Prepared from "Original" and "New" Winter Base Fuel.

Test Date	Fuel Base	Mass Emission Values, gram/mile or miles/gal.											
		FTP Composite				HFET				NYCC			
		HC	CO	NOx	MPG	HC	CO	NOx	MPG	HC	CO	NOx	MPG
90 Honda Accord (Veh. 5)													
1-24	Orig. (1)	0.181	3.23	0.40	24.36	0.041	0.41	0.111	37.4	0.34	8.1	0.98	12.9
9-1	Orig.	0.158	2.72	0.39	25.08	0.027	0.94	0.099	37.0	0.46	13.6	0.76	13.4
9-2	Orig.	0.148	2.51	0.39	25.03	0.026	0.63	0.128	37.6	0.23	8.8	0.60	13.0
9-4	Orig.	0.159	2.65	0.33	25.39	0.033	1.09	0.102	39.1	0.34	8.1	0.98	12.9
	mean of 3	0.155	2.63	0.37	25.17	0.029	0.89	0.110	37.9	0.34	10.2	0.78	13.1
	std. dev.	0.005	0.09	0.03	0.16	0.003	0.19	0.013	0.9	0.10	2.4	0.16	0.2
	%RSD	3	3	8	0.6	11	22	12	2	28	24	20	1.7
9-9	New	0.171	2.65	0.40	25.0	0.036	1.26	0.12	37.0	0.76	10.8	0.99	13.0
9-10	New	0.163	2.19	0.41	25.5	0.024	0.44	0.17	37.6	0.79	12.0	0.85	14.1
9-11	New	0.181	2.84	0.45	25.6	0.021	0.53	0.13	37.7	0.97	14.7	0.87	13.5
	mean of 3	0.172	2.56	0.42	25.4	0.027	0.74	0.14	37.4	0.84	12.5	0.90	13.5
	std. dev.	0.007	0.27	0.02	0.3	0.006	0.37	0.02	0.3	0.09	1.6	0.06	0.5
	%RSD	4	11	5	1.2	24	49	17	0.8	11	13	7	3
%Dif. vs. Orig.		11	-3	14	1	-6	-16	26	-1	144	23	15	3
90 Dodge Dynasty (Veh. 6)													
2-24	Orig. (1)	0.61	5.20	0.412	21.42	0.07	1.14	0.092	33.6	0.37	7.7	0.65	11.24
9-1	Orig.	0.77	3.81	0.350	21.23	0.22	2.91	0.097	36.0	5.11	13.9	1.03	10.99
9-3	Orig.	0.57	4.33	0.386	21.61	0.10	1.81	0.111	34.2	3.89	21.0	1.01	11.03
9-4	Orig.	0.63	3.61	0.365	21.86	0.10	1.84	0.170	34.1	4.35	16.6	0.96	11.08
	mean of 3	0.65	3.92	0.367	21.57	0.14	2.19	0.126	34.8	4.45	17.2	1.00	11.0298
	std. dev.	0.08	0.30	0.015	0.26	0.06	0.51	0.032	0.8	0.50	2.9	0.03	0.04
	%RSD	13	8	4	1.2	40	23	25	2.4	11	17	3	0.3
9-9	New	0.65	3.29	0.351	21.63	0.102	1.89	0.114	33.09	5.09	11.3	1.14	10.95
9-10	New	0.67	3.88	0.290	21.44	0.114	2.04	0.116	33.00	4.39	14.3	0.79	10.97
9-14	New	0.76	4.38	0.348	21.44	0.121	2.19	0.097	32.88	5.36	15.4	0.95	10.20
	mean of 3	0.70	3.85	0.330	21.50	0.112	2.04	0.109	32.99	4.95	13.7	0.96	10.71
	std. dev.	0.05	0.45	0.028	0.09	0.008	0.12	0.009	0.09	0.41	1.7	0.14	0.36
	%RSD	7	12	9	0.4	7	6	8	0.3	8	13	15	3
%Dif. vs. Orig.		7	-2	-10	0	-21	-7	-13	-5	11	-20	-4	-3

(1) This test is the one performed in the matrix with the other 75°F tests. It is included for comparison purposes but is not included in the means and standard deviations.

4. TEST PROCEDURES

A. TEST CELL EQUIPMENT

Exhaust emission equipment consisted of a Horiba CDC-9000 twin 20 inch roll, 150 hp, electric dynamometer. A six-bag Horiba CVS-46 constant volume sampler (CVS), operating at a nominal flow of 325 cfm, was used to collect diluted tailpipe samples. The CVS had been modified to permit automatic purge and leak checks of each bag prior to use. Dilute sample temperatures were maintained at $110 \pm 10^\circ\text{F}$ during the test. The drivers aid was a Horiba SADA 2040 with programmed driving cycles including the FTP, HFET, and NYCC. A Hartzell Model N24DW, fixed-speed cooling fan of 5300-CFM capacity was used in front of the vehicle during the tests. Vehicle hoods were maintained fully open during the Urban Dynamometer Driving Schedule (UDDS) cycles and were closed during the 10 minute soak period.

All FTP evaporative emission tests were conducted using a Sealed Housing for Evaporative Determination (SHED) constructed to meet CFR 40, Section 86.107 requirements. The total evaporative hydrocarbon emission analyses were conducted using a Beckman Model 400 FID analyzer. Evaporative tests were conducted in two phases: Diurnal Breathing Loss (DBL) to simulate HC losses as fuel temperatures increase from night to day, and Hot Soak (HS) to simulate HC losses after a road-use vehicle has been parked. Evaporative testing variations centered on non-certification SHED temperatures (DBL & HS) and DBL fuel temperature ranges. The diurnal temperature ramp for the 75°F tests followed the standard 60° to 84°F profile, while the 95°F tests were 80° to 104°F over a 60 minute period. During the diurnal tests, a heat source on the fuel tank was used to raise the temperature of the fuel to the starting diurnal temperature. It continued to provide heat to maintain the fuel temperature ramp of 0.4°F per minute for one hour with a $\pm 3^\circ\text{F}$ tolerance. Hot Soak enclosure temperatures for the 75°F tests were initially set to 75°F but this temperature was not maintained throughout the test. For the 95°F tests, the initial temperature was 95°F and was maintained at that temperature throughout the one hour test sequence.

Evaporative Running Loss emission tests were performed in a SHED enclosure equipped with a standard Clayton ECE-50 twin roll dynamometer. The direct drive flywheel equipped dyno was capable of inertia selections from 1000 to 6875 pounds in 125 pound increments. The SHED volume (5670 ft^3) was approximately twice the capacity of a conventional evaporative emission enclosure. Combustion air was provided directly to the operating vehicle engine from outside of the enclosure. Engine exhaust was routed from the vehicle to the outside of the enclosure into a CVS. The base enclosure was fabricated to meet proposed vehicle certification specifications for evaporative emission testing, including standard temperature measurements. Additional air handling and cooling were added to manage the additional heat load from the operating vehicle and to permit testing at elevated temperatures (95° - 105°F). Additional analyzers (CO and CO_2) were added to monitor the enclosure for vehicle exhaust leaks during the tests.

Enclosure cooling was provided by a main chilled water to air heat exchanger which was supplemented by three small auxillary air conditioning units equipped with Freon to air heat exchangers. The three small air conditioning units were staged at $1/2^\circ$ intervals. The lower individual capacity of each of the small three air conditioning units reduced the total breathing of the enclo-

sure compared with the larger temperature cycle observed with a single, higher capacity unit. The air conditioner fans ran continuously to mix the enclosed air. A standard 5300 CFM Hartzell fan was used to provide under-hood cooling. A variable speed blower was used for under vehicle and fuel tank temperature control. Fuel heating was provided by a convection heater/blower which was directed to the bottom surface of the vehicle fuel tank. Fuel heating was controlled automatically by a programmable temperature achiever. Electronic resistance heaters were used to elevate the enclosure to 95°F for the start of the test. Vehicle heat (with cooling as required) was used to maintain the elevated temperatures inside the enclosure.

Enclosure propane background, calibration, and retention checks were performed in accordance with CFR requirements (CFR, Title 40, Part 86, Subpart B Section 86.117-78, "Evaporative Emissions Enclosure Calibrations"), except that the retention standard was set at a maximum loss of 5% in a one hour period at 95°F with all fans, air conditioners, and blowers running.

B. TEST METHODS

The vehicle test procedure (except for Running Loss) is shown in Figure 4-1. Canister capacity was determined for each vehicle (as received) prior to each test initiation. This procedure consisted of:

1. Purge the canister with ambient air at the vehicle's average purge flow rate
2. Fill it to capacity as defined below with butane
3. Measure weight gain

The average canister purge rate was determined for each vehicle by taking a four mile round trip with a rotometer connected in series with the canister purge line. This information was established so that laboratory canister capacity determination reflected actual vehicle operation. This flow rate was used throughout the program. Canister weight was monitored every five minutes and was considered fully purged when a change of less than one gram was noted in a five minute interval. The canister was then loaded with a 50/50 mixture of pressurized butane/air at the rate of 1.0 g/min butane. The canister was weighed at one minute intervals and considered saturated when the rate of change was less than 0.25 g/min. The capacity was calculated as the difference between the saturated weight and the purged weight. This process was repeated until two consecutive butane capacities agreed within two grams. The canister capacity was taken as the average of these two values.

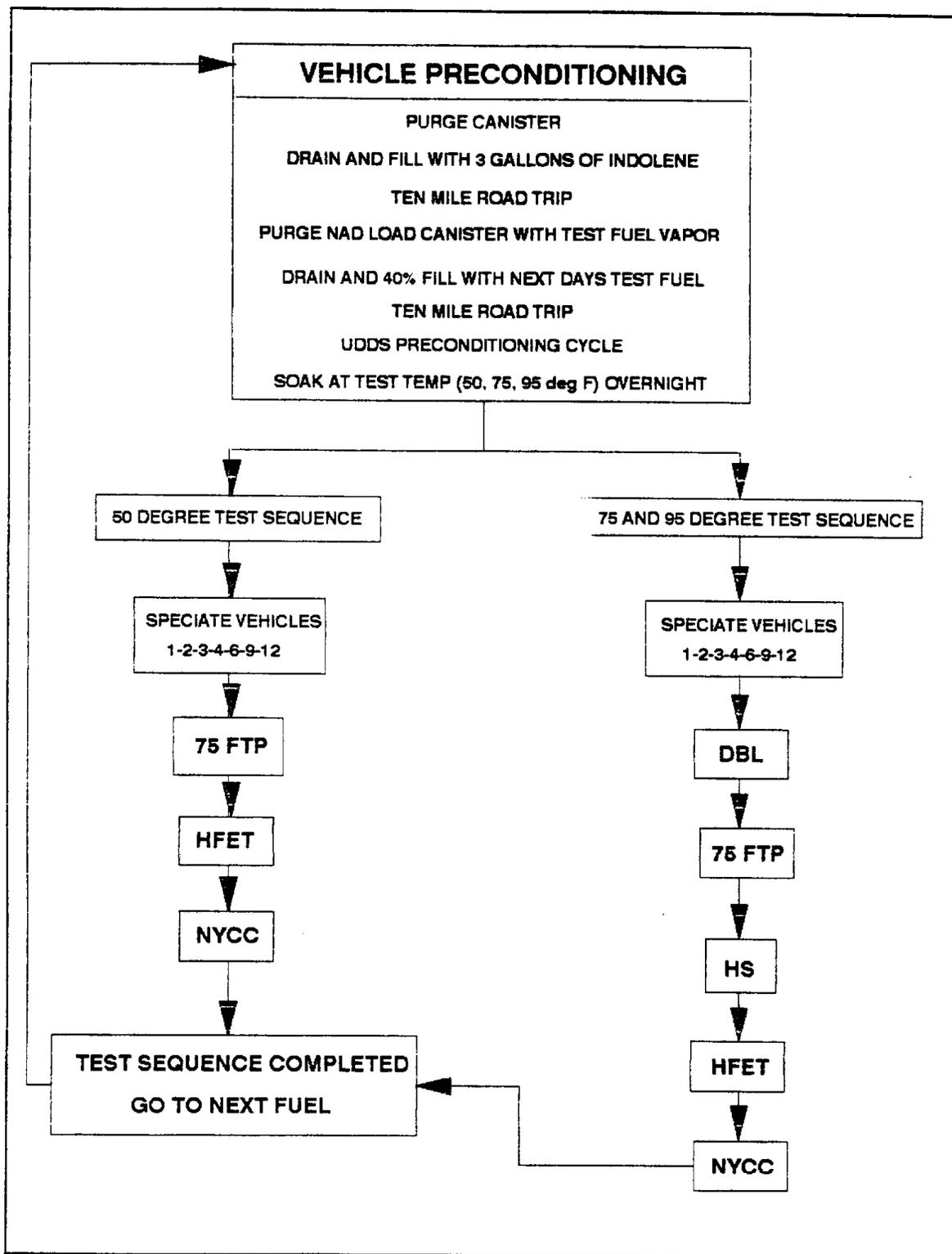
All test vehicles were evaluated using a modified form of the Federal Test Procedure (CFR, Title 40, Part 86, Subpart B, Section 86.101-145, sections applicable to light-duty vehicles). The FTP consists of an UDDS preconditioning; overnight soak period; diurnal breathing loss (DBL); exhaust emissions test over cold transient, stabilized, and hot transient segments (bags 1, 2, and 3); and a hot soak (HS) test. Principle variations to the FTP procedures were in ambient testing temperatures, preconditioning, DBL and HS, which are described below. Also, a double HFET and NYCC test as defined above followed the FTP.

The modified preconditioning procedures were:

1. Canister purge

Figure 4-1.

VEHICLE TEST SEQUENCE



2. Canister loaded with Indolene[®] vapors
3. Drain and fill with 3 gallons Indolene[®]
4. Operate vehicle for 10 miles on road
5. Canister purged and loaded with test fuel vapors to 100% of the butane mass capacity
6. Drain and add a 40% fill of test fuel
7. Operate vehicle for 10 miles on road
8. Drive on dyno through a UDDS prep cycle
9. Soak at 50, 75 or 95°F, overnight

Regulated emissions testing (HC, CO, & NO_x) was conducted on all prescribed fuels and vehicles. Non-regulated exhaust FTP & NYCC speciation of hydrocarbons, aldehydes, alcohols, and ketones were performed on all fuels and temperatures, but only on selected vehicles.

For the 50°F test sequence, the vehicle was moved directly from soak at 50°F to the test cell for the initiation of the exhaust FTP, HFET and NYCC. After the soak period for the 75° and 95°F sequences, an additional fuel tank drain and 40% fill of fresh test fuel was performed followed with an evaporative FTP (DBL), a sampled exhaust FTP, an evaporative FTP (HS), a HFET and finished with a hot start NYCC, Figure 4-1.

The diurnal temperature ramp for the 75°F tests followed the standard 60° to 84°F profile, while the 95°F tests temperature ramp was from 80° to 104°F over a 60 minute period. Hydrocarbon levels were recorded continuously during the Diurnal and Hot Soak tests. SHED enclosure speciation was performed for seven of the thirteen vehicles on all fuels. The samples were collected in 100-liter Tedlar[®] bags at the start and end of each SHED segment. These bags were analyzed for hydrocarbons, and alcohols (ethanol fuels only) as described under the speciation procedures.

Exhaust HFET speciation tests were only performed at the 50° and 75°F temperatures. Four exhaust FTP speciation samples were taken from the CVS Tedlar[®] bag samples 1, 2, 3 and background sample 2. The speciated samples for the NYCC and HFET cycles consisted of one test sample and a background sample. They were analyzed using a Varian 3600 dual column GC system. Impinged alcohol and aldehydes samples were analyzed by the GC and HPLC procedures described under speciation.

C. RUNNING LOSS PROCEDURES

The 95°F Running Loss consisted of three UDDS driving cycles separated by 2-minute soak periods. Canisters were loaded with butane from a purge-down status to achieve a final loaded weight determined for each vehicle as follows: a fresh 40% fill of Summer Base (Fuel M), a UDDS preconditioning was performed followed by a one-hour soak with the vehicle hood down and the key off. A second UDDS cycle was run, followed by another one-hour soak. The canister was removed from the vehicle at the end of the second hot soak and weighed, and this total canister weight was defined as the largest weight for butane loading.

Preconditioning for each test was:

1. Drain and 40% fill with fresh test fuel
2. Canister weight adjusted with butane to reference value
3. Drive on dyno through a UDDS prep cycle
4. Soak overnight at 95°F

Following the overnight soak, the vehicle was pushed into the running loss enclosure. Initial HC levels in the sealed enclosure were recorded when the CVS exhaust emission bag sampling began. Three UDDS cycles were run with 120-second idles between each cycle. Samples were taken at the beginning and end of each cycle for a total of six data points.

D. TEST MATRICES

The tests were performed at three temperatures: 50°, 75°, and 95°F. All tests of a given temperature were performed at the same time (i.e., all fuels and vehicles were tested at 50° before the 75° or 95°F tests were started). The order of testing at a given temperature was randomized for the fuel/vehicle combinations.

The 50°F testing consisted of the six winter fuels and thirteen vehicles. One vehicle was also tested on Indolene[®]. The fuel/vehicle matrix in Table 4-1 represented 66 test sequences consisting of sampled exhaust FTP, HFET, and NYCC. The sequence also included complete hydrocarbon, aldehyde, and alcohol speciation on seven of the test vehicles.

The 75°F testing included all thirteen vehicles with the six Winter-Based fuels, the five Summer-Based fuels and Auto/Oil RF-A. The fuel/vehicle matrix in Table 4-2 represented 144 test sequences (13 vehicles x 11 fuels + 1 vehicle x 1 fuel) consisting of sampled exhaust and evaporative FTP, HFET, and NYCC. The sequence included complete hydrocarbon, aldehyde and alcohol speciation on seven of the test vehicles.

The 95°F testing matrix Table 4-3 was identical to the 50°F matrix except it used the five summer based fuels. Again, one of the vehicles was tested on Indolene[®] making a total of 66 tests.

The 95°F running loss tests were completed on six vehicles and five summer based fuels along with RF-A. The fuel/vehicle matrix in Table 4-3 represented 37 running loss tests {(6 vehicles x 6 fuels) + (1 vehicle x 1 fuel)}. Hydrocarbon speciation was performed on all 37 tests, and alcohol speciation was performed on the 12 tests with ethanol fuels.

E. SPECIATION PROCEDURES

Three identically equipped Varian 3600 GCs were used for HC Speciation. Each GC was equipped with two Valco valve injectors; two DB-1, 60m x 0.32mm, 1 µm film, capillary columns (J&W #123-1063); and two FID detectors. Samples were collected in 50-100 liter Tedlar[®] bags from the FTP phases, FTP phase 2 background, diurnal heat build, heat loss and running loss samples and backgrounds. Two bag samples were simultaneously injected and analyzed in a timely manner to minimize the formation of degradation products. The gas samples were trans-

Table 4-1.
50 F° Test Matrix

Fuel/RVP	Test Code for the Given Vehicle Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
HC Base 9.5	1	1	1	1	1	2	2	2	1	2	2	1	2
7.8% EtOH 9.6	1	1	1	1	1	2	2	2	1	2	2	1	2
15% MTBE 9.6	1	1	1	1	1	2	2	2	1	2	2	1	2
17% ETBE 9.7	1	1	1	1	1	2	2	2	1	2	2	1	2
7.8% EtOH 10.7	1	1	1	1	1	2	2	2	1	2	2	1	2
Indolene 9.0	1	0	0	0	0	0	0	0	0	0	0	0	0

Test Matrix Code:

0--No Testing.

1--Exhaust FTP's, HFET's, NYCC's, and full Speciation of HC, Alcohols and Aldehydes.

2--Exhaust FTP's, HFET's, and NYCC's only.

Table 4-2.
75 F^o Test Matrix

Fuel/RVP	Test Code for the Given Vehicle Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
HC Base 7.7	1	1	1	1	1	2	2	2	1	2	2	1	2
5.7% EtOH 7.6	1	1	1	1	1	2	2	2	1	2	2	1	2
11% MTBE 7.7	1	1	1	1	1	2	2	2	1	2	2	1	2
13% ETBE 7.5	1	1	1	1	1	2	2	2	1	2	2	1	2
5.7% EtOH 8.5	1	1	1	1	1	2	2	2	1	2	2	1	2
HC Base 9.5	1	1	1	1	1	2	2	2	1	2	2	1	2
7.8% EtOH 9.6	1	1	1	1	1	2	2	2	1	2	2	1	2
15% MTBE 9.6	1	1	1	1	1	2	2	2	1	2	2	1	2
17% ETBE 9.7	1	1	1	1	1	2	2	2	1	2	2	1	2
7.8% EtOH 10.7	1	1	1	1	1	2	2	2	1	2	2	1	2
RF-A 8.7	1	1	1	1	1	2	2	2	1	2	2	1	2
Indolene 9.0	1	0	0	0	0	0	0	0	0	0	0	0	0

Test Matrix Code:

0--No Testing.

1--Evap & Exhaust FTP's, HFET's, NYCC's, and full Speciation of HC, Alcohols and Aldehydes.

2--Evap & Exhaust FTP's, HFET's, and NYCC's only.

Table 4-3.
95 F° Test Matrix

Fuel/RVP	Test Code for the Given Vehicle Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
HC Base 7.7	3	3	3	1	1	2/4	2	2	3	2	2	3	2
5.7% EtOH 7.6	3/4	3/4	3/4	1	1	2/4	2	2	3/4	2	2	1	2
11% MTBE 7.7	3	3	3	1	1	2/4	2	2	3	2	2	1	2
13% ETBE 7.5	3	3	3	1	1	2/4	2	2	3	2	2	1	2
5.7% EtOH 8.5	3/4	3/4	3/4	1	1	2/4	2	2	3/4	2	2	3/4	2
RF-A 8.7	3	3	3	1	1	2/4	2	2	3	2	2	3	2
Indolene 9.0	3	0	0	0	0	0	0	0	0	0	0	0	0

Test Matrix Code:

0--No Testing.

1--Evap & Exhaust FTP's, HFET's, NYCC's, and full Speciation of HC, Alcohols and Aldehydes.

2--Evap & Exhaust FTP's, HFET's, and NYCC's only.

3--Evap & Exhaust FTP's, HFET's, NYCC's, Running Loss and full Speciation of HC, Alcohols and Aldehydes

4--Running Loss and Speciation of HC and Alcohols (EtOH fuels only).

ferred to the GC injector valve using a stainless steel bellows pump, providing sample to the injector valve at a controlled pressure. Data processing was facilitated with a Varian Star chromatography data system. Fuel speciation was performed identically to the exhaust hydrocarbons speciation except the sample was prepared by injecting fuel into a septum-equipped Tedlar[®] bag containing zero-grade nitrogen (about 0.3 µl fuel per liter of nitrogen).

On January 1, 1992, the GC injectors were modified and the temperature gradient changed to give better peak separation and more efficient analysis. Correlation data indicated the new and old methods gave essentially identical speciation results and the same detection limits of approximately 50 ppbC which corresponds to about 0.6 mg/mi for species of formula (C₁H_{1.85})_n. All fuel speciation was conducted with the post-January 1 conditions. The GC parameters affected by this change are the following:

	<u>Pre-Jan. 1</u>	<u>Post-Jan. 1</u>
Loop Size, µL	500	100
Split Ratio	10:1	none
Injector Temp., °C	150	150
Detector Temp. °C	300	250
Column Head Pressure (psi)	12	17
SS Sample Pump Pressure (psi)	9	17
Oven Program		
Initial Temp., °C	-60	-38
Initial Hold Time (min.)	6	3.5
Ramp #1 (°/min.)	5	15
Temp #1, °C	110	0
Ramp #2 (°/min.)	7	10
Temp #2, °C	232	50
Hold Time (min.)	4	0
Ramp #3 (°/min.)	-	3.7
Temp #3, °C	-	172
Ramp #4 (°/min.)	-	25
Temp #4, °C	-	220
Hold Time (min.)	-	3
Total Elution Time (min.)	62	49

Each day, a 21 component mix gas standard (3 to 9 ppmC, each component) was analyzed as a quality control check on the operating conditions. This gas standard was made by Scott Specialty Gases as per a specification of the Coordinating Research Council. Whenever this daily performance check chromatogram indicated an instrument malfunction, that GC was taken off line and corrected. A set of daily peak height calibration coefficients were generated and used for that day's sample calculations.

The aldehyde/ketone and alcohol components were collected by flowing 29-52 liters of the diluted gas stream from the CVS sampler through two impinger flasks, connected in series, held at 0°C in an ice bath. The sampled CVS gas was impinged at a flow rate of 3.5 liters/min through each sampler containing 30 ml of impinger fluid. The aldehyde-/ketone impinger fluid was a solu-

tion of 2,4 dinitrophenylhydrazine (2,4-DNPH) in acetonitrile (0.04% w/v) with two drops of 1N perchloric acid added to catalyze the formation of the 2,4-DNPH derivative. The alcohol impinger fluid was HPLC grade water.

High pressure liquid chromatographic (HPLC) analysis of aldehydes and ketones were performed on a Spectra Physics SP8800 HPLC ternary gradient system equipped with a Varian SP4400 data integrator and a Spectra Physics SP8875 autosampler with a 20 µL loop. The HPLC column was an ODS 4.6mm X 22cm, 5µm column (Rainin #ODS-224) with a solvent flow of 1.0 ml/min at ambient temperature. The elutants were detected at 360nm using a Spectra Physics SP200 variable wavelength detector. On May 20, 1992, a new solvent gradient program was initiated reducing the injection time and solvent consumption. Correlation data indicated the new and old methods gave essentially identical speciation results and the same detection limits of about 2.5 ppbV in the diluted exhaust gas. This corresponds to about 0.2 mg of formaldehyde per mile for a bag 1 phase. The solvent gradient conditions were the following:

	<u>Volume Percent</u>		
	<u>Water</u>	<u>Acetonitrile</u>	<u>Methanol</u>
<u>Pre-Mar. 20</u>			
Initial	40	27	33
15 min.	0	5	95
19 min.	0	5	95
20 min.	40	27	33
26 min.	40	27	33
<u>Post-Mar. 20</u>			
Initial	30	43	27
5 min.	15	40	45
8 min.	0	5	95
10 min.	0	5	95
12 min.	30	43	27
15 min.	30	43	27

The sample from each impinger in the paired series was analyzed separately by HPLC and the results combined for the total analyte. A standard nine component mix of aldehyde and ketone DNPH derivatives was analyzed before and after each test set and the average response factors from the two standards were used to quantify the test data.

The alcohol samples were analyzed using a Varian 3600 GC equipped with a Varian 8035 autosampler, an FID detector and a DB-1, 30m x 0.53mm, 5 µm film, capillary column (J&W #125-1035). The instrument conditions are as follows:

Injector Temp.	150°C.
Detector Temp.	250°C.
Injection Volume	0.5 µl
Oven Program	
Initial Temp.	60°C.
Initial Hold Time (min.)	2
Ramp (°/min.)	10

Final Temp.	100°C.
Total Elution Time (min.)	6

An internal standard (1.0 ml of 104 ppm 1,4-dioxane, Aldrich #29,630-9) was added to each of the tandem impinger samples which were analyzed separately by GC. The analyte concentration was determined by the internal standard method using response factors from the analysis of standards. The results from the two tandem impingers were combined for the total analyte.

All of the speciation data was reduced in a similar fashion. The raw chromatograms and raw peak detection reports were generated by a specific data integrator. Text files of the peak detection results were transmitted to a host computer where peak matching software was applied for initial peak identification. Data clerks inspected these peak assignments in every chromatogram for correct analyte identification and quantitation. Peak height was used for hydrocarbon and aldehyde/ketone speciation and peak area was used for alcohol speciation. The chromatographic results after final QA inspection were electronically copied to a calculating template, put in spreadsheet form, and the final results reported in hardcopy and electronic format.

5. RESULTS AND DISCUSSION

The Results and Discussion section is divided into five parts. Part A describes the characteristics of the database. This includes the structure of the database, descriptions of the vehicles and fuels, and preparation of the data for analysis. Part B describes the objectives and logic of the analysis effort and the general data analysis approach which was used to investigate the database. Also, the general techniques and technical terms which are used throughout the analysis sections are presented. In Part C, examples of specific techniques that were used repeatedly are described in detail using the analysis of the NO_x trends as an example. Part D and Part E present the evaluations of exhaust emissions and evaporative emissions, respectively. These sections include regression analysis, as well as general description of the data.

A. CHARACTERIZATION OF THE DATABASE

To assist in the organization and analysis of the data, a SAS database was created. The data was organized into seven SAS data files, which serve as the database for this project. Table 5-1 shows the organization of the database. The SAS database was also transformed into a database made up of seven ASCII files, which have been provided to the California Air Resources Board.

The FLEET file gives the descriptions of the 13 vehicles in the test fleet. The contents of this file are shown in Table 5-2. The vehicle information in this file is merged with the other information in the other six files using the VEHID vehicle identifier. The special features of these vehicles are discussed in detail later.

The FUEL file describes the 14 test fuels used in the study. The contents of this file are the first seven columns of Table 5-3. The FUELID is the fuel identifier used to merge the fuel descriptions in this file with the other files in the database. The oxygen content and RVP values given in the fuel file are approximates only; the measured values are given in Section 3. The special features of this fuel set are discussed in detail later.

The remaining five files use TEMP, VEHID, TESTDATE, and FUELID as test descriptors to connect the various database files. The CYCLE file has 328 observations and contains the results for total emissions measurements for diurnal and hot-soak evaporative emissions and exhaust emissions for FTP, HFET, and NYCC driving cycles. The RUNLOSS file contains the total running loss results for the six bags of each test. The RUNLOSS file has 37 observations. The FTPBAG file contains the total emission results for each of the three bags of the FTP cycle. The FTPBAG file has 305 observations. The EXHSPEC file contains the speciation results for the seven vehicles where the exhaust emissions were speciated. The EXHSPEC file has 25,211 observations. The EVAPSPEC file contains the speciated emissions results for the diurnal, hot-soak, and running loss tests. The EVAPSPEC file has 16,080 observations. The EXHSPEC and EVAPSPEC files have, for each test condition, 144 observations corresponding to each of the gas chromatography peaks or other analyses used to perform the speciation.

1. Vehicle Descriptions. Descriptions of the 13 test vehicles are given in Table 5-2. Each vehicle can be described by the following five parameters:

- Vehicle number (VEHID),

Table 5-1
Database Structure

fleet.ascii			
VEHID			
VIN			
MODEL			
MAKE			
FUELSYS			
EMSTECH			
DISP	(L)		
CNSTR			
fuel.ascii			
SEASON			
BLENDTYP			
FUELID			
FUELDESC			
OXY	(XO)		
RVP	(psi)		
STOCK			
cycle.ascii			
TEMP			
VEHID			
TESTDATE			
FUELID			
FUELDESC			
DI	(g)		
HS	(g)		
FTPHC	(g/mi)		
FTPFCO	(g/mi)		
FTPNOX	(g/mi)		
FTPCCO2	(g/mi)		
FTPMPG	(mi/gal)		
HFETHC	(g/mi)		
HFETCO	(g/mi)		
HFETNOX	(g/mi)		
HFETCO2	(g/mi)		
HFETMPG	(mi/gal)		
NYCCHC	(g/mi)		
NYCCCO	(g/mi)		
NYCCNOX	(g/mi)		
NYCCCO2	(g/mi)		
NYCCMPG	(mi/gal)		
OXY	(XO)		
RVP	(psi)		
STOCK			
ftpbag.ascii			
TEMP			
VEHID			
TESTDATE			
FUELID			
FUELDESC			
FTPFCO	(g/mi)		
FTPNOX	(g/mi)		
FTPCCO2	(g/mi)		
FTPMPG	(mi/gal)		
B1HC	(g/mi)		
B1CO	(g/mi)		
B1NOX	(g/mi)		
B1CO2	(g/mi)		
B2HC	(g/mi)		
B2CO	(g/mi)		
B2NOX	(g/mi)		
B2CO2	(g/mi)		
B3HC	(g/mi)		
B3CO	(g/mi)		
B3NOX	(g/mi)		
B3CO2	(g/mi)		
OXY	(XO)		
RVP	(psi)		
STOCK			
exhspec.ascii			
TEMP			
VEHID			
TESTDATE			
FUELID			
CAS			
CMPD			
FTPCCOMP	(g/mi)		
FTP1GPM	(g/mi)		
FTP2GPM	(g/mi)		
FTP3GPM	(g/mi)		
HFETGPM	(g/mi)		
NYCCGPM	(g/mi)		
OXY	(XO)		
RVP	(psi)		
STOCK			
evapspec.ascii			
TEMP			
VEHID			
TESTDATE			
FUELID			
CAS			
CMPD			
DIG	(g)		
HSG	(g)		
RLG	(g)		
OXY	(XO)		
RVP	(psi)		
STOCK			
runloss.ascii			
TEMP			
VEHID			
TESTDATE			
FUELID			
FUELDESC			
RL1TG	(g)		
RL2TG	(g)		
RL3TG	(g)		
RL4TG	(g)		
RL5TG	(g)		
RL6TG	(g)		
OXY	(XO)		
RVP	(psi)		
STOCK			

Table 5-2. Contents of FLEET.ASCII

VEHID	VIN	MODEL	MAKE	MODEL	FUELSYS	EMSTECH	DISP	CNSTR
1	1G3NK54D1LM758792	1990	Oldsmobile	Calais	Multipoint	3wayAdaptive	2.3	CLOSED
2	1G8CS18B9F8272246	1985	Chevrolet	S-10 Blazer	Carburetted	3wayNonadaptive	2.8	CLOSED
3	3J29K3M398333	1973	Oldsmobile	Cutlass	Carburetted	Noncatalyst	5.7	OPEN
4	1MEPM6045LH636961	1990	Mercury	Cougar	Multipoint	3wayAdaptive	3.8	CLOSED
5	1HGCB7543LA000067	1990	Honda	Accord	Multipoint	3wayAdaptive	2.2	OPEN
6	1B3XC4639LD798740	1990	Dodge	Dynasty	Multipoint	3wayAdaptive	3.0	CLOSED
7	1P3BP26C/DF304361	1983	Plymouth	Reliant	Carburetted	3wayNonadaptive	2.2	CLOSED
8	1FAPP23J6HW304524	1987	Ford	Escort	Multipoint	3wayAdaptive	1.9	CLOSED
9	1G1JD77P0GJ294422	1986	Chevrolet	Cavalier	ThrottleBody	3wayAdaptive	2.0	OPEN
10	F6W83H279879	1976	Ford	Granada	Carburetted	Oxycatalyst	5.7	CLOSED
11	1C3BF66P/EX500443	1984	Chrysler	New Yorker	Carburetted	3wayNonadaptive	5.2	CLOSED
12	RA29147581	1978	Toyota	Celica	Carburetted	Oxycatalyst	2.2	OPEN
13	1FACP52U7MG204075	1991	Ford	Taurus	Multipoint	3wayAdaptive	3.0	CLOSED

Table 5-3. Description of Fuels

Blend Season	Fuel ID	Fuel Description	Blending Stock	Blend Type	Oxygen Content (wt%O)	RVP (psi)	Temperatures Where used		
							50°F	75°F	95°F
Summer	M	SummerBase	OriginalSummer	Base	0.0	7.7	•	•	•
Summer	O	11%MTBE	OriginalSummer	MTBE	2.0	7.7	•	•	•
Summer	Q	12.7%ETBE	OriginalSummer	ETBE	2.0	7.7	•	•	•
Summer	S	5.7%EtOH	OriginalSummer	EtOH	2.0	7.7	•	•	•
Summer	U	5.7%EtOH/SB	OriginalSummer	EtOH/SB	2.0	8.5	•	•	•
Winter	N	WinterBase	OriginalWinter	Base	0.0	9.7	•		
Winter	X	LowRVPWinterBase	OriginalWinter	LowRVPBase	0.0	9.1	•		
Winter	Y	NewStockWinterBase	NewWinter	NewStockBase	0.0	9.7	•		
Winter	P	15%MTBE	OriginalWinter	MTBE	2.7	9.7	•	•	
Winter	R	17.2% ETBE	OriginalWinter	ETBE	2.7	9.7	•	•	
Winter	T	7.75% EtOH	OriginalWinter	EtOH	2.7	9.7	•	•	
Winter	V	7.75%EtOH/SB	OriginalWinter	EtOH/SB	2.7	10.7	•	•	
Rfrnce	A	IndustryAvg	IndAvg	IndAvg	0.0	8.5	•	•	•
Rfrnce	E	Indolene	Indolene	Indolene	0.0	9.0	•	•	•

- Fuel induction system type (FUELSYS),
- Exhaust emissions system technology (EMSTECH),
- Engine displacement (DISP), and
- Canister bottom design (CNSTR).

It is well known that the emissions behavior of different vehicles is different even within general classifications of vehicle technology. Nevertheless, one of the goals of this study is the classification of vehicles by some measure of technology which can be used to describe, in a more general fashion, the response of vehicles to oxygenate blends.

A statistical impediment to the technological classification of vehicles is the fact that different technological descriptions of vehicles are confounded with each other because of the chronological nature of technological progress. For example, earlier model year vehicles tend to be carburetted and have oxidation catalysts or no catalysts, while late model vehicles tend to be fuel injected and have TWC/AL emission control technology. A vehicle which is carburetted and has TWC/AL is not in the data set. Of course, such a vehicle is also rare in the vehicle population.

The point is that the response of different technology vehicles to oxygenated gasoline blends will be difficult to assign to a specific technological factor by statistics alone. The statistical analysis which is used in this study does attempt to make the distinction in choice of the parameter which should be used to group technologies. However, it should be pointed out that the choice of a technology factor which is important to oxygenated blend differences among vehicles was, in many cases, chosen by a slim margin. In situations such as this, it is important to bring an engineering perspective to aid in the choice of the technology parameter which is important to emissions behavior.

2. Fuel Descriptions. Table 5-3 shows a description of the 14 test fuels and indicates the parts of the testing matrix where each was used. The fuels can be classified into three "Blend Season" categories: Summer, Winter, and Reference. The two reference fuels, "Fuel ID" A and E, were used to characterize the performance of the vehicles using an industry average fuel, Fuel A and Indolene[®], Fuel E. The summer and winter fuels form the bulk of the data and are the main focus of the data analysis. In the discussions which follow, fuels are referred to by the single letter code shown in the "Fuel ID" column of Table 5-3. Each fuel is described uniquely by the "Fuel Description". However, to understand the compositions of the fuels and the data analysis implications, additional test fuel descriptors "Blending Stock", "Blend Type", "Oxygen Content", and "RVP" are provided in Table 5-3. The oxygen content and RVP values given are nominal ones.

As indicated in Table 5-3, all five summer fuels share a common hydrocarbon blending stock, Original Summer Stock, and six of the seven winter fuels share another common blending stock, Original Winter Stock. The remaining winter fuel, Fuel Y, has a different hydrocarbon stock, New Winter Stock, which was blended to match the Original Winter Stock as closely as possible but is not identical to it. Fuels indicated as sharing a common hydrocarbon stock are identical in content except for the butane content (which was used for all final RVP adjustments) and the oxygenate content.

The Table 5-3 indication "Blend Type" is used in the data analysis to differentiate the various base blends, types of oxygenates, and blending method (matched RVP vs. splash). The descriptor Base indicates that the fuel is a base blend made according to the test plan specifications: the original blending stocks (except for butane) were used, the percent oxygen is zero, and the RVP is 7.7 psi for Summer Base and 9.7 psi for Winter Base. The descriptors MTBE, ETBE, and EtOH indicate the type of oxygenate used in the fuel. The weight percent oxygen is 2.0% for summer blends and 2.7% for winter blends. The descriptor EtOH/SB indicates that the fuel was splash-blended using ethanol which means that the fuel was prepared by first adjusting the respective hydrocarbon stock with butane to the proper RVP (7.7 psi for Summer Stock and 9.7 psi for Winter Stock) and then adding the requisite amount of EtOH. Thus, the final RVPs of the EtOH/SB fuels are not controlled to the summer and winter specifications of the other fuels (i.e., the matched RVP blending method).

Difficulties associated with the blending of the winter base fuels were discussed earlier in the report. As a consequence of the resolution of these blending difficulties, the set of winter test fuels have three different non-oxygenated base fuels: N, X, and Y. Fuels N and X have identical hydrocarbon blending stocks with the only difference being the butane levels and, consequently, the RVPs. As indicated in Table 5-3, the 50°F matrix is the only one for which the base fuel used did not strictly match the original experimental plan. Fuel X (called Low RVP Winter Base in Table 5-3) lacked sufficient butane to achieve the planned RVP (9.1 psi instead of 9.7 psi) and Fuel Y (called New Stock Winter Base in Table 5-3) had the planned RVP but did not match identically the hydrocarbon content of the other winter fuels.

3. Carter Reactivity Factors for Speciations. For a subset of the vehicles, the exhaust and evaporative hydrocarbon emissions were speciated. The list of compounds for which volatile organic compounds (VOCs) were quantified are shown in Table 5-4. The speciation results will be used to determine the effects of the test parameters on emission levels of toxic compounds and on the estimated photochemical reactivity of the hydrocarbons which are emitted.

There are 144 species which are in the database. Each specie corresponds to a peak in the gas chromatograph trace or the analysis result by another method. Since some compounds eluted on the gas chromatograph in the same peak, some peaks contain more than one compound, as is shown in Table 5-4. In addition, some peaks were not able to be identified, and these peak names are labeled Unknown.

Carter reactivity factors are assigned to each of the 144 species, so that an overall estimate of photochemical reactivity can be made for each test. Table 5-4 shows the Maximum Incremental Reactivity (MIR) values which have been assigned to each of the specie. These are based on Carter reactivity factors as of September 1992, which were provided to ATL by the California ARB. The MIR is an estimate of the grams of ozone produced for each gram of Volatile Organic Compound (VOC) which is emitted into the atmosphere. The table also shows the compound or category which was used to assign the Carter reactivity factor to the species in the database. In many cases, the compound matches the species name. However, in other cases, a generic compound category (for example, C6 terminal alkene) is necessary to estimate the MIR.

The estimated photochemical reactivity for a given test is obtained by multiplying the emissions and the MIR for each specie for the test and then summing all of these products for the test.

Table 5-4. Speciated Compounds and Their Carter Reactivity Factors

Analyte Number	Analyte Name in Database	Carter Factors (SEP 92)	
		Compound or Category	Maximum Incremental Reactivity (g O3/g VOC)
1	Methane	methane	0.0148
2	Ethylene	ethene	7.29
3	Acetylene (Ethyne)	acetylene	0.50
4	Ethane	ethane	0.25
5	Propene	propene	9.40
6	Propane	propane	0.48
7	Allene (Propadiene)		7.29
8	Propyne	propyne	4.10
9	2-Methylpropane	isobutane	1.21
10	2-Methylpropene	isobutene	5.31
11	1-Butene	1-butene	8.91
12	1,3-Butadiene	1,3-butadiene	10.89
13	n-Butane	n-butane	1.02
14	t-2-Butene	trans-2-butene	9.94
15	2,2-Dimethylpropane	neopentane	0.37
16	1-Butyne	1-butyne	9.24
17	c-2-Butene	cis-2-butene	9.94
18	3-Methyl-1-butene	3-methyl-1-butene	6.22
19	2-Methylbutane (isopentane)	isopentane	1.38
20	2-Butyne		9.24
21	1-Pentene	1-pentene	6.22
22	2-Methyl-1-butene	2-methyl-1-butene	4.90
23	n-Pentane	n-pentane	1.04
24	2-Methyl-1,3-butadiene	2-methyl-1,3-butadiene	9.08
25	t-2-Pentene		8.80
26	3,3-Dimethyl-1-butene	C6 terminal alkenes	4.42
27	c-2-Pentene		8.80
28	2-Methyl-2-butene	2-methyl-2-butene	6.41
29	Unknown #1		8.80
30	Cyclopentadiene		7.66
31	2,2-Dimethylbutane	2,2-dimethyl butane	0.82
32	Cyclopentane	cyclopentane	7.66
33	3- & 4-Methyl-1-Pentenes	C6 terminal alkenes	4.42
34	Cyclopentane	cyclopentane	2.38
35	MTBE	methyl t-butyl ether	0.62
36	2,3-Dimethylbutane	2,3-dimethyl butane	1.07
37	Unknown #2		4.42
38	2-Methylpentane	2-methyl pentane	1.53
39	4-Methyl-t-2-pentene	C6 internal alkenes	6.69
40	3-Methylpentane	3-methylpentane	1.52
41	2-Methyl-1-pentene & 1-Hexene	C6 terminal alkenes	4.42
42	n-Hexane	n-hexane	0.98
43	t-3-Hexene	C6 internal alkenes	6.69
44	t-2-Hexene	C6 internal alkenes	6.69
45	3-Methyl-t-2-pentene	C6 internal alkenes	6.69
46	2-Methyl-2-pentene	C6 internal alkenes	6.69
47	3-Methylcyclopentene		5.67
48	c-2-Hexene	C6 internal alkenes	6.69

Table 5-4. Speciated Compounds and Their Carter Reactivity Factors

Analyte Number	Analyte Name in Database	Carter Factors (SEP 92)	
		Compound or Category	Maximum Incremental Reactivity (g O3/g VOC)
49	ETBE	ethyl t-butyl ether	1.98
50	3-Methyl-c-2-pentene	C6 internal alkenes	6.69
51	2,2-Dimethylpentane	Branched C7 alkanes	1.40
52	Methylcyclopentane	methylcyclopentane	2.82
53	2,4-Dimethylpentane	2,4-dimethyl pentane	1.78
54	2,2,3-Trimethylbutane	Branched C7 alkanes	1.32
55	1-Methylcyclopentene	.	5.67
56	Benzene	benzene	0.42
57	3-Me-1-Hexene & 3,3-DiMePentane	C7 terminal alkenes	3.48
58	Cyclohexane	cyclohexane	1.28
59	2-Methylhexane	Branched C7 alkanes	1.08
60	2,3-Dimethylpentane	2,3-dimethyl pentane	1.51
61	Cyclohexene & 3-Methylhexane	cyclohexene	5.67
62	c-1,3-Dimethylcyclopentane	C7 cycloalkanes	1.85
63	t-1,2-Dimethylcyclopentane	C7 cycloalkanes	1.85
64	2,2,4-TriMePentane (IsoOctane)	isooctane	0.93
65	t-2 & t-3-Heptenes	C7 internal alkenes	5.53
66	n-Heptane	n-heptane	0.81
67	? Unsaturated C7's	.	5.53
68	c-2-Heptene	C7 internal alkenes	5.53
69	MeCyHexane & 2,2-DiMeHexane	methylcyclohexane	1.85
70	2,4,4-Trimethyl-2-Pentene	C8 internal alkenes	5.29
71	2,5-DiMeHexane & EtCyPentane	2,5-dimethylhexane	1.63
72	2,4-Dimethylhexane	Branched C8 alkanes	1.50
73	3,3-DiMeHexane	Branched C8 alkanes	1.50
74	2,3,3 & 2,3,4-Trimethylpentanes	Branched C8 alkanes	1.50
75	Toluene	toluene	2.73
76	2,3-DiMeHexane & 2,3-MeEtPentane	Branched C8 alkanes	1.20
77	2-Methylheptane	Branched C8 alkanes	0.96
78	1-MeCyHexene & 4-MeHeptane	.	
79	3-Methylheptane	Branched C8 alkanes	0.99
80	C8's (Di & TriMeCyclic C5 & C6)	C8 cycloalkanes	1.94
81	2,2,5-Trimethylhexane	Branched C9 alkanes	0.97
82	1,1-Dimethylcyclohexane	C8 cycloalkanes	1.94
83	t-4-Octene	C8 internal alkenes	5.29
84	n-Octane	n-octane	0.61
85	t-1,3-Dimethylcyclohexane	C8 cycloalkanes	1.94
86	2,4-Dimethylheptane	Branched C9 alkanes	1.34
87	c-1,2-Dimethylcyclohexane	C8 cycloalkanes	1.94
88	3,5-Dimethylheptane	Branched C9 alkanes	1.14
89	Ethylbenzene	ethyl benzene	2.70
90	2-MeOctane & 2,3-DiMeHeptane	Branched C9 alkanes	1.14
91	meta- & para-Xylenes	m-xylene+p-xylene	7.38
92	4-Methyloctane	Branched C9 alkanes	1.14
93	3-Methyloctane	Branched C9 alkanes	1.14
94	Styrene	styrene	2.22
95	ortho-Xylene	o-xylene	6.46
96	Unknown #3	.	4.58

Table 5-4. Speciated Compounds and Their Carter Reactivity Factors

Analyte Number	Analyte Name in Database	Carter Factors (SEP 92)	
		Compound or Category	Maximum Incremental Reactivity (g O3/g VOC)
97	n-Nonane	n-nonane	0.54
98	Unknown #4	.	4.58
99	Isopropylbenzene (Cumene)	isopropyl benzene	2.24
100	2,2-Dimethyloctane	Branched C10 alkanes	1.01
101	?ABranched C10's		2.30
102	2,4-Dimethyloctane	Branched C10 alkanes	1.01
103	n-Propylbenzene	n-propyl benzene	2.12
104	1-Methyl-3-Ethylbenzene	C9 dialkyl benzenes	7.20
105	1-Methyl-4-Ethylbenzene	C9 dialkyl benzenes	7.20
106	1,3,5-Trimethylbenzene	1,3,5-trimethyl benzene	10.12
107	?BBranched C10's		7.20
108	1-Ethyl-2-Methylbenzene	C9 dialkyl benzenes	7.20
109	3-Methylnonane	Branched C10 alkanes	1.01
110	1,2,4-Trimethylbenzene	1,2,4-trimethyl benzene	8.83
111	n-Decane	n-decane	0.47
112	Iso-Butylbenzene	C10 monoalkyl benzenes	1.87
113	1,2,3-Trimethylbenzene	1,2,3-trimethyl benzene	8.85
114	Indan	indan	1.06
115	1,3-Diethylbenzene	C10 dialkyl benzenes	6.45
116	1-Methyl-3-Propylbenzene	C10 dialkyl benzenes	6.45
117	1,4-Diethylbenzene	C10 dialkyl benzenes	6.45
118	1,2-Diethylbenzene	C10 dialkyl benzenes	6.45
119	1-Methyl-2-Propylbenzene	C10 dialkyl benzenes	6.45
120	1,4-Dimethyl-2-Ethylbenzene	C10 trialkyl benzenes	9.07
121	1,3-Dimethyl-4-Ethylbenzene	C10 trialkyl benzenes	9.07
122	1,2-Dimethyl-4-Ethylbenzene	C10 trialkyl benzenes	9.07
123	1,3-Dimethyl-2-Ethylbenzene	C10 trialkyl benzenes	9.07
124	n-Undecane	n-undecane	0.42
125	1-Methyl-4-Isobutylbenzene	C11 dialkyl benzenes	5.84
126	1,2,4,5-Tetramethylbenzene	C10 tetraalkyl benzenes	9.07
127	1,2,3,5-Tetramethylbenzene	C10 tetraalkyl benzenes	9.07
128	Methylindan	.	1.06
129	1,2,3,4-Tetramethylbenzene	C10 tetraalkyl benzenes	9.07
130	1-Dodecene	C12 terminal alkenes	1.52
131	Naphthalene	Naphthalene	1.18
132	n-Dodecane	n-dodecane	0.38
133	Other	.	
134	Formaldehyde	formaldehyde	7.15
135	Acetaldehyde	acetaldehyde	5.52
136	Acrolein	acrolein	6.77
137	Acetone	acetone	0.56
138	Propionaldehyde	C3 aldehydes	6.53
139	Crotonaldehyde	crotonaldehyde	5.42
140	Methylethylketone	C4 ketones	1.18
141	Benzaldehyde	benzaldehyde	-0.55
142	Toluialdehyde		-0.56
143	Methanol	methanol	0.56
144	Ethanol	ethanol	1.34

This produces a total grams of ozone per mile for exhaust emissions and total grams of ozone for evaporative emissions.

4. Preparation of Data for Analysis. The results of total emissions and speciated emissions testing were calculated by ATL and entered onto Lotus worksheets in an agreed-upon format. A column format was used to provide easy entry of the spreadsheets into SAS data files. The spreadsheets were sent to Radian Corporation via floppy disk and entered onto the workstation hard disk for data analysis.

Once the entire data set was set up in the SAS files, several techniques were used to quality check the database and search for possible errors. When these suspect values were identified, Automotive Testing Laboratory personnel investigated each value for confirmation or correction. Several techniques were used to check the values of entries in the database.

First, the four file merging parameters, VEHID, TEMP, FUELID, and TESTDATE, were checked against each other in the files to make sure that there were no extra or missing test conditions. As a part of this check, the number and spelling of the compound names in the EXH-SPEC and EVAPSPEC speciation files were checked against each other to ensure that no species names were extra or missing.

The next level of checking involved graphical checks of the measured values. Plots of each emission type were made against VEHID, CYCLE, TEMP, BLENDTYP, SEASON, and emissions control technology. For the exhaust emissions test results and the evaporative emissions test results, plots of the total HC emissions, as measured by FID, were compared for each test condition with the sum of the speciated emissions for each compound as measured by the gas chromatography. Also, the total exhaust emissions measurements were plotted against each other (HC versus CO versus NO_x) and the total evaporative emissions measurement for each test condition were plotted against each other (diurnal versus hot-soak versus running loss).

Finally, during the statistical analysis portion of the data analysis, outliers as a result of regressions were designated as suspect and investigated. More detail of the methods used for identifying outliers by regression will be presented in Section C. It should be noted that, since no statistical analysis was performed on the CO₂ values or the miles per gallon values, these values have not undergone this last stage of data checking.

B. GENERAL ANALYSIS APPROACH

The analysis of experimental data can be approached in many different ways, and the approach used is usually different for every investigator. With sufficient data available, many of the different approaches implemented by different investigators should yield similar conclusions. For the data considered in this study, the analysis approach was designed to attempt to classify test parameter emissions effects as large or small effects. Independent of the size of the effects, some can be expected to be well-known; others may be new discoveries. Therefore, it can be viewed as a comprehensive screening study. The analysis of a database of this size can be expected to continue by others for some time.

The analysis presented in this study is statistical and is based on the measurement of the size of effects by regression of the data. Because most of the parameters in the study are categorical,

rather than continuous, class regression is the statistical technique which was used. In this section, the analysis approach is discussed in general terms. The section provides a background for the detailed analysis and results which are presented in the last half of the report.

Because the analysis depends on the data which is available, the first subsection describes some of the features of the database which are important to any analysis method. Then, class regression is described in some detail. A key theme of this subsection is that class regression is similar to taking averages of data values, but it is more powerful because it keeps track of uncertainty and handles missing values and duplicate values in an appropriate manner. In the next section, the levels for each of the parameters in the database are described. Because the results will be presented in terms of these levels, it is important to understand the meaning of moving between different parameter levels. Finally, the multiple-step data analysis process is described in a general way. This process for each emissions type starts with the raw data and ends with plots and tables which describe how different test variables affect emissions. Later, in Section C, the multiple-step process is presented in greater detail by working through the analysis of exhaust NO_x data as an example.

1. Database Attributes. The objective of the project was to investigate the emissions behavior of a relatively small number of test vehicles for several, rather than a few, different parameters. The database contains a great deal of data on the behavior of these vehicles under different test conditions. Analysis of this data describes the emissions trends for these vehicles. The uncertainty (error bars) associated with a given effect, therefore, applies specifically to the test fleet and not to the vehicle population.

A well balanced data set will mean that the size of the main effects and many of the multiple factor interactions can be determined without ambiguity. The test program was planned with test conditions that covered almost all combinations of the test variables. Measurements were taken at the planned test conditions with little missing data. Such a set of data is therefore relatively well balanced, but not perfectly balanced.

To maximize the amount of information at different test conditions in the database, no true duplicate tests were planned or performed. Some repeat tests were performed when the first test result at a given condition appeared to be out of line with those "near" it. This type of repeat test is not a true measure of variability since the repeated test condition was not chosen randomly, but instead was chosen in a biased manner; in this case they were chosen because the first value was suspicious.

An analysis of variance of a data set without duplicate measurements can rank the effects from most important to least important by each parameter's contribution to the variability of the measured values. But, it was important to estimate the error in the measurements so that the uncertainty in the size of the effects could be estimated. To determine the statistical significance of an effect, the uncertainty in the size of the effect must be known. Usually, the uncertainty in measurements is determined from duplicate measurements. No true duplicate measurements were performed in this study. As a result, the uncertainty in the measurements must be estimated by the lack of fit of regression models. Thus, the use of regression becomes a necessary part of determining the uncertainty assigned to effects measured in the study.

2. Class Regression Concepts. One of the problems of investigating the emissions effects of low oxygenate gasoline blends is that the oxygenate effects are weak compared to the effects of emissions control technology, individual vehicle idiosyncracies, driving cycle, and ambient temperature. For example, in this study, NO_x varies from 0.003 to 8 g/mi as a result of changes in all of the variables, but the expected size of the oxygenate effect on NO_x is only about 10%. To measure the effects of the different oxygenated blends on emissions, the variability produced in the emissions values by all of the larger effects must be accounted for. Thus, the approach taken for the statistical analysis of the data is to model the effects that produce large changes in emissions, so that the relatively small effect of the oxygenate can be "seen" and estimated.

In this study, as shall be shown later, almost all of the parameters of interest are categorical in nature. One approach would be to use averages of the measured values at each different level of a parameter. An example of this would be to compare the average NO_x for the FTP cycle with the average NO_x for HFET cycle. This approach is valid; however, when the number of variables and their levels become large, as in this study, the number of averages which can be considered becomes very large. The alternative approach is to use class regression, which preserves the advantages of simple averaging but contains additional benefits.

Class regression is a regression technique that measures the average effect of categorical (or class) variables. The technique provides the same results as would be obtained by taking averages for perfectly balanced data sets. There are several additional reasons for using class regression over averaging methods. Class regression:

- Estimates the statistical significance of effects
- Helps identify outliers
- Handles unbalanced data sets appropriately
- Assists in selecting the appropriate transformation
- Accounts for variability, that is, it is an analysis of variance
- Quickly ranks the size of parameter effects
- Evaluates interactions between parameters

Class regression works similarly to the more familiar continuous regression by adjusting the fitting parameters subject to the constraint that the sum of the square of the differences between the measured and fitted values is a minimum. For each class parameter in the regression, the regression estimates a separate value for each level of that parameter. The solution of the regression provides a matrix of values for each parameter, and each element of a matrix corresponds to a particular level of the parameter. Comparison of the values for the matrix elements of each parameter then describes the effect of the change in levels on emissions.

As the number of variables in a data set increases, the possible model statements grow in number and complexity. The analyst must use his knowledge of the system under investigation and his curiosity to thoroughly examine the trends in the data in an unbiased manner. For example, if the fuel economy (MPG) of two vehicles (VEHID) was tested at two driving cycles (CYCLE) and at two ambient temperatures (TEMP), the chosen model statement might be:

$$\text{MPG} = \text{VEHID} * \text{CYCLE} \text{ TEMP}$$

This model statement has two terms: an interaction between vehicle and cycle, and a temperature term. The interaction term¹ indicates that the analyst is testing to see if the effect of cycle on fuel economy might be different for the two vehicles. The temperature term indicates that the analyst is testing the size of the temperature effect with the assumption that the effect of temperature is the same for both vehicles and for both driving cycles.

For this example, the solution to the regression might be:

$$\begin{matrix} & \text{FTP} & \text{NYCC} \\ \text{A} & \left(\begin{matrix} 19 \pm 2.6 \\ 7 \pm 2.6 \end{matrix} \right) & \\ \text{B} & \left(\begin{matrix} 41 \pm 2.6 \\ 11.7 \pm 4.2 \end{matrix} \right) & \end{matrix} + \begin{matrix} \text{TEMP} \\ 75 \left(\begin{matrix} 0.3 \pm 2.6 \\ -0.3 \pm 2.6 \end{matrix} \right) \\ 95 \end{matrix}$$

The first matrix shows the effects of vehicle and cycle. It is a 2 x 2 matrix because there were two vehicles and two driving cycles. For vehicle A, moving from FTP to NYCC caused the MPG to drop by 8, while for vehicle B the drop was 29.3, a significant difference. This is an example of an interaction. The second matrix, which is for temperature, is a 1 x 2 matrix since temperature was tested at two levels: 75 and 95°F. The temperature effect between 75 and 95°F was 0.6 and was not a significant difference. Note that the solution matrices can be used to predict MPG. For example, the predicted MPG for vehicle A driving an NYCC at 95°F would be 6.7 mile/gallon (7 + (-0.3)).

3. *Regression Parameters and Levels.* The regression parameters and their levels are shown in Table 5-5. These parameters were used to design the test program, as well as to analyze the results.

a. Vehicle Descriptors and their Levels--VEHID is a class descriptor of the individual test vehicle for which results are presented; VEHID has 13 levels with the level names 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13. The names correspond to the vehicles shown in Table 5-2. To further describe the vehicles, the technology description parameters for the vehicles are given beneath VEHID in Table 5-5. These are for exhaust emissions technology (EMSTECH) with four levels, fuel induction system type (FUELSYS) with three levels, canister bottom design (CNSTR) with two levels, and engine displacement (DISP) which is a continuous parameter. Each of the levels for the technology descriptors may contain more than one individual vehicle.

In the analysis presented in this study, the behavior of individual vehicles is determined first. Then, to increase the confidence that trends seen in one vehicle may actually apply more generally to a technology group, the next step of each analysis is to see which technology descriptor can best be used to describe the observed trends.

¹ Note that in the model statement given above, the main effects for vehicle and cycle are implicitly included in the VEHID * CYCLE term. This is true for class regressions and not true for continuous regressions. In other words, the VEHID * CYCLE term is equivalent to VEHID + CYCLE + VEHID * CYCLE. Both methods of expressing the main effects and interactions use four degrees of freedom, and the fit to the data and all statistics describing the fit are the same.

Table 5-5
Parameter Levels

VEHID	(class): 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13 EMSTECH (class): Noncatalyst Oxycatalyst 3way NonAdaptive 3way Adaptive FUELSYS (class): Carburetted Throttle Body Multipoint CNSTR (class): Open Bottom Closed Bottom DISP (continuous): Liters
CYCLE	(class): FTP HFET NYCC Bag1 Bag2 Bag3
BLENDTYP	(class): LoRVPBase HiRVPBase MTBE ETBE EtOH EtOH/SB
SEASON	(class): Summer Winter
TEMP	(class): 50 75 95

b. Driving Cycle Levels--The three driving cycles tested in this program were the FTP, HFET, and NYCC. However, because in most cases the detailed results of the three bags of the FTP were available, we added Bags 1, 2, and 3 of the FTP to the cycle list so that additional information about the influence of different driving patterns on emissions could be determined.

c. Fuel Descriptors--Table 5-3 shows a summary of the 14 test fuels. At the bottom of the table, the characteristics of the two reference fuels, FUELIDs A and E, are shown. These fuels were used to characterize the performance of the vehicles using an industry average and an Indolene® fuel. The remaining 12 fuels were used to characterize the bulk of the emissions performance of the test vehicles. The manner in which these fuels are described determines the conclusions that are reached in the regression analysis of the data. The fuels can be described in different ways. Each way will result in a different view of trends in the emissions of the vehicles. We show below two ways to describe the fuels and selected one method to be used throughout the remainder of the report. Other data analysts may choose other equally acceptable ways to describe the fuels.

The first and perhaps the simplest method of describing the fuels is to use only the FUELID variable. For the 12 fuels, FUELID each had a code, and the levels are given the names of the fuels: M, O, Q, S, U, N, X, Y, P, R, T, and V. A class regression performed on the data will determine 12 values which fit the data best. The solution matrix for VEHIID would have 12 elements--one for each of the 12 levels of VEHIID--as shown below. Note that the regression will actually determine n-1 or 11 independent matrix values since the effect of fuel is described by the regression as emission differences among the fuels.

FUELID	
M	-
O	-
Q	-
S	-
U	-
N	-
X	-
Y	-
P	-
R	-
T	-
V	0

This fuel description method does not recognize known relationships among the fuels. For example, it does not indicate that the oxygen contents of M, N, X, and Y are all 0.0% oxygen, and it does not indicate that the RVPs of M, O, Q, and S all are 7.7 psi, and it does not indicate that O and P both contain MTBE. This method of fuel description makes no assumptions about relationships among the fuels; as far as the analysis of the effects of the fuels go, they might as well have had totally unrelated compositions and properties. Even so, using such a description of the fuels is legitimate and has the advantage that no assumptions in fuel description are necessary. The disadvantages are that the uncertainties for each of the solution matrix values is larger than they would be if our knowledge about relationships among the fuels would be used.

For the purposes of the analysis in this report, we chose to use our knowledge of the fuel properties to describe the fuel set in a different way. The impetus for doing this was that to be able to detect the small effect of the oxygenates in the large emissions effects produced by technology, vehicle, cycle, and temperature, we saw a need to maximize the number of degrees of freedom assigned to error as much as possible. We did this by minimizing the number of fuel values to be determined by the regression. In addition, ARB had a desire to estimate the separate effects of oxygenate and volatility on emissions. Therefore, the following description of the fuel set was used.

Each fuel in the set can be described by a combination of Blend Type (BLENDTYP), Oxygen Content (OXY), and Blend Season (SEASON). As shown in Table 5-3, Blend Type has 5 class levels: ETBE, EtOH, EtOH/SB, MTBE, and Base. (Note that we are assuming here that the different Blend Types for the winter fuels will be shown to be not significantly different or differing bases will be dropped from the regression following a separate analysis.) Oxygen Content is a continuous variable and has values of 0.0, 2.0, and 2.7% oxygen. Finally, Blend Season has two class levels of Summer and Winter. For the purposes of the analysis shown in this report, each fuel was described with the following relationship which uses 5 independent regression values:

$$\begin{array}{l}
 \text{BLENDTYP} \cdot \text{OXY} + \text{SEASON} \\
 \begin{array}{l}
 \text{ETBE} \\
 \text{EtOH} \\
 \text{EtOH/SB} \\
 \text{MTBE} \\
 \text{Base}
 \end{array}
 \begin{pmatrix}
 - \\
 - \\
 - \\
 - \\
 0
 \end{pmatrix}
 \cdot \text{OXY} + \begin{array}{l}
 \text{Summer} \\
 \text{Winter}
 \end{array}
 \begin{pmatrix}
 - \\
 0
 \end{pmatrix}
 \end{array}$$

Certain assumptions are made with this fuel set description. The first term of the description (BLENDTYP * OXY) makes the assumption that for a given type of oxygenate, the emissions response is proportional to the oxygenate concentration. Since the fuels in the database containing oxygenates have oxygen contents of only either 2.0 or 2.7%, this assumption really is made only between those two concentrations. Even so, because of the regulatory implications of using 2.0% versus 2.7% oxygen fuels, some are uncomfortable with this assumption of proportionality.

It should be noted that this assumption does not mean that no emissions response curvature as a function of oxygen content exists; it means that we judged the advantages of assuming a proportional response over this narrow range of oxygen content to outweigh the disadvantages for the purposes of the analysis of this small test vehicle fleet. The advantage is that the degrees of freedom for error is increased, and this results in a reduction in the size of the uncertainty for the calculated effect values. This advantage will mean that we will be more likely to see small, but significant BLENDTYP effects. The disadvantage is that the response of some emissions types for some vehicle technologies may be stronger or weaker than a proportional response between these two oxygen concentrations.

The different values for the levels of BLENDTYP are coefficients of the oxygen content of the fuel (OXY) and give the emissions effect per percent oxygen caused by the level of BLENDTYP. It is important to note that for ETBE, EtOH, MTBE, and Base, the BLENDTYP levels indicate matched RVP blending methods, but for EtOH/SB the splash blending method was used.

Thus, when the values calculated for the different levels of BLENDTYP are examined, the effect of BLENDTYP actually contains the net combined effect of the oxygenate compound and the effect of a higher RVP (about 0.9 psi higher) for EtOH/SB relative to the RVPs of the other blends.

The two levels of SEASON provide the effect caused by changes between the summer and winter blends. This provides the combined effect of change of RVP and change of blending components. Moving from Summer to Winter blends causes an increase in RVP of about 2 psi and a change from the Original Summer Blending Stock to the Original Winter Blending Stock. These two effects can not be separated from each other with this data. Note that this Blend Season structure assumes that the effect of New Winter Blending Stock will be shown to be not significantly different from Original Winter Blending Stock in a separate analysis. If these stocks are found to have different effects on emissions, then data from the New Stock will be dropped from regressions.

d. Temperature Descriptors--Table 5-3 shows the three levels of ambient temperature that were used in this study. The summer fuels were tested at only 75° and 95°F, and the winter fuels were tested at only 50° and 75°F. To avoid making any assumptions about the functional relationships of emissions on ambient temperature, we chose to make ambient temperature a class variable with three levels.

4. *Decision Process.* The process used to arrive at a good regression model for each of the emissions types in the data set has been arrived at in an eight-step process. In general, the process involves examining all of the data in a single regression initially, and then using the results of preliminary regressions to determine the best way to group individual vehicles by a technology category for generalization in the final regressions. In almost all cases in this project, class regression using the GLM (General Linear Model) procedure in SAS was used. This procedure is similar to an analysis of variance, except that the GLM procedure can handle missing values and unbalanced data sets, such as the data set under consideration here.

The analysis approach can be described as having eight steps. Each of these steps is described in general here. Then, in the next section, a specific example will be given to demonstrate the procedures in detail.

a. Regress Data Against Main Effects Only--The first step for each investigation of an emission type was the regression of all emissions values for all test conditions against all of the design parameters. This provides a first look at the relative size of effects of parameters on emissions. The results of this regression indicated which parameters had the largest effect on the emissions under consideration and provided some guidance to the interactions between parameters which should be considered.

b. Create a Preliminary Model With Interactions--Several regressions were then performed to determine which two-factor interactions had large effects on the emissions. This preliminary model needed to explain a large part of the variability in the emissions so that the appropriate transformation could be selected. In general, the interactions of parameters that have strong main effects will also have strong effects. Interactions between parameters that are weak will also be weak.

c. Determine Appropriate Transformation--Once this preliminary model was found, the residuals of the fit to the regression were considered to determine the best transformation of the emission values for future regressions. Transformations are used to make the error in the measured emissions value about the same size over the range of measurements. In this study, where the measured values range over orders of magnitude, the natural log transformation would commonly be used. The log transformation was used to develop the preliminary models in Steps 1 and 2 for this reason. However, in this step, we investigated several transformations for each emission type to determine which was best for this data set. The use of an appropriate transformation is important because the use of any statistical methods (even simple averaging techniques) assumes that errors are normally distributed. Failure to choose an appropriate transformation could result in erroneous conclusions.

d. Consider Outlier Data Points--Data points that had particularly large residuals in the best transformation regression were examined. ATL was notified of these points to determine if there had been an inadvertent error in work-up of the emission values, for example. To avoid increasing the regression's estimate of measurement error, data values that were confirmed and continued to have large residuals were left out of further regressions. It should be noted that only a few points for each regression were left out, and that including them or removing them actually had a small effect on regression results. Thus, emissions values, that were procedurally acceptable but appeared to be out of line with other associated emissions values, were retained in the database, but were not used in the regressions.

e. Evaluate Winter Base Fuels (Exhaust Only)--Because of the fuel blending difficulties with the winter base fuels, a special analysis was performed to determine if there was a significant difference between the emissions responses of Fuels N, X, and Y. These fuels had different RVPs and/or blending stocks. This special analysis was only performed on exhaust emissions because no evaporative emissions testing was performed on the non-planned fuels X and Y since these fuels were tested at only 50°F. A regression analysis was used. The basic concept that was used was that if no consistent difference could be shown, then the difference in emissions response of these base fuels was probably not significant. This does not mean that real differences did not exist, it just means that the differences were too small to be detected with this data set.

f. Find a Satisfactory Individual Vehicle Model--Next, additional regressions were performed to investigate the weaker parameters and weaker interactions and their effects on the emissions. The result of this stage of the regression analysis provided a regression model which described the emissions behavior of individual vehicles. Technology groupings were not yet used in the model.

g. Test and Select Technology Groupings--The response of different vehicles to the blend types were then compared to determine the technological feature of the vehicles which could serve as a vehicle grouping parameter. Regression techniques were used to select the appropriate technological grouping parameter. At this point, the regression was rerun with the replacement of VEHD in the regression with alternative technology parameters, FUELSYS, EMSTECH, CNSTR, and DISP, to determine which provided the best fit of the data. It should be noted, however, that VEHD still remained in the model statement of this simplified model because, even within a technology grouping, vehicle to vehicle differences are large and need to be accounted for to provide good estimates of the uncertainty in the other parameters in the model.

h. Describe Effect of Parameters on Emissions--Various graphical and tabular techniques were used to communicate the size and statistical significance of the results for the different study parameters for each emission type.

C. SPECIFIC ANALYSIS EXAMPLE FOR NO_x

In this subsection, the detailed methodology that was used to analyze exhaust NO_x emissions will be presented as an example of the techniques used for all emission types. NO_x was selected for this example because of the current interest in NO_x emissions and its analysis demonstrates all of the features that were used throughout the study. The results of the other emissions types are presented later in Section 5, without all of the details that are shown for this NO_x analysis.

1. *Regress Data Against Main Effects Only.* The data set that was analyzed for NO_x contained 1751 observations. The parameters which were considered for NO_x were vehicle (VEHID), driving cycle (CYCLE), ambient temperature (TEMP), blend type (BLENDTYP), and blend season (SEASON). For the data set, the NO_x values range from 0.003 g/mi to 8.0 g/mi. For such a large range of values, the initial transformation of the values that is used first is the natural log transformation. Therefore, the natural log of NO_x was regressed against the main effects of the test parameters. The SAS notation for this regression is:

$$\ln\text{NO}_x = \text{VEHID CYCLE TEMP BLENDTYP SEASON}$$

Each of these parameter names represents a matrix of values with each value corresponding to a level of the parameter. For example, CYCLE is a matrix with six elements; each element corresponds to one of the six cycles tested: FTP, HFET, NYCC, Bag1, Bag2, and Bag3. The class regression adjusts the values of all of the elements of the five matrices to best fit the natural log of the measured NO_x values. The statistics that describe this regression are given in Table 5-6 as Model 1.

The table shows that for Model 1, the r^2 for the regression was 0.856, the model used 27 coefficients to describe the data. VEHID, CYCLE, TEMP, and BLENDTYP had significant effects on $\ln\text{NO}_x$, but SEASON was not significant. From Model 1 it can be seen that the main effects had the following order of importance to $\ln\text{NO}_x$:

$$\text{VEHID} > \text{CYCLE} \gg \text{TEMP} > \text{BLENDTYP} > \text{SEASON}$$

The criteria used to judge a regression as a good fit of the data were a model r^2 of at least 0.95, a model F value as large as possible, and the significance of individual terms in the model of at least 95%. The 95% confidence level has been used throughout this report since that value is usually generally accepted in the statistical analysis of data. Other levels of statistical significance can legitimately be used; however, getting acceptance of other levels by other scientists reviewing the results can be problematic. If the r^2 criteria could not be met without adding numerous interaction terms to the model statement, an r^2 of less than 0.95 was accepted.

2. *Create a Preliminary Model With Interactions* Next, improvements to the main effect model, Model 1, were made by adding the interaction between VEHID*CYCLE to create Model 2. As shown in Table 5-6, this model had a much better r^2 than Model 1, but also added 60 more coefficients. VEHID*BLENDTYP was added to Model 2 to create Model 3. This interaction

Table 5-6
Summary of Search Phase for Log (NO_x) Regressions
on 1751 NO_x Observations

	F	r2	Significance	Number of Coefficients
Model 1	402	0.856	99.99	27
VEHID	721		99.99	
CYCLE	302		99.99	
TEMP	7.9		99.99	
BLENDTYP	5.5		99.97	
SEASON	0.3		39	
Model 2	331	0.942	99.99	87
VEHID	1745		99.99	
CYCLE	732		99.99	
VEHID*CYCLE	42		99.99	
TEMP	20		99.99	
BLENDTYP	12.9		99.99	
SEASON	0.5		54	
Model 3	191	0.948	99.99	159
VEHID	1832		99.99	
CYCLE	766		99.99	
VEHID*CYCLE	44		99.99	
TEMP	21		99.99	
BLENDTYP	13.6		99.99	
VEHID*BLENDTYP	2.2		99.99	
SEASON	0.4		47	
Model 4	160	0.948	99.99	189
VEHID	1824		99.99	
CYCLE	763		99.99	
VEHID*CYCLE	44		99.99	
TEMP	21		99.99	
BLENDTYP	13.5		99.99	
VEHID*BLENDTYP	2.2		99.99	
CYCLE*BLENDTYP	0.8		22	
SEASON	0.4		48	

Table 5-6
(Continued)

	F	r2	Significance	Number of Coefficients
Model 5	192	0.948	99.99	158
VEHID	1834		99.99	
CYCLE	767		99.99	
VEHID*CYCLE	44		99.99	
TEMP	33		99.99	
BLENDTYP	13.6		99.99	
VEHID*BLENDTYP	2.2		99.99	
Model 6	192	0.948	99.99	158
VEHID	1271		99.99	
VEHID*CYCLE	99		99.99	
TEMP	33		99.99	
VEHID*BLENDTYP	3.0		99.99	

was found to significantly improve the model, as shown on Table 5-6, by this term's significance of 99.99%. Next, CYCLE*BLENDTYP was tested for Model 4. This interaction was not found to improve the model significantly, as indicated by its significance of only 22%. Therefore, CYCLE*BLENDTYP was dropped from further consideration. In addition, it was seen for Models 1 to 4 that the parameter SEASON consistently showed no significant effect on $\ln\text{NO}_x$ and, accordingly, it was also dropped from regression. This resulted in Model 5, which used 158 parameters to describe the measured $\ln\text{NO}_x$ with an r^2 of 0.948.

For interactions in class regression, main effects can be collapsed into two-factor interactions which result in a simplified model that has the same model statistics. Thus, Model 5 was collapsed to Model 6 with just four terms. Model 6 describes the data with exactly the same precision as Model 5, but it is easier to write down. Therefore, the best preliminary model we found to describe $\ln\text{NO}_x$ is given by:

$$\ln\text{NO}_x = \text{VEHID} \quad \text{VEHID}*\text{CYCLE} \quad \text{TEMP} \quad \text{VEHID}*\text{BLENDTYP}$$

This preliminary model indicates that NO_x emissions were different for different vehicles and that the response to driving cycles was different for different vehicles. In addition, temperature seemed to have a significant effect and the response of different vehicles to the blend type was significant. One noteworthy missing term was the CYCLE*BLENDTYP interaction. This indicates that the effect of BLENDTYP was independent of the type of driving that was performed. This preliminary model statement will be used to examine transformations for NO_x , to search for outliers, and to serve as a starting point for the development of a final exhaust NO_x model for this data set.

3. Determine Appropriate Transformation. One of the requirements for proper analysis of data is that the variance or error in the data is homogeneous over the range of the observation which is being modeled. For observations which do not have a large range, a regression of the untransformed observation (that is, the linear observation) is usually satisfactory. However, when observations vary over orders of magnitude, regression of the observation in a linear domain may result in a variance which is also changing over the range of the observation values. Failure to consider this so-called homogeneity of the variance may result in misinterpretation of data. Therefore, variance homogeneity must be considered when regressions are performed, and even when simple averages are made.

The appropriate transformation to be used can best be determined by measuring the variance over the range of observations through the use of duplicate measurements. However, as in this data set, when duplicate measurements are not available, the next best method is to examine the residuals of good regressions of the observations when different transformations are used.²

Transformations are commonly made by raising the observations to an exponent. Regression of linear observations corresponds to an exponent of 1, square root to an exponent of 0.5, log corresponds to an exponent of 0 (in the limit), inverse square root corresponds to an exponent of -0.5, and reciprocal corresponds to an exponent of -1. For automotive emissions measured over a

² Weisberg, Sanford. Applied Linear Regression, Second Edition, John Wiley & Sons, 1985, p. 147; Box, G. E. P., W. G. Hunter, and J. S. Hunter. Statistics for Experimenters, John Wiley & Sons, 1978, p. 231.

wide range of conditions, the log of the observation has traditionally been used. However, in this data analysis, for every emissions type which was analyzed, the most appropriate transformation was investigated.

This was done by first developing a relatively good model of the log of the emissions so that large effects were explained. Then, transformations of the measured quantity, in this case NO_x , were evaluated by looking at the residuals of the regression plotted against the measured values. The residuals of a regression are the part of the measured value that is not explained by the regression. If, for a given transformation, the residuals showed a constant spread over the range of the observation values, then that transformation was judged to be acceptable for the data set. If the residuals formed a funnel shaped cluster, then the exponent on the transformation of the emissions values was adjusted.

For this NO_x example, the Model 6 model statement was used to examine transformations. Figure 5-1 shows the residuals versus measured value plot for the log transformation. The figure shows that the spread of residuals is narrower on the right side of the plot where NO_x values are high. This indicates that the log transformation could be improved upon. The next transformation that was attempted was the linear transformation with the model statement:

$$\text{NO}_x = \text{VEHID} \text{ VEHID}*\text{CYCLE} \text{ TEMP} \text{ VEHID}*\text{BLENDTYP}$$

This linear transformation produced the residual plot shown in Figure 5-2. In this plot, the residuals are narrowest on the left side of the plot where NO_x values are low. Incidentally, in this case, the linear transformation has the undesirable property of predicting many negative values for NO_x .

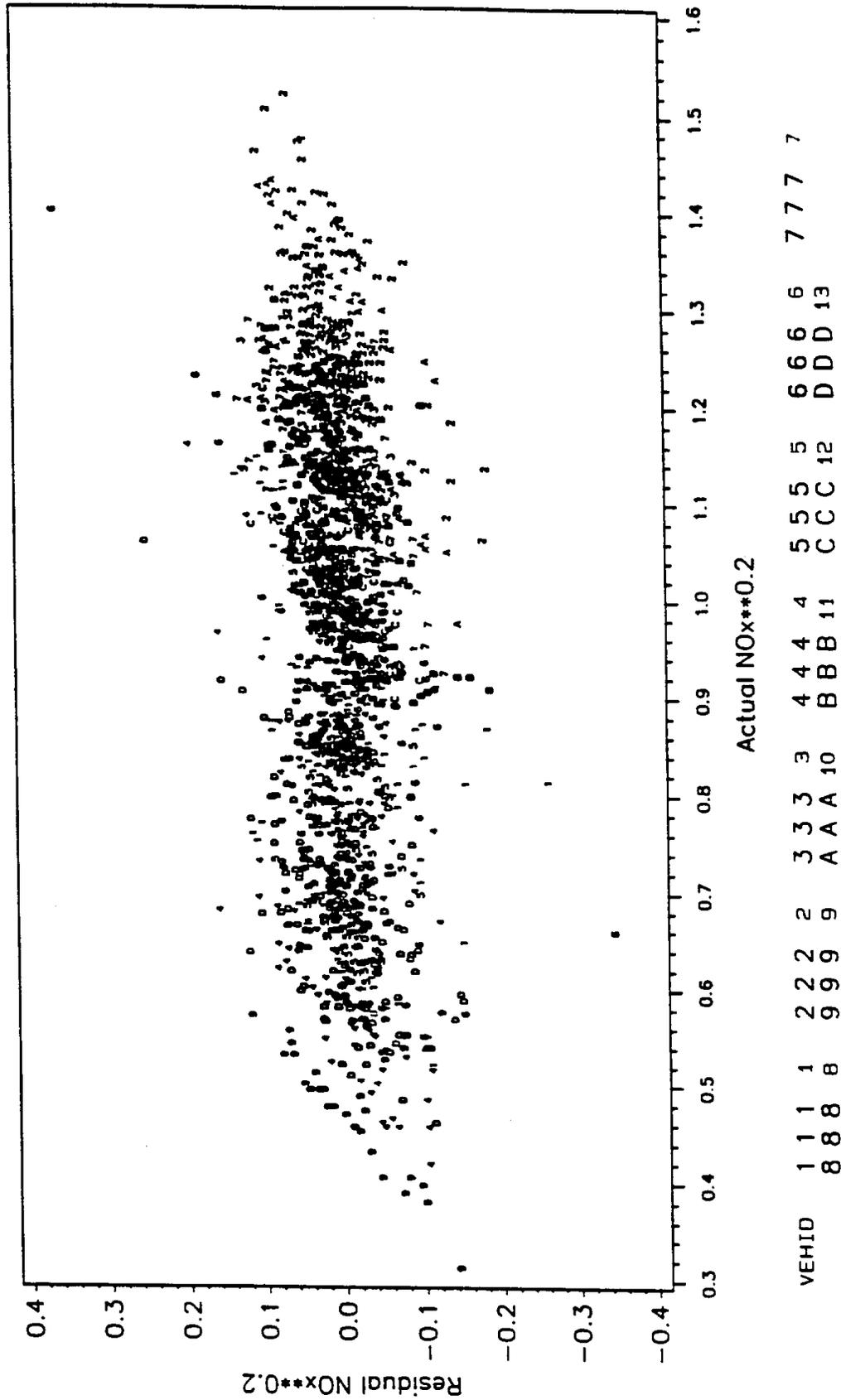
Based on the residual plots with the log and linear transformations, it is clear that a transformation somewhere between the two would provide an optimum residual plot. Through a process of trial and error of trying different transformations, it was found that $\text{NO}_x^{0.2}$ provided a good transformation with homogeneous (that is, constant spread) residuals across the range of measured NO_x values. This residual plot is shown in Figure 5-3. Therefore, the $\text{NO}_x^{0.2}$ was used for all further analysis of exhaust NO_x data.

4. Consider Outlier Data Points. An examination of the residual plot in Figure 5-3 caused us to suspect outliers for three data points with the following vehicle/ $\text{NO}_x^{0.2}$ values: 6, 0.66; 13, 1.06; and 6, 1.4. The measured values of NO_x for these points were reviewed with ATL and no reason was found to believe that they were in error. Since the values could not be corrected, they were dropped from the regression. The data points dropped were: Vehicle 6/75°/Fuel N/NYCC on 18MAR92 = 0.125 g/mi, Vehicle 13/95°/Fuel U/NYCC on 21AUG92 = 1.348 g/mi, and Vehicle 6/95°/Fuel M/NYCC on 5MAY92 = 5.39 g/mi. This left 1748 data points to be analyzed.

5. Evaluate Winter Base Fuels (Exhaust Only). The next step in the analysis of the NO_x data is to determine whether Fuels X and Y are different from Fuel N in their influence on exhaust NO_x emissions. Again, class regression was used as a tool to help determine the significance of these effects. These regressions were performed on the 1748 NO_x observations that were left after the 3 outliers were removed using the $\text{NO}_x^{0.2}$ transformation.

Up to this point, the influence of BLENDTYP on NO_x emissions was present in the regression as a term with a different value for each of the seven levels of BLENDTYP: Base, LowRVP-

Figure 5-3
Total Exhaust NOx Emissions
 Model: NOx**0.2 = vehid*cycle temp blendtyp vehid*blendtyp



Base, NewStockBase, ETBE, EtOH, EtOH/SB, and MTBE. The concentration of the oxygenate was not considered as a major influence, since oxygen concentrations of the bases were all 0.0% oxygen, and oxygen concentration of the oxygenated fuels were either 2.0 and 2.7%. If the NO_x effect produced by an oxygenate at 2.3% oxygen is on the order of 10%, then the error introduced by assuming that 2.7% is 2.3% oxygen would give an effect on emissions of only about 2%. This small effect is inconsequential for preliminary regressions when it is compared with the three orders of magnitude variability in the NO_x emissions data.

However, now, we do want to bring in the effect of oxygen concentration to begin fine tuning the model. The model statement is slightly modified:

$$\text{NO}_x^{0.2} = \text{VEHID} \text{ VEHID}*\text{CYCLE} \text{ TEMP} \text{ VEHID}*\text{BLENDTYP}*\text{OXY}$$

In this statement, the OXY represents the percent of oxygen in the fuel, and has values of 0.0, 2.0, or 2.7 % oxygen. OXY is a continuous variable; therefore, the VEHID*BLENDTYP matrix provides coefficients for the continuous variable OXY to be multiplied by. The coefficients represent the NO_x effect per percent of oxygen in the fuel. The statistics for this regression are shown in Table 5-7 for Model 7. They show that the r² for the regression is 0.950 and that all four terms of the regression have a significant effect on the fit of the data.

To evaluate the emissions effect of oxygenate in the fuel, a comparison of results for an oxygenated fuel are made with the results for the base fuel. Ideally, the fuels that are compared use the same blending stocks and have the same volatility. Examination of Table 5-3 shows where comparisons can be made. For 75°F measurements of the summer blends, the base fuel (Fuel M) and the oxygenated fuels (Fuels O, Q, S and U) have the same blending stock and the same volatility (except for Fuel U which was the splash blended EtOH fuel). The same is true of the 75°F measurements of the winter blends; the base fuel (Fuel N) and the oxygenated fuels (Fuels P, R, T, and V) have the same blending stock and the same volatility. But for the 50°F measurements of the winter blends, Fuel N was not tested at all; the only base fuels tested were Fuels X and Y. Fuel X used the same blending stock as the winter oxygenate blends, but the RVP was too low. Fuel Y had the correct RVP but used a different blending stock than for the oxygenated blends.

Since Fuels X and Y but not N were tested at 50°F, a statistical analysis for each exhaust emission type needs to determine if Fuel X or Fuel Y or both exhibited exhaust emissions behavior significantly different from Fuel N. If Fuel X or Fuel Y differs significantly from Fuel N for a given emission type, then all results from that base fuel should be dropped from the analysis data set of that emission type so those values do not bias the results of the analysis.

To determine if Fuel X or Fuel Y was significantly different from Fuel N, we used regression analysis to model the data set's patterns of emission values as a function of all of the parameters in the study. Another way of explaining this is that regression was used to estimate the emissions that Fuel N would have produced at 50°F (if it had been available for testing) and then it was used to compare the actual measured results of Fuels X and Y with these estimated results from Fuel N. This analysis was done separately for each exhaust emission type (HC, CO, NO_x, ozone, benzene, formaldehyde, acetaldehyde, and 1,3-butadiene).

To evaluate whether Fuels X (LowRVPWinterBase) or Y (NewStockWinterBase) are significantly different from Fuel N (WinterBase), three new class variables are created. The first new class variable is called BLEND1. It has levels of Base, ETBE, EtOH, EtOH/SB, and MTBE. For

Table 5-7

Evaluation of Winter Base Fuels for NO_x^{0.2}

	F	r2	Significance	Number of Coefficients
Model 7	4850	0.950	99.99	132
VEHID	526		99.99	
VEHID*CYCLE	86		99.99	
TEMP	37		99.99	
VEHID*BLENDTYP*OXY	3.2		99.99	
Model 8	4916	0.952	99.99	134
VEHID	538		99.99	
VEHID*CYCLE	89		99.99	
TEMP	42		99.99	
VEHID*BLEND1*OXY	3.1		99.99	
LOWBASE	0.7		60	
NEWBASE	33		99.99	
Model 9	4787	0.952	99.99	132
VEHID	436		99.99	
VEHID*CYCLE	85		99.99	
TEMP	47		99.99	
VEHID*COBLEND*OXY	2.9		99.99	

BLEND1, the Base level is used to name those observations where BLENDTYP was Base, or LowRVPBase, or NewStockBase. All other category names for BLEND1 are the same as those for BLENDTYP. Thus, BLEND1 is the same as BLENDTYP, but makes no distinction between the three different kinds of bases.

The second new variable that is created is called LOWBASE. This class variable has two levels. For any observations that have a BLENDTYP of LowRVPBase, LOWBASE has the value Low. Otherwise, LOWBASE has the value NotLow. The third class variable that was created is called NEWBASE. NEWBASE has two levels. When BLENDTYP is NewStockBase, NEWBASE has the value New. Otherwise, NEWBASE has the value NotNew.

A new regression statement was used that assumed that all three bases were the same by substituting BLEND1 for BLENDTYP:

$$\text{NO}_{x4}^{0.2} = \text{VEHID} \text{ VEHID}*\text{CYCLE} \text{ TEMP} \text{ VEHID}*\text{BLEND1}*\text{OXY}$$

Then, the regression for NO_x was run to determine whether the addition of parameters LOWBASE or NEWBASE to Model 7 significantly improved the regression. The statistical results of this regression are shown in Table 5-7 under Model 8. The results of the regression show that LOWBASE did not have a significant effect on the regression, but NEWBASE did. This means that as far as the data for NO_x are concerned, the Fuel X (LowRVPWinterBase) and Fuel N (WinterBase) were not seen to be significantly different. On the other hand, NEWBASE was found to have a significant effect. This indicates that the Fuel Y (NewStockWinterBase) produced significantly different NO_x emissions from Fuel N.

Accordingly, all NO_x observations for Fuel Y were dropped from the NO_x analysis. A new fuel blend parameter called COBLEND was created to reflect that Low RVP Base blends and Base blends behave the same. COBLEND had levels of Base, MTBE, ETBE, ETOH, and ETOH/SB, where Base included observations where BLENDTYP was Base or LowRVPBase. Thus, the refined model became:

$$\text{NO}_x^{0.2} = \text{VEHID} \text{ VEHID}*\text{CYCLE} \text{ TEMP} \text{ VEHID}*\text{COBLEND}*\text{OXY}$$

The statistics of this Model 9 are given in Table 5-7. This model uses 1664 observations since 84 NO_x observations for Fuel Y (NewStockWinterBase) were dropped.

6. Find a Satisfactory Individual Vehicle Model. With the selection of the appropriate transformation, the removal of three outlier points, and the resolution of the winter base fuel problems, the database and the regression model are ready for final examination to create a model that fits the NO_x emissions of the individual vehicles.

The starting point for this development is Model 9 and has the statistics shown in Table 5-8. This model is the same one that was arrived at after Fuel Y was eliminated from the data set and Fuels N and X were combined in the previous analysis step. Additional terms were added to Model 9 to see if they had a significant effect on the fitting of NO_x emissions for individual vehicles. Model 10 is the result of those efforts. It was found that $\text{VEHID}*\text{TEMP}$ was significant, which indicates that not only was TEMP significant as it was in Model 9, but different responses of different vehicles to TEMP were also significant. In addition, $\text{CYCLE}*\text{TEMP}$ and $\text{TEMP}*\text{COBLEND}$ were found to be significant.

Table 5-8
Evaluation of NO_x^{0.2} Models for Individual Vehicles

	F	r2	Significance	Number of Coefficients
Model 9	4787	0.952	99.99	132
VEHID	436		99.99	
VEHID*CYCLE	85		99.99	
TEMP	47		99.99	
VEHID*COBLEND*OXY	2.9		99.99	
Model 10	4372	0.962	99.99	178
VEHID	538		99.99	
VEHID*CYCLE	40		99.99	
VEHID*TEMP	14		99.99	
VEHID*COBLEND*OXY	2.7		99.99	
CYCLE*TEMP	4.3		99.99	
TEMP*COBLEND	2.4		99.5	

Interpretation of Model 10 is difficult, because of the large number of terms and interactions that are present in the model. As we shall see in the next step of the model development, when vehicle technologies are considered, several of the terms in Model 10 will be dropped. This will simplify the interpretation of the final technology-based model.

7. Test and Select Technology Groupings. The final stage of the NO_x model development involves the consideration of different technology groupings for the vehicles. They are considered because the results of the study need to be somehow generalized from individual vehicles to a more general term of vehicle technology. The four descriptors of vehicle technology that were tested were FUELSYS with levels of carburetted, multipoint, and throttle body; EMSTECH with levels of TWC/AL, TWC/NAL, oxy-catalyst, and non-catalyst; CNSTR with levels of closed-bottom canister and open-bottom canister; and DISP, which is the continuous variable for engine displacement. Each of these four technology parameters was substituted sequentially for VEHID in Model 10. However, VEHID by itself was retained to account for the vehicle-to-vehicle idiosyncrasies which affect emissions within a technology grouping. Table 5-9 shows a comparison of the regression results with these substitutions in Models 11, 12, 13, and 14.

The results of Models 11 through 14 indicate that Models 11 and 12 are superior to Models 13 and 14. Models 11 and 12 use EMSTECH and FUELSYS to describe technology and provide similar results. The reason these two models give similar results is that EMSTECH and FUELSYS are confounded because of the chronological nature of technological progress. We chose to use Model 11 based on EMSTECH for the final workup of the regression, because most of the other emissions types in the study show that EMSTECH had a slight advantage over FUELSYS.

The other observation to note about the regressions in Table 5-9 is that in most cases, the last three terms of the regression, CYCLE*TEMP, TEMP*COBLEND, and SEASON did not provide a significant improvement to the terms above them. Therefore, these last three terms were dropped to produce the final technology-based model for NO_x:

$$\text{NO}_x^{0.2} = \text{VEHID EMSTECH*CYCLE EMSTECH*TEMP} \\ \text{EMSTECH*COBLEND*OXY}$$

The statistics for this model are also given in Table 5-9 as Model 15. Note that the EMSTECH*COBLEND*OXY term is the least important in this regression. The terms for VEHID, CYCLE, and TEMP were more important.

It is notable that at this point CYCLE*COBLEND and SEASON were still not significant, just as they were found to be not significant in development of the preliminary modeling in Step 1. These type of conclusions were reached by examining the partial F values for these effects. The partial F evaluates the significance to the model of adding the effect after all other effects already in the model were evaluated. For example, when CYCLE*COBLEND was added to Model 15, the partial F value was only 0.3, the statistical significance was only 1%, and none of the 30 coefficients in the matrix were significantly different from zero.

A parity plot can be used to show the goodness of fit of the final model to the data. A parity plot is made of the model's predicted values versus the measured values. Each point on the plot is determined from each test condition in the study. If all the points fall on the 1:1, or parity, line, then the model fits the data perfectly, and the r² is 1.000. This rarely occurs. In practice the points fall off the parity line to a degree and reflect the lack of fit of the model to the data and the

Table 5-9
Comparison of NO_x^{0.2} Technology Models

	F	r2	Signifi- cance	Number of Coefficients
Model 11 VEHID EMSTECH*CYCLE EMSTECH*TEMP EMSTECH*COBLEND*OXY CYCLE*TEMP TEMP*COBLEND SEASON	5292 444 46 10.4 2.1 1.8 1.3 0.2	0.926	99.99 99.99 99.99 99.99 99.1 94 81 31	80
Model 12 VEHID FUELSYS*CYCLE FUELSYS*TEMP FUELSYS*COBLEND*OXY CYCLE*TEMP TEMP*COBLEND SEASON	5740 313 57 7.6 2.0 1.9 1.2 0.1	0.921	99.99 99.99 99.99 99.99 97.8 95.2 74 39	69
Model 13 VEHID CNSTR*CYCLE CNSTR*TEMP CNSTR*COBLEND*OXY CYCLE*TEMP TEMP*COBLEND SEASON	5011 1008 1.6 1.8 1.0 1.0 0.9 0.2	0.891	99.99 99.99 83 84 53 67 45 33	58
Model 14 VEHID DISP*CYCLE DISP*TEMP DISP*COBLEND*OXY CYCLE*TEMP TEMP*COBLEND SEASON	5489 868 6.2 5.5 1.0 26 1.3 0.2	0.893	99.99 99.99 99.99 99.6 57 99.99 78 33	54

Table 5-9
(Continued)

	F	r2	Signifi- cance	Number of Coefficients
Model 15	7376	0.925	99.99	57
VEHID	442		99.99	
EMSTECH*CYCLE	153		99.99	
EMSTECH*TEMP	15.4		99.99	
EMSTECH*COBLEND*OXY	3.6		99.99	

uncertainty in the measured values. A parity plot is useful for getting a feel for the goodness of fit of the model and for determining if there is an obvious bias at any part of the measurement range.

In this report, parity plots for all final regression models will be shown on a log scale because of the wide range of measurement values. Figure 5-4 shows the parity plot for Model 15 for NO_x . This plot shows how well the model predicts the 1664 NO_x measurements used in the regression. The parity line has been drawn on the plot. Note that the predicted values follow the measured values throughout their range.

8. Describe Effect of Parameters on Emissions. Many techniques can be used to describe the size and significance of effects of the different parameters on the measured emissions. For this NO_x analysis, the matrix representation of the solution of the regression will be shown and how it can be used to predict values of test conditions. Because such a matrix representation does not indicate the uncertainty in the values for each parameter level but the SAS output listing does, for each final regression of each emission type we will provide the SAS output listing in Appendix K. Readers inexperienced in statistical analysis may not be able to understand all of the details of these listings, but the listings will help the local statistician understand trends. For the reader not familiar with SAS output, we will provide a plot with ± 2 standard deviation error bars for the effects of the different blend types on emissions by technology type.

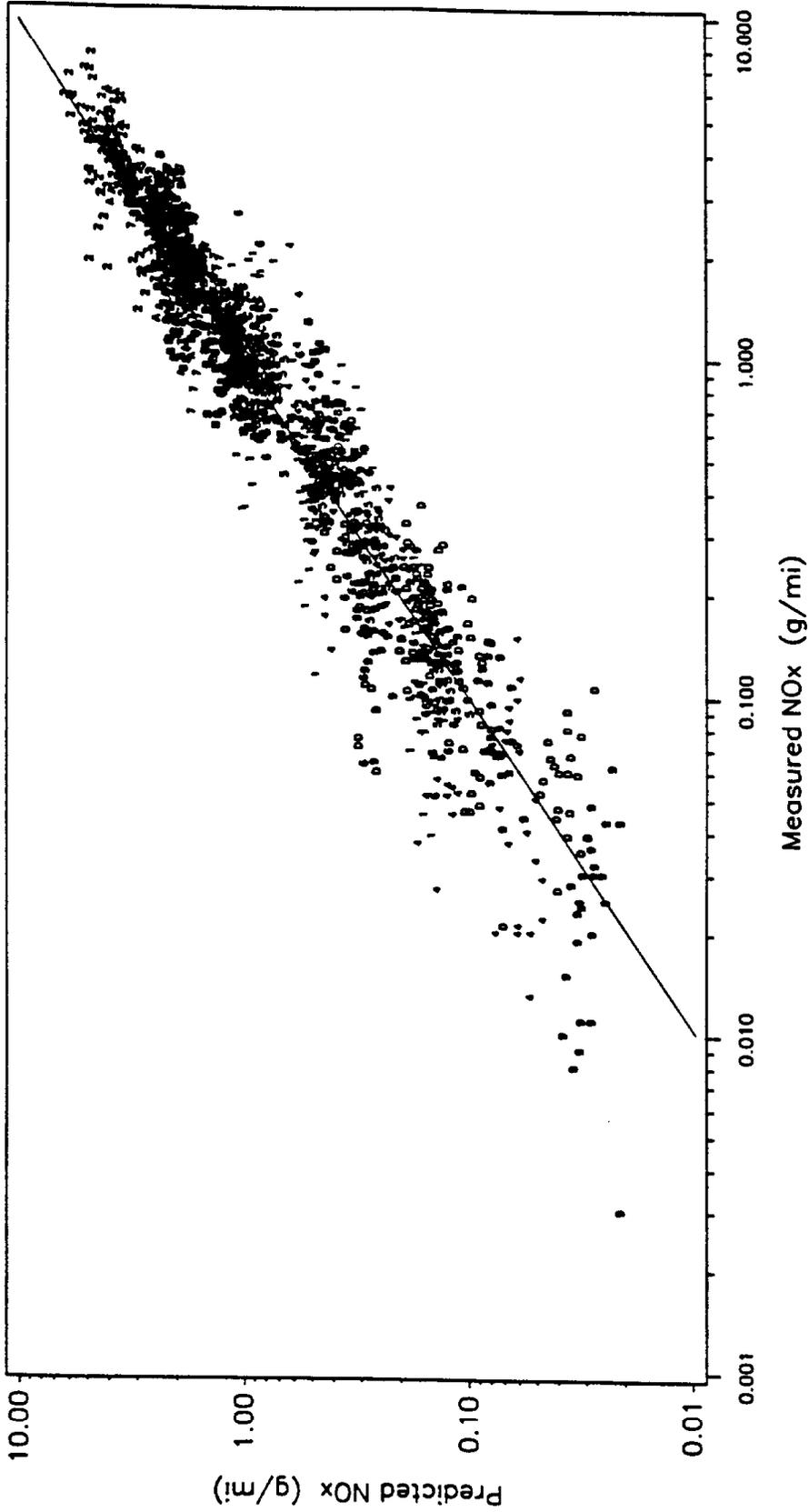
Figure 5-5 shows the matrix description of the effects of parameters on NO_x emissions as determined by regression Model 15. This figure is taken directly from the coefficients in the SAS output in Appendix K. The SAS code used to generate this output is also included in Appendix K as an example. The values for oxygenated blends in the EMSTECH*COBLEND matrix which are significantly different from the Base blend are shown in bold. Note that Figure 5-5 can be used to estimate the NO_x emissions for a specific test condition. For example, for Vehicle 6, which has TWC/AL technology, driving the FTP cycle at 75°F with MTBE at 2.0% oxygen (the Summer blend), the predicted $\text{NO}_x^{0.2}$ would be $0.973 + (-0.085) + (-0.021) + (-0.0105)*(2.0) = 0.846$, and the NO_x would therefore be 0.43 g/mi.

While this example demonstrates the meaning of the matrix description of the solution of the regression, the main use of the solution matrices is to determine which effects are significant to NO_x emissions. To do this, the standard errors of estimate for each coefficient in the matrices are used. By constructing a plot with the coefficient ± 2 standard errors of estimate for each element of a matrix, the significance of each coefficient can be visualized. Such a plot can be made for each matrix in the model statement; however, in this report we will show such a plot only for the effects of blend type and oxygen content for different technologies on the emissions. Analogous plots can be made for the other matrices in a regression, but perhaps more simply, the SAS outputs in the appendices provide the same information in a numerical rather than graphical means.

For NO_x emissions, the plot of interest is for the regression term EMSTECH*COBLEND*-OXY. Since OXY is the continuous variable for oxygen content, the matrix EMSTECH*COBLEND provides multiplicative coefficients for OXY. Each coefficient represents the effect on $\text{NO}_x^{0.2}$ caused per percent of oxygen content. However, it is important to remember that this should only be applied to oxygen levels between 2.0 and 2.7% oxygen.

The plot of effects on $\text{NO}_x^{0.2}$ for blend type with respect to the Base blend for the different technologies is shown in Figure 5-6. Note that if an effect is found to be significant in the trans-

Figure 5-4
Total Exhaust NOx Emissions
 Model: NOx**0.2 = vehid emstech*cycle emstech*temp emstech*coblend*oxy



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$\text{NO}_x^{0.2} =$

VEHID	1	3WAL	0.986
	2	3WNA	1.371
	3	NON	1.297
	4	3WAL	0.866
	5	3WAL	0.953
	6	3WAL	0.973
	7	3WNA	1.195
	8	3WAL	1.138
	9	3WAL	0.785
	10	OXY	1.302
	11	3WNA	1.191
	12	OXY	1.152
	13	3WAL	0.810

+

EMSTECH*CYCLE		3WA	3WN	OXY	NON
	Bag1	.035	.060	-.132	-.069
	Bag2	-.172	-.130	-.167	-.139
	Bag3	-.104	-.024	-.113	-.046
	FTP	-.085	-.048	-.142	-.095
	HFET	-.273	-.051	-.175	-.138
	NYCC	0	0	0	0

+

EMSTECH*TEMP	50	-.007	-.088	-.015	-.025
	75	-.021	-.055	-.015	-.016
	95	0	0	0	0

+

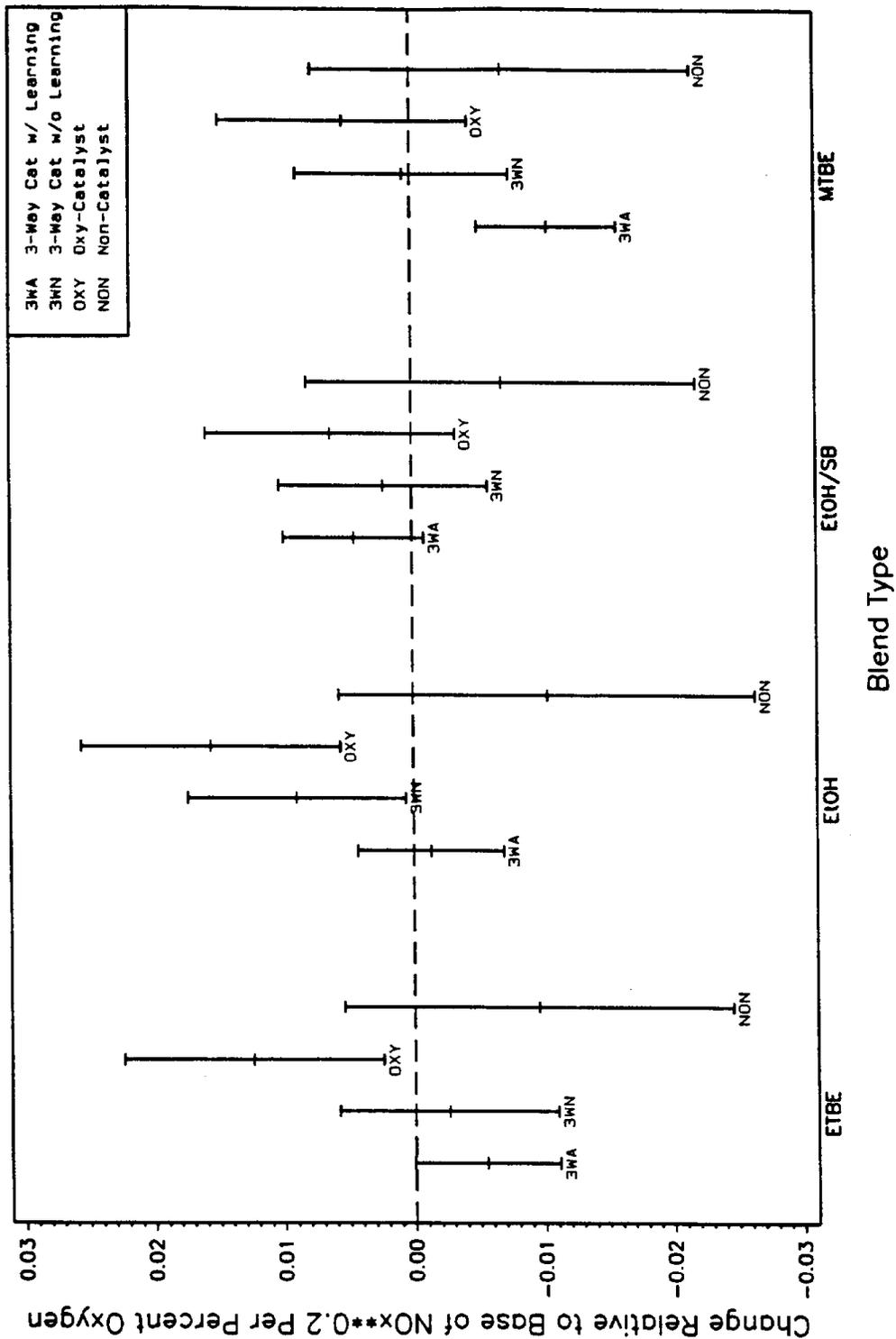
EMSTECH*COBLEND	ETBE	-.0055	-.0026	.0124	-.0096
	EtOH	-.0013	.0090	.0156	-.0103
	EtOH/SB	.0045	.0022	.0063	-.0069
	MTBE	-.0105	.0006	.0052	-.0070
	Low+OrigBase	0	0	0	0

*OXY

Figure 5-5
Matrix Description of Parameter Effects on NO_x

Effect of Blend Type on NOx Emissions

model: NOx**0.2 = vehid emstech*cycle emstech*temp emstech*coblend*oxy



formed space ($\text{NO}_x^{0.2}$), then it will also be significant when the effect is taken back to the untransformed space (NO_x). We must examine effects for significance on plots in the transformed space since that is where the variance is homogeneous. The error bars in the figure represent the coefficient ± 2 standard errors of estimate taken from the SAS output in the appendix. If zero falls outside of a set of error bars, then the corresponding condition produced NO_x values significantly different (at the 95% confidence level) from those produced by the Base blend. If the error bars cross zero, then the corresponding condition is not significantly different from the Base blend.

Thus, for NO_x , significant effects relative to the Base blend were seen for five conditions. ETBE and MTBE showed reductions in NO_x for the TWC/AL vehicles in the test fleet. EtOH showed increases in NO_x for the TWC/NAL vehicles in the test fleet. ETBE and EtOH showed increases in NO_x for the oxy-catalyst vehicles in the test fleet.

For other combinations of EMSTECH and COBLEND, no significant differences at the 95% confidence level were seen. This does not mean that effects are not present, but that with this data set we can not be very confident that the differences seen are not caused by randomness alone. The estimates of levels of confidence for all of the coefficients are given in the SAS output in the appendix.

The figure can also be used to compare the effects relative to each other where neither is a Base blend. This type of evaluation is done by considering pairs of effects; however, to evaluate significance, the error bars of just one of the conditions should be considered. That is, if the center point of the second condition falls outside of the error bars of the first condition, then there is a significant difference at the 95% confidence level. For example, for the TWC/AL vehicles, the figure shows that MTBE produced significantly lower NO_x emissions than EtOH and EtOH/SB, but that MTBE and ETBE produced about the same level of NO_x emissions.

To estimate the size of effects in terms of grams per mile NO_x , the effects must be "untransformed." The most common way to describe the effect of oxygenated fuels on emissions relative to the base fuel is as the percent change in emissions. If the log transformation was used, the effects measured in a regression of the log-transformed emissions becomes a constant percentage emissions change which is independent of the base level of emissions. In this study, log transformations were usually found to describe the data best. But for other transformations, the percentage change in emissions depends on the base level of emissions and therefore must be calculated for different emission levels.

For example, if the emission level for a given TWC/AL vehicle and given operating condition on unoxxygenated fuel was 2 g/mi, the predicted emission level for 2.0% MTBE would be estimated by transforming the base emissions to $\text{NO}_x^{0.2}$, making the effect correction for MTBE from Figure 5-5, and "untransforming" the result by taking the fifth power to get the predicted NO_x emission: $(2^{0.2} + (-0.0105 * 2.0))^5 = 1.82$ g/mi, which is a 9% reduction in NO_x . If the base level had been 0.5 g/mi, then the reduction in NO_x associated with MTBE would be 12%.

D. EVALUATION OF EXHAUST EMISSIONS

Tables 5-10 and 5-11 show the test matrices for the reference fuels and for the oxygenated fuels, respectively. The reference fuels were tested to provide a baseline against which the results of the oxygenated and base fuels could be compared.

Table 5-10. Reference Fuel Test Design for Exhaust Emissions

RVP (psi)	Temp (F)	Fuel	FTP			HFET			NYOC			
			HC	CO	NOx	HC	CO	NOx	HC	CO	NOx	
9.0	75	Industry Avg	13	7	7	13	7	7	13	7	7	7
9.0	95	Indolene	1	1	1	1	0	0	1	1	1	1
	75	Indolene	1	1	1	1	1	1	1	1	1	1
	50	Indolene	1	1	1	1	1	1	1	1	1	1

13 denotes VEHIDs 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
 7 denotes VEHIDs 1, 2, 3, 4, 5, 9, 12
 6 denotes VEHIDs 1, 2, 3, 6, 9, 12
 1 denotes VEHID 1

Table 5-11. Oxygenated Fuel Test Design for Exhaust Emissions

SEASON	TEMP	BLENDTYP	FTP			HFET			NYOC				
			HC	CO	NOx	HC	CO	NOx	HC	CO	NOx		
Summer	75	Base	7	7	7	7	7	7	7	7	7	7	7
		MTBE	7	7	7	7	7	7	7	7	7	7	7
		ETBE	7	7	7	7	7	7	7	7	7	7	7
		EIOH	7	7	7	7	7	7	7	7	7	7	7
		EIOH-SB	7	7	7	7	7	7	7	7	7	7	7
Summer	95	Base	7	7	7	0	0	0	7	7	7	7	7
		MTBE	7	7	7	0	0	0	7	7	7	7	7
		ETBE	7	7	7	0	0	0	7	7	7	7	7
		EIOH	7	7	7	0	0	0	7	7	7	7	7
		EIOH-SB	7	7	7	0	0	0	7	7	7	7	7
Winter	50	Base	7	7	7	7	7	7	7	7	7	7	7
		MTBE	7	7	7	7	7	7	7	7	7	7	7
		ETBE	7	7	7	7	7	7	7	7	7	7	7
		EIOH	7	7	7	7	7	7	7	7	7	7	7
		EIOH-SB	7	7	7	7	7	7	7	7	7	7	7
Winter	75	Base	7	7	7	7	7	7	7	7	7	7	7
		MTBE	7	7	7	7	7	7	7	7	7	7	7
		ETBE	7	7	7	7	7	7	7	7	7	7	7
		EIOH	7	7	7	7	7	7	7	7	7	7	7
		EIOH-SB	7	7	7	7	7	7	7	7	7	7	7

13 denotes VEHIDs 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
 7 denotes VEHIDs 1, 2, 3, 4, 5, 9, 12
 6 denotes VEHIDs 1, 2, 3, 6, 9, 12
 1 denotes VEHID 1

The oxygenated fuels test matrix shown in Table 5-11 shows the structure of the experimental design used to measure the effects on exhaust emissions. All 13 test vehicles were planned to be tested at each of three standard cycles, each of the five blend types at a high and low temperature, and for both blend seasons. Speciation of the hydrocarbon emissions for seven vehicles was planned to have been measured at all test conditions except for the HFET cycle, 95°F, and the summer blends.

1. Responses to Reference Fuels The exhaust emissions of the test vehicles were measured using two reference fuels. One was Indolene®(Fuel E) and the other was an industry average reference fuel (Fuel A). The exhaust CO, HC, and NO_x emissions for tests using the reference fuels are given in Tables 5-12, 5-13, and 5-14, respectively.

A comparison of the responses of the CO, HC, and NO_x emissions for the thirteen vehicles using the Summer Base fuel (Fuel M), the Winter Base fuel (Fuel N), and the Industry Average fuel (Fuel A) are shown in Figures 5-7, 5-8, and 5-9. The three fuels have different blending stocks and have nominal RVPs of 7.7 psi for M, 8.5 psi for A, and 9.7 psi for N. The data plotted in the figures were all taken at 75°F. The measured emissions are plotted with a log scale because of the large range of data values. The horizontal scale denotes the eighteen different combinations of driving cycle and fuel. Within each of these eighteen bands, the data for each test is plotted using a symbol which denotes the vehicle identity number. To help avoid overprinting, the symbols within each band have been moved slightly left or right according to exhaust emission control technology group. The order within each band from left to right is: TWC/AL, TWC/NAL, oxy-catalyst, and non-catalyst.

The figures provide a visual comparison of the Industry Average fuel A with the Summer and Winter Base fuels M and N under different test conditions. In general, the figures show that while test results varied among the fuels, the measured values were similar. The figures show that the differences in emissions responses caused by these non-oxygenated fuels were smaller than differences produced by individual vehicles, exhaust emission control technologies, and driving cycle. Thus, it is apparent that the Summer and Winter Base fuels produce exhaust emission behavior for HC, CO, and NO_x that is similar to that produced by an industry average fuel.

2. Exhaust Carbon Monoxide (CO). The results of the exhaust carbon monoxide measurements are given in the table in Appendix D. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The CO emissions in grams per mile are listed as a function of vehicle (VEHID), blend season (SEASON), temperature (TEMP), blend type (BLENDTYP), and driving cycle (CYCLE). Test date (TESTDATE) is used in the table to make the distinction between results from replicate tests.

The following preliminary class regression statement was used to evaluate the main effects of the five parameters in the absence of any interactions:

$$\ln\text{CO} = \text{VEHID} \quad \text{CYCLE} \quad \text{BLENDTYP} \quad \text{TEMP} \quad \text{SEASON}$$

This analysis of variance indicated that the five parameters had the following order of magnitude effect on the lnCO:

$$\text{CYCLE} > \text{VEHID} \gg \text{TEMP} > \text{BLENDTYP} > \text{SEASON}$$

Table 5-12. Total Exhaust CO Emissions for Reference Fuels

Vehicle	Temperature (F)	Test Date	Fuel ID	Fuel Description	FTP (g/mi)	Bag 1 (g/mi)	Bag 2 (g/mi)	Bag 3 (g/mi)	HFET (g/mi)	NYCC (g/mi)
1	50	09/13/91	E	Indolene	4.000	13.453	0.141	4.130	0.776	17.472
1	50	12/05/91	E	Indolene	4.718	16.568	0.146	4.383	0.742	10.516
1	75	01/14/92	A	Industry Ave.	2.011	7.028	0.047	1.925	1.020	11.613
1	75	11/21/91	E	Indolene	4.137	10.721	0.052	6.868	0.798	5.771
1	95	04/23/92	E	Indolene	3.067	4.137	0.266	7.534	3.303	25.945
2	75	01/20/92	A	Industry Ave.	19.887	41.465	11.684	19.107	6.994	69.754
2	75	08/06/92	A	Industry Ave.						27.763
3	75	01/23/92	A	Industry Ave.	26.306	46.194	22.096	19.257	8.174	36.336
4	75	12/09/91	A	Industry Ave.	4.844	8.573	3.479	4.609	2.249	13.313
4	75	08/06/92	A	Industry Ave.						11.971
5	75	01/03/92	A	Industry Ave.	3.874	8.671	2.396	3.047	0.796	12.843
6	75	12/11/91	A	Industry Ave.	7.448	10.340	5.555	8.834	2.794	21.190
6	75	08/06/92	A	Industry Ave.	4.793	8.642	3.189	4.903	2.817	11.392
7	75	01/03/92	A	Industry Ave.	10.528	20.375	7.139	9.506	0.860	29.892
8	75	12/09/91	A	Industry Ave.	4.276	6.780	2.815	5.140	0.751	15.440
9	75	12/11/91	A	Industry Ave.	13.735	18.152	10.741	16.057	4.750	47.567
10	75	01/15/92	A	Industry Ave.	18.159	40.878	7.227	21.610	12.663	40.885
11	75	02/13/92	A	Industry Ave.	12.758	21.803	6.215	18.274	2.854	21.125
13	75	03/25/92	A	Industry Ave.	5.073	14.511	2.278	3.228	0.639	8.319

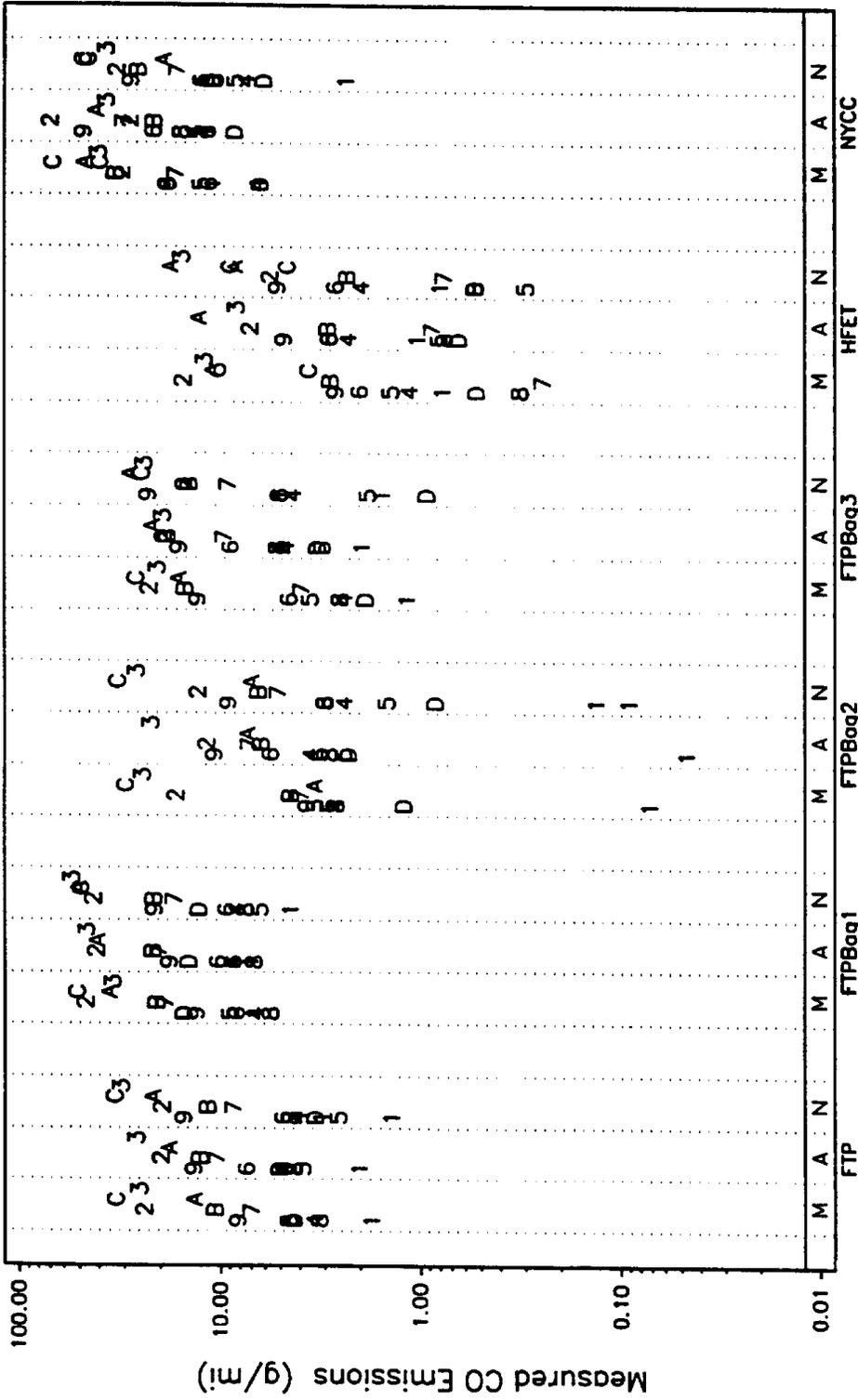
Table 5-13. Total Exhaust HC Emissions for Reference Fuels

Vehicle	Temperature (F)	Test Date	Fuel ID	Fuel Description	FTP (g/mi)	Bag 1 (g/mi)	Bag 2 (g/mi)	Bag 3 (g/mi)	HFET (g/mi)	NYCC (g/mi)
1	50	09/13/91	E	Indolene	0.337	1.358	0.021	0.162	0.047	0.579
1	50	12/05/91	E	Indolene	0.381	1.524	0.030	0.179	0.048	0.360
1	75	01/14/92	A	Industry Ave.	0.206	0.774	0.031	0.107	0.061	0.399
1	75	11/21/91	E	Indolene	0.310	1.142	0.020	0.227	0.090	0.336
1	95	04/23/92	E	Indolene	0.279	0.888	0.025	0.297	0.085	0.732
2	75	01/20/92	A	Industry Ave.	1.420	2.771	0.913	1.359	0.483	7.317
2	75	08/06/92	A	Industry Ave.	1.879	2.551	1.693	1.724	0.846	3.719
3	75	01/23/92	A	Industry Ave.	0.427	1.174	0.209	0.273	0.090	0.799
4	75	12/09/91	A	Industry Ave.						1.194
4	75	08/06/92	A	Industry Ave.						0.775
5	75	01/03/92	A	Industry Ave.	0.263	0.767	0.130	0.135	0.046	0.775
6	75	12/11/91	A	Industry Ave.	2.371	2.062	3.167	1.105	0.181	4.094
6	75	08/06/92	A	Industry Ave.	0.837	1.940	0.221	1.163	0.190	1.832
7	75	01/03/92	A	Industry Ave.	0.438	1.335	0.078	0.441	0.194	0.393
8	75	12/09/91	A	Industry Ave.	0.291	0.604	0.180	0.266	0.071	0.849
9	75	12/11/91	A	Industry Ave.	0.447	0.951	0.260	0.421	0.212	1.078
10	75	01/15/92	A	Industry Ave.	1.740	3.054	1.239	1.693	1.272	5.535
11	75	02/13/92	A	Industry Ave.	0.858	1.283	0.529	1.157	0.205	2.090
13	75	03/25/92	A	Industry Ave.	0.392	1.134	0.182	0.229	0.087	0.800

Table 5-14. Total Exhaust NO_x Emissions for Reference Fuels

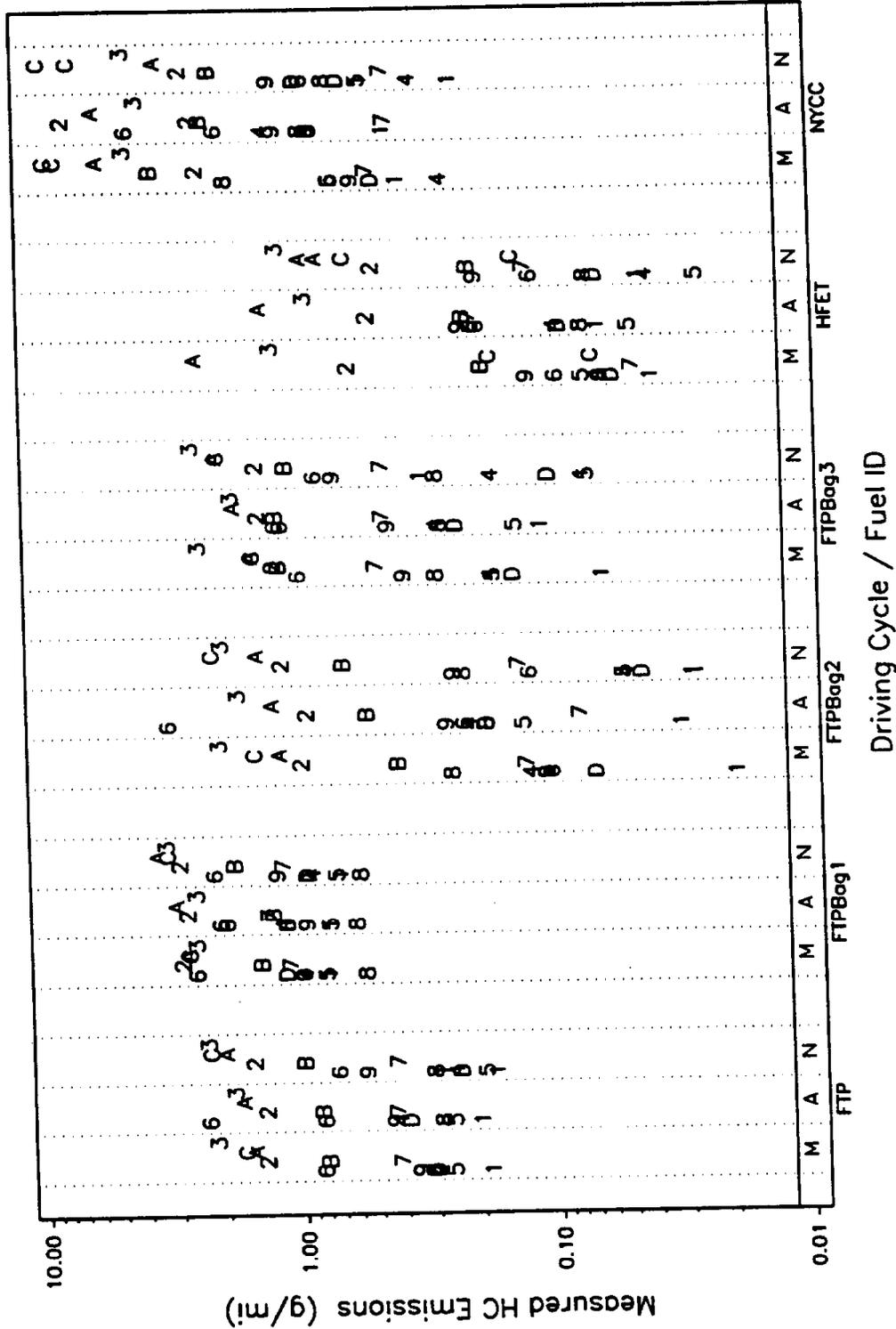
Vehicle ID	Temperature (F)	Test Date	Fuel ID	Fuel Description	FTP (g/mi)	Bag 1 (g/mi)	Bag 2 (g/mi)	Bag 3 (g/mi)	HFET (g/mi)	NYCC (g/mi)
1	50	09/13/91	E	Indolene	0.501	1.024	0.438	0.225	0.092	0.730
1	50	12/05/91	E	Indolene	0.480	0.846	0.481	0.201	0.097	1.128
1	75	01/14/92	A	Industry Ave.	0.505	0.644	0.466	0.471	0.205	1.208
1	75	11/21/91	E	Indolene	0.571	0.870	0.558	0.367	0.090	1.517
1	95	04/23/92	E	Indolene	0.478	1.353	0.318	0.120	0.244	0.231
2	75	01/20/92	A	Industry Ave.	3.975	5.135	3.283	4.409	3.576	5.763
2	75	08/06/92	A	Industry Ave.	1.857	2.460	1.617	1.855	1.595	3.095
3	75	01/23/92	A	Industry Ave.	0.363	0.773	0.151	0.453	0.090	0.579
4	75	12/09/91	A	Industry Ave.	0.411	0.812	0.255	0.402	0.146	1.163
4	75	08/06/92	A	Industry Ave.	1.154	1.167	1.381	0.715	0.191	3.037
5	75	01/03/92	A	Industry Ave.	0.384	0.758	0.191	0.466	0.112	0.488
6	75	12/11/91	A	Industry Ave.	1.123	2.480	0.539	1.203	1.517	1.036
6	75	08/06/92	A	Industry Ave.	0.831	1.061	0.682	0.939	0.805	1.518
7	75	01/03/92	A	Industry Ave.	0.244	0.600	0.107	0.234	0.055	0.188
8	75	12/09/91	A	Industry Ave.	1.639	2.248	1.416	1.599	1.237	4.200
9	75	12/11/91	A	Industry Ave.	1.929	2.740	1.419	2.279	1.607	2.983
10	75	01/15/92	A	Industry Ave.	0.316	0.629	0.160	0.374	0.124	0.230
11	75	02/13/92	A	Industry Ave.						
13	75	03/25/92	A	Industry Ave.						

Comparison of CO Emissions of the 13 Test Vehicles (1, 2, 3, 4, 5, 6, 7, 8, 9, 10(A), 11(B), 12(C), 13(D)) for Industry Average and Base Fuels at 75 F

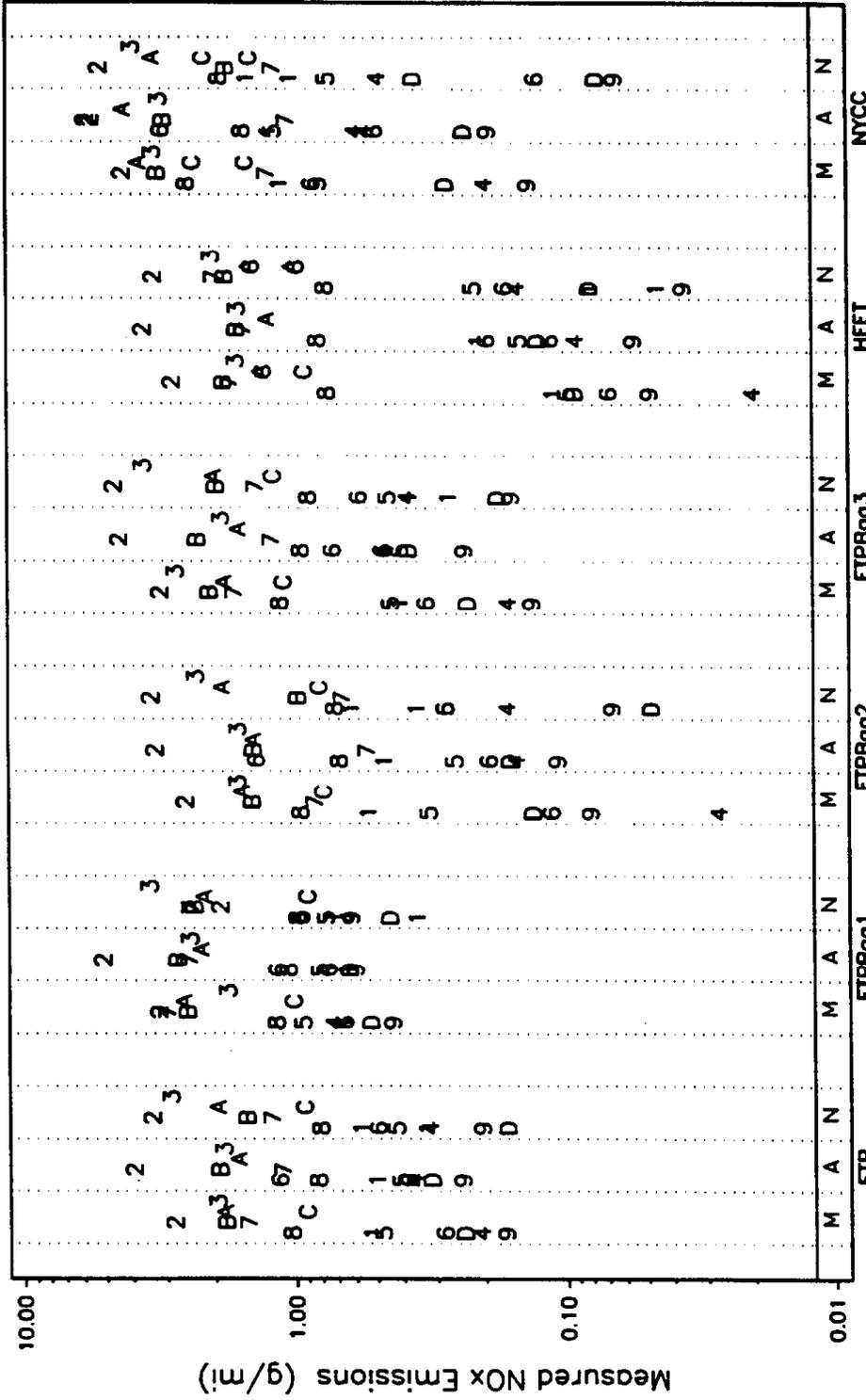


Driving Cycle / Fuel ID

Figure 5-8
Comparison of HC Emissions of the 13 Test Vehicles
 (1, 2, 3, 4, 5, 6, 7, 8, 9, 10(A), 11(B), 12(C), 13(D))
for Industry Average and Base Fuels at 75 F



Comparison of NOx Emissions of the 13 Test Vehicles (1, 2, 3, 4, 5, 6, 7, 8, 9, 10(A), 11(B), 12(C), 13(D)) for Industry Average and Base Fuels at 75 F



Evaluation of the transformation to be used for the CO emissions was made by regressions against the following combination of effects:

VEHID VEHID*CYCLE VEHID*BLENDTYP TEMP SEASON

Both the CO emissions and the natural log of the CO emissions were regressed against these parameters and the residuals were examined for homogeneity. The regression using linear CO resulted in a funnel shaped residual pattern; the natural log of the CO emissions produced a homogeneous residual pattern. Therefore, the log of the CO emissions was the transformation chosen. No outliers were detected in these regressions. All 1751 observations were used for subsequent analyses.

Then, a long series of regressions was used to try to discover the best model statement which would describe the CO emissions. The continuous oxygen concentration OXY was brought into the model statement as the interaction with VEHID*BLENDTYP. In the process of performing these regressions, several observations were made:

- The cycle had a strong effect on the CO emissions.
- The individual vehicle had a strong effect on the CO emissions.
- There was a strong interaction between cycle and vehicle. That is, vehicles responded differently to different cycles.
- There was a significant, but relatively weak, interaction between vehicle and blend type. In other words, vehicles responded slightly differently to a given blend type.
- The interaction between cycle and blend type was weak and sometimes just significant and sometimes not. This indicates that a given blend type produced about the same size of CO emission change in one cycle as it did in another cycle.
- Blend season and temperature were difficult to examine because of the small size of the effects they produced, which tended to be buried in the noise of the data.
- Comparison of the CO responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel Y was significantly different from Fuel N, but Fuel X was not significantly different from Fuel N. Therefore, observations with Fuel Y were dropped from further consideration for CO effects, and Fuels X and N were considered the same fuel for further CO regressions. This left 1667 CO observations.

The best overall model which described the emissions of the individual vehicles was given by:

$\ln\text{CO} = \text{VEHID*CYCLE} \text{ CYCLE*TEMP} \text{ VEHID*TEMP} \text{ SEASON}$
 $\text{VEHID*BLENDTYP*OXY}$

The regression fit the measured CO values with a standard deviation of about 34%, the r^2 was 0.941, and the model F was 465. The SAS output and parity plot of the regression are given in Appendix K.

To assist in the assignment of general vehicle technology behavior factors, the vehicles which have similar behavior can be classified together. Classifications were made by performing alternative regressions by substitution of technology parameters for vehicle parameters in the above equation. The VEHIDs in VEHID*TEMP and VEHID*BLENDTYP*OXY were replaced with

technology candidate parameters for emission control technology (EMSTECH), fuel induction system (FUELSYS), canister bottom type (CNSTR), or engine displacement (DISP). The VEHID in VEHID*CYCLE was retained for these regressions, since the emissions performance of individual vehicles within the same technology grouping will vary considerably due to the idiosyncrasies of each individual vehicle.

The overall results of this exercise indicated that EMSTECH provided the best technology grouping. The EMSTECH groups were Non-Catalyst, Oxy-Catalyst, TWC/NAL, and TWC/AL. Then, the best exhaust CO regression model using EMSTECH groupings was found to be:

$$\ln\text{CO} = \text{VEHID*CYCLE} \text{ CYCLE*TEMP} \text{ EMSTECH*TEMP} \\ \text{SEASON EMSTECH*BLENDTYP*OXY}$$

The SAS output listing and the parity plot from this final technology-based regression are given in Appendix K. From this regression, the effects on CO emissions relative to the combined base fuels (Base and LowRVPBase) for the four EMSTECH groups are shown in Figure 5-10. Note that the vertical axis is the percent change in CO with respect to the combined Base fuels for an oxygenated fuel blend with 2.0% oxygen. Assuming linearity, the expected effects for 2.7% oxygen fuel would be about 27/20 times the effects shown in the figure. The error bars give the 95% confidence limits on the mean value.

For the TWC/AL vehicles, none of the blend types produced significant reductions in CO, and no blend type produced significantly lower CO than another blend type. For the TWC/NAL vehicles, ETBE, EtOH, and MTBE produced significant decreases in CO, and ETBE produced significantly lower CO than EtOH/SB. The two oxy-catalyst vehicles showed no significant differences in CO from the Base blend, but again ETBE produced lower CO than EtOH/SB. The non-catalyst vehicle showed significant reductions in CO for all blends, but no blend was superior to the other blends within the uncertainty. Note for the first three technologies, the shape of the CO emissions response with respect to blend type: ETBE tended to produce the lowest CO, and EtOH/SB tended to produce the highest CO, but these tendencies were not always statistically significant.

The regression also indicated that the summer blends produced 9 percent lower CO emissions than the winter blends, and this difference was significant at the 95% confidence level. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

3. *Exhaust Total Hydrocarbons (HC)*. The results of the exhaust total hydrocarbons measurements are given in the table in Appendix C. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The HC emissions in grams per mile are listed as a function of vehicle (VEHID), blend season (SEASON), temperature (TEMP), blend type (BLENDTYP), and driving cycle (CYCLE). Test date (TESTDATE) is used in the table to make the distinction between results from replicate tests.

Figure 5-11 shows a plot of the measured HC versus the measured CO for each test condition. This plot shows that vehicles and test conditions which tend to have low CO also tend to have low HC, and that the HC emissions were about 10% of the CO emissions in terms of grams per mile. Figures 5-12 to 5-24 show the plots of measured hydrocarbon versus measured CO for the

Figure 5-10
Effect of Blend Type on CO Emissions

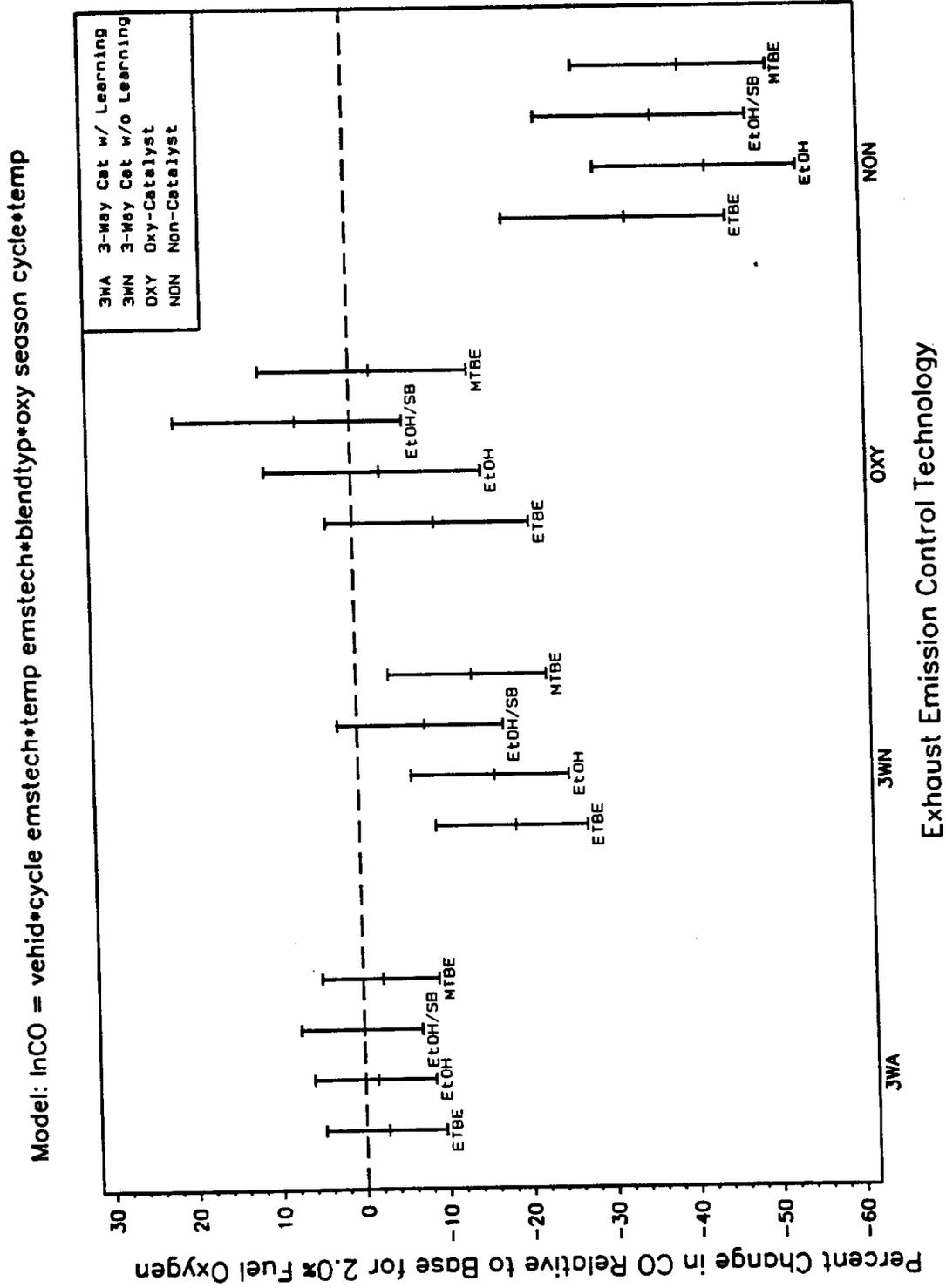
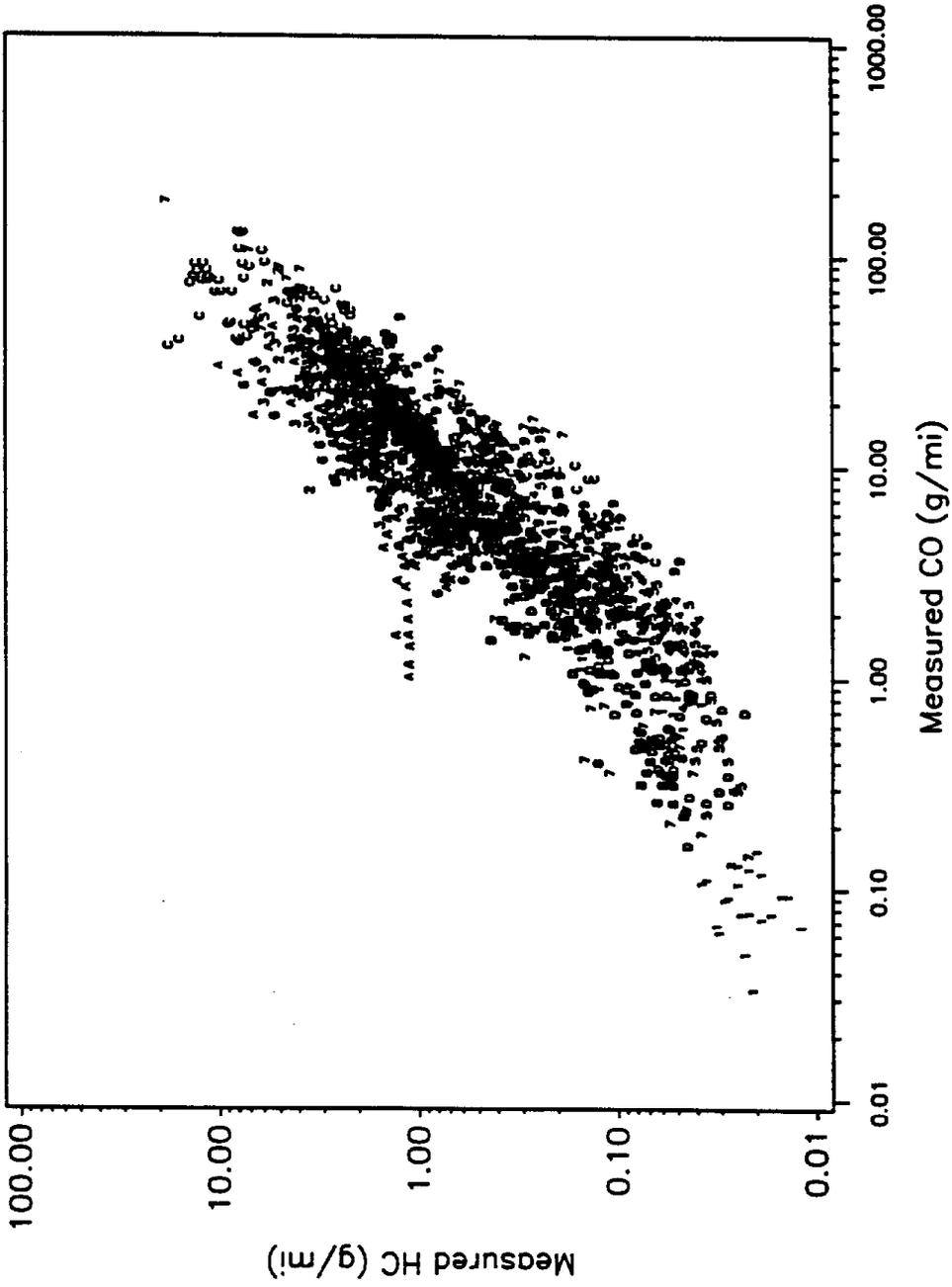


Figure 5-11
Correlation Plot of Exhaust HC and CO



VEHID	111	1	222	2	333	3	444	4	555	5	666	6	777	7	888	8	999	9	AAA	10	BBB	11	CCC	12	DDD	13
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Figure 5-12
Correlation Plot of Exhaust HC and CO

VEHID=1 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

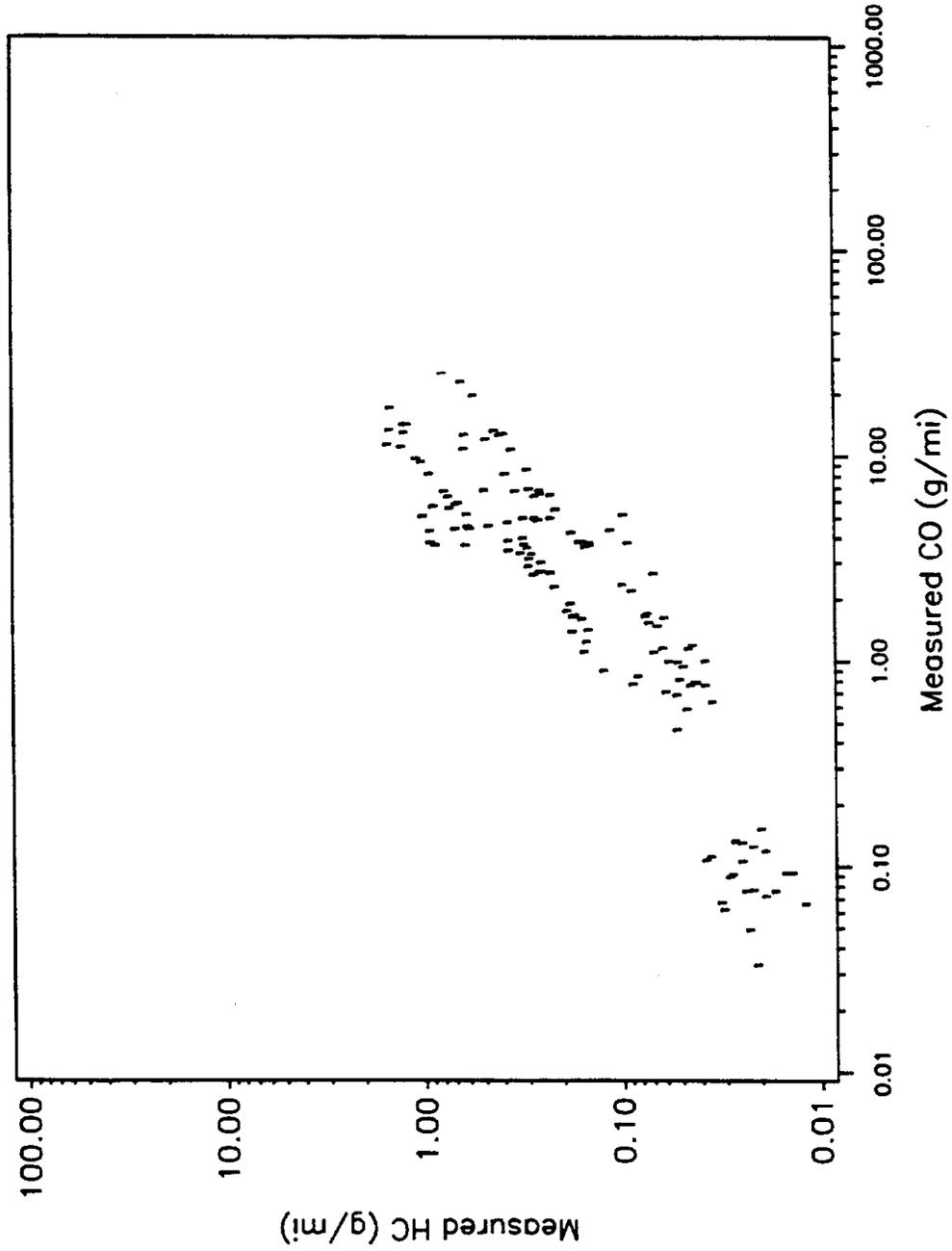


Figure 5-13 Correlation Plot of Exhaust HC and CO

VEHID=2 FUELSYS=Carburetted EMSTECH=3wayNonadapt

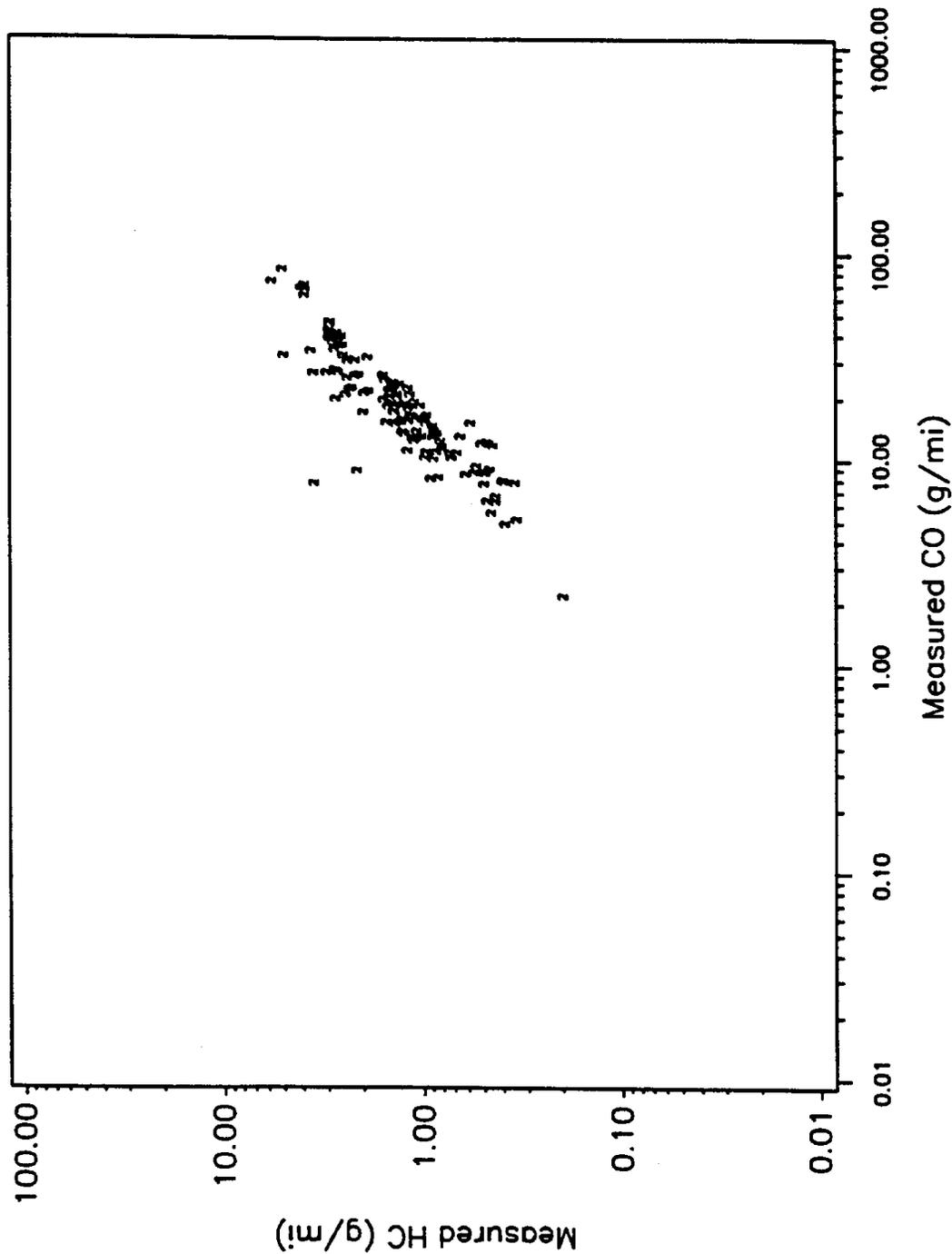


Figure 5-14
Correlation Plot of Exhaust HC and CO

VEHID=3 FUELSYS=Carburetted EMSTECH=Noncatalyst

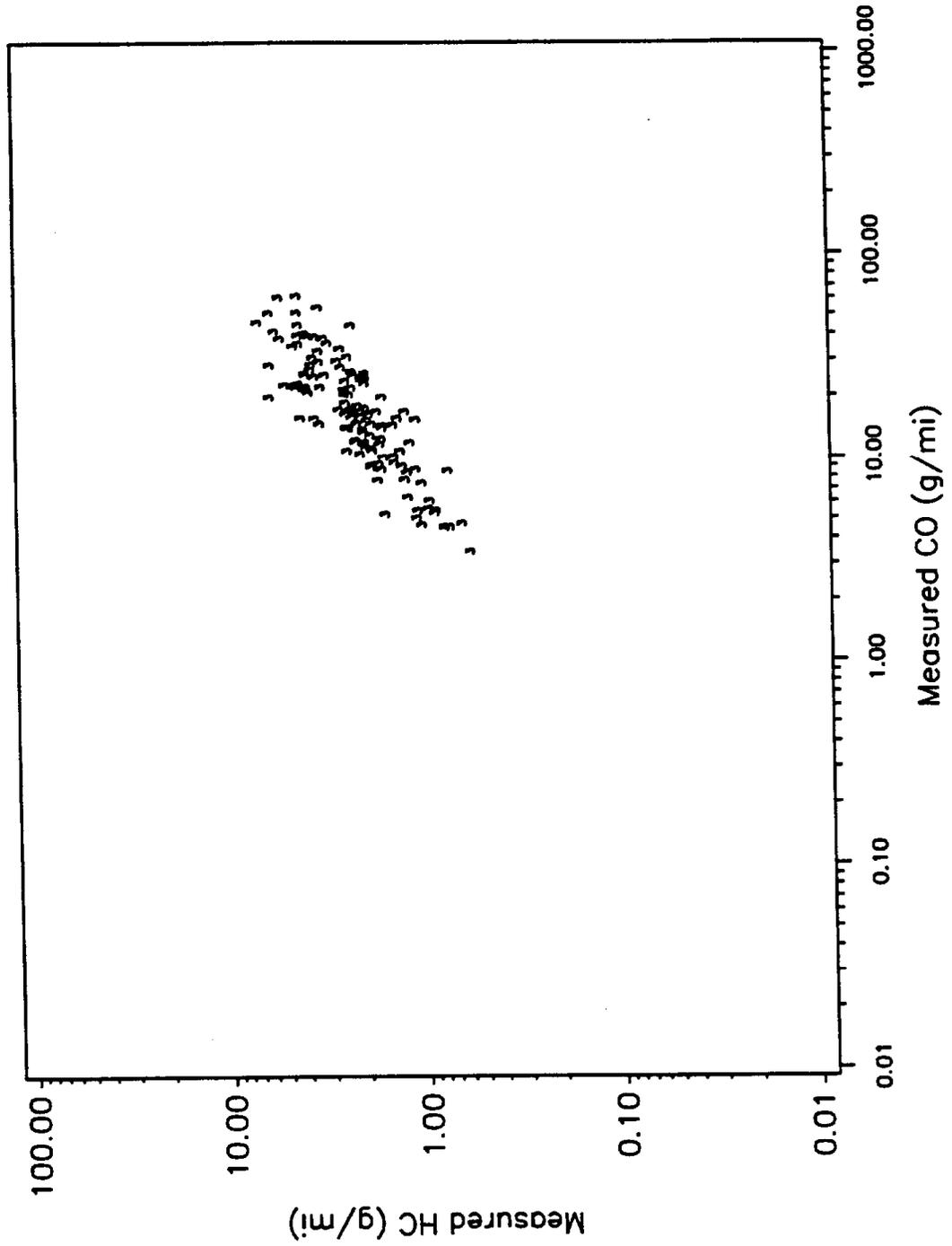


Figure 5-15
Correlation Plot of Exhaust HC and CO

VEHID=4 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

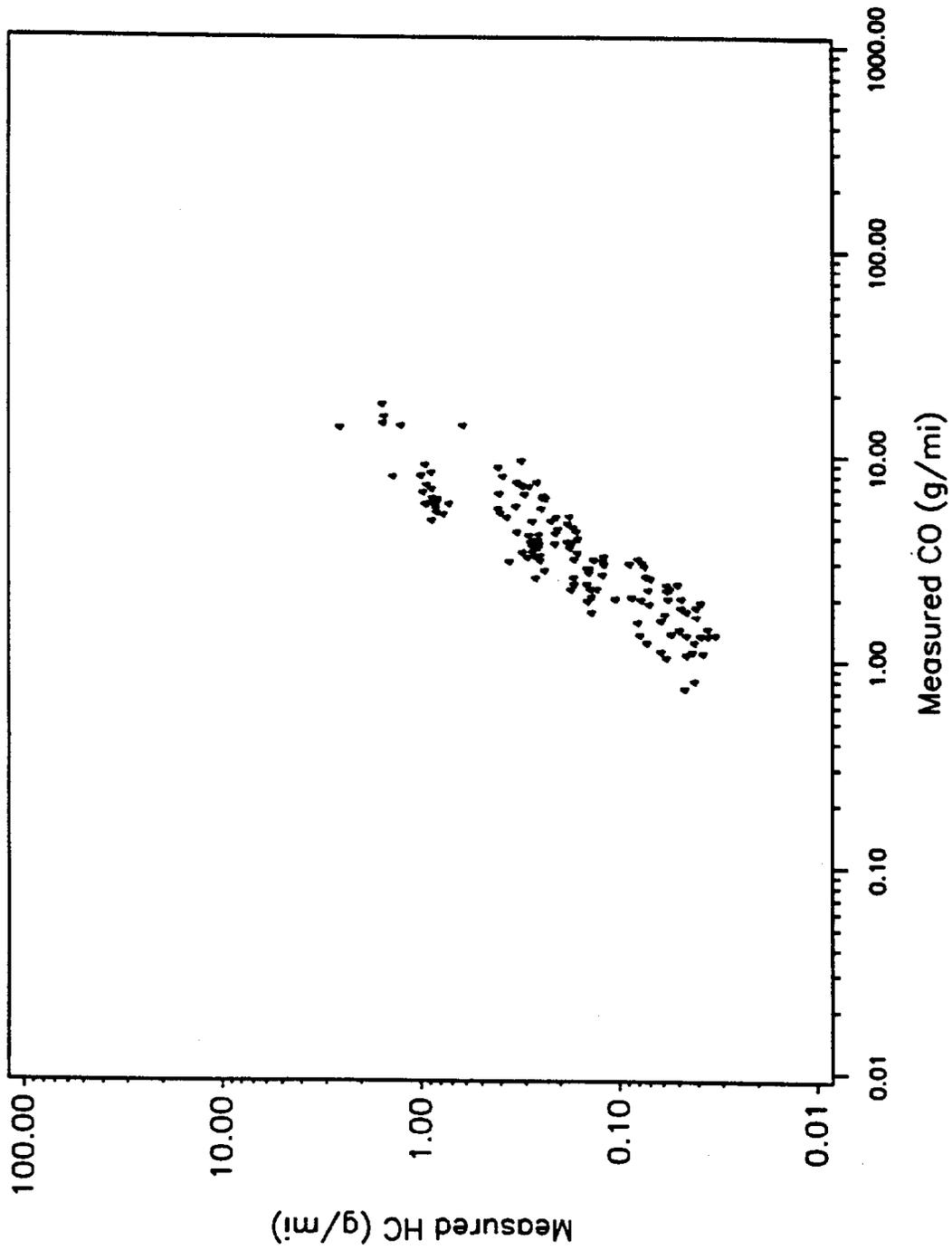


Figure 5-16
Correlation Plot of Exhaust HC and CO

VEHID=5 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

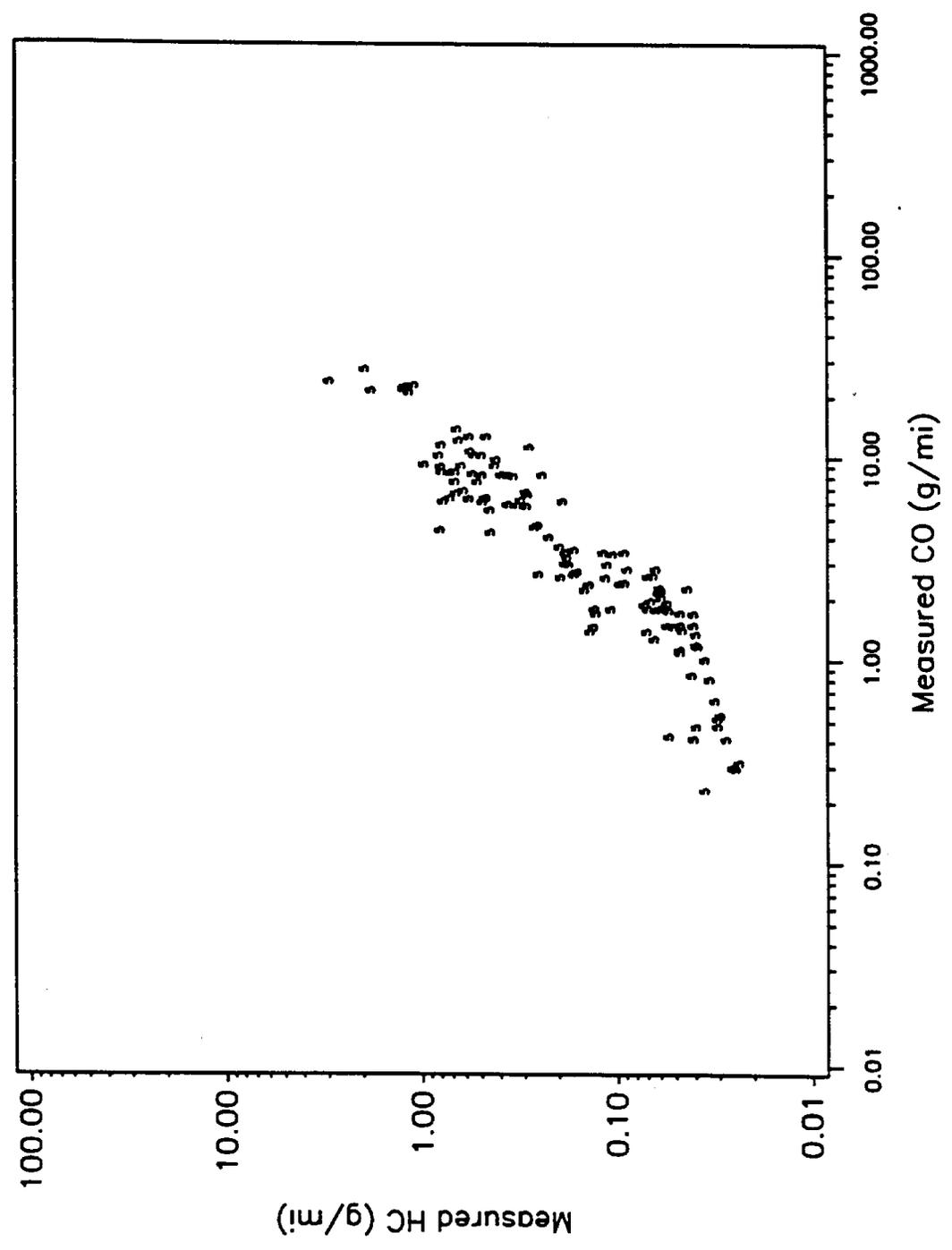


Figure 5-17
Correlation Plot of Exhaust HC and CO

VEHID=6 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

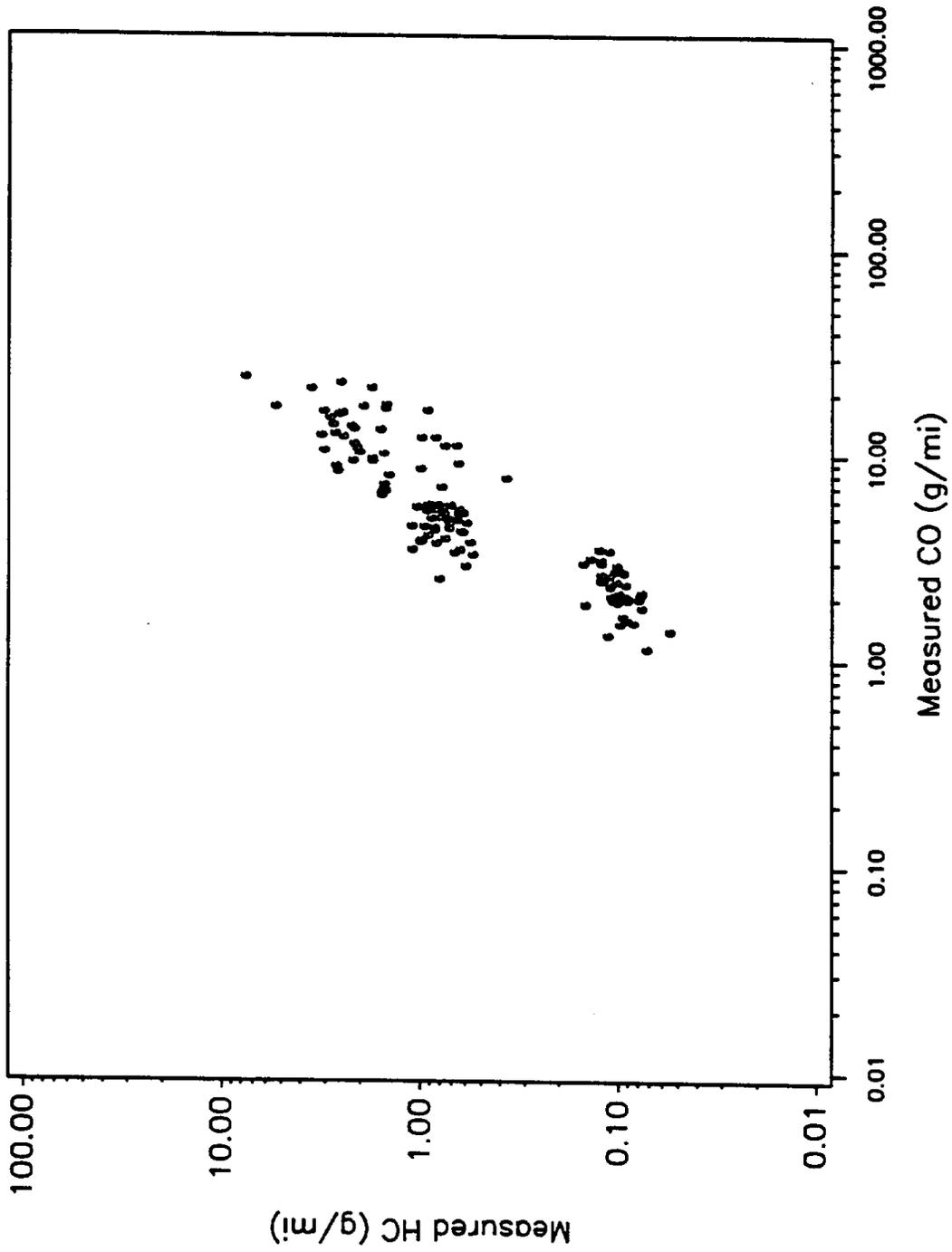


Figure 5-18
Correlation Plot of Exhaust HC and CO

VEHID=7 FUELSYS=Carburetted EMSTECH=3wayNonadapt

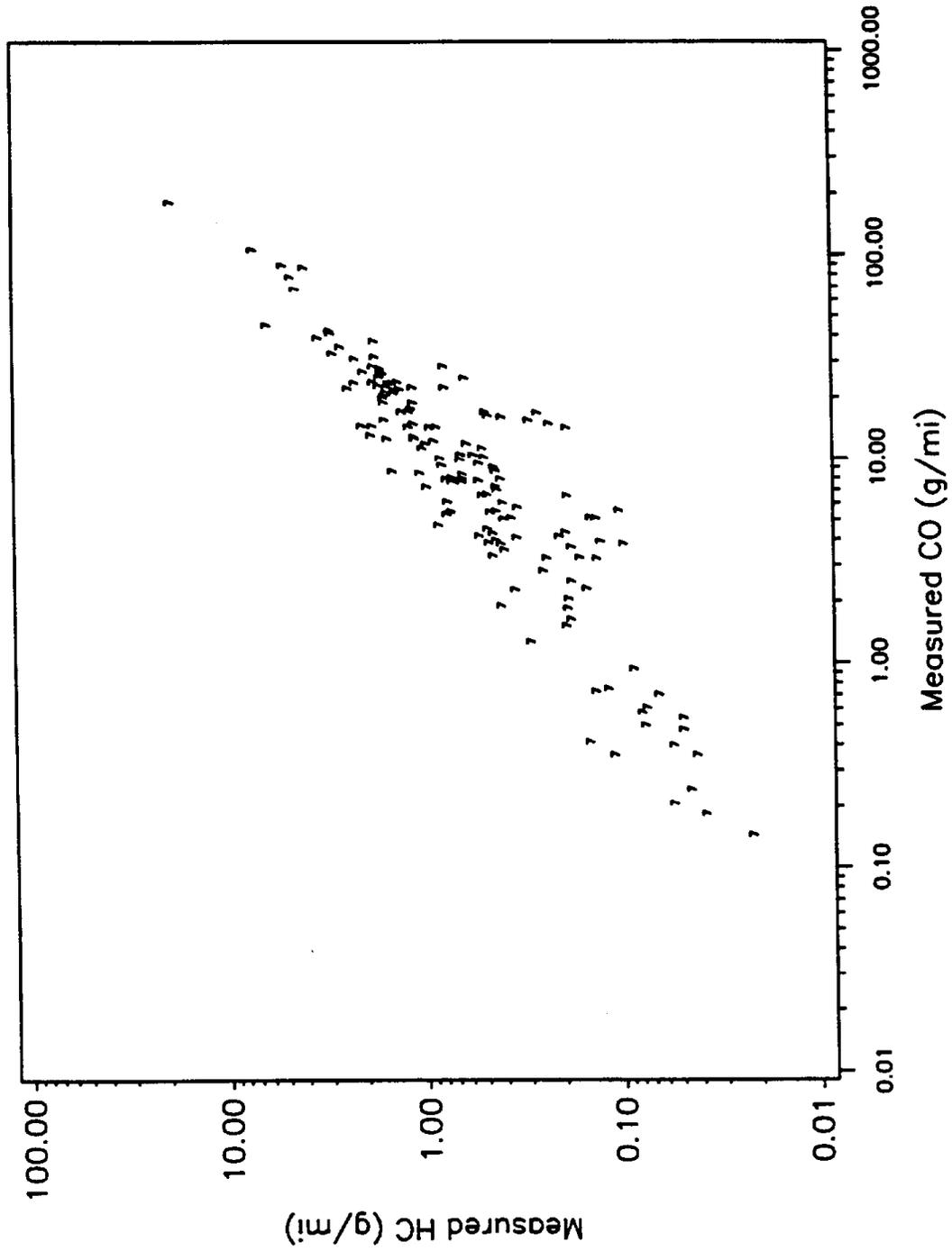


Figure 5-19
Correlation Plot of Exhaust HC and CO

VEHID=8 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

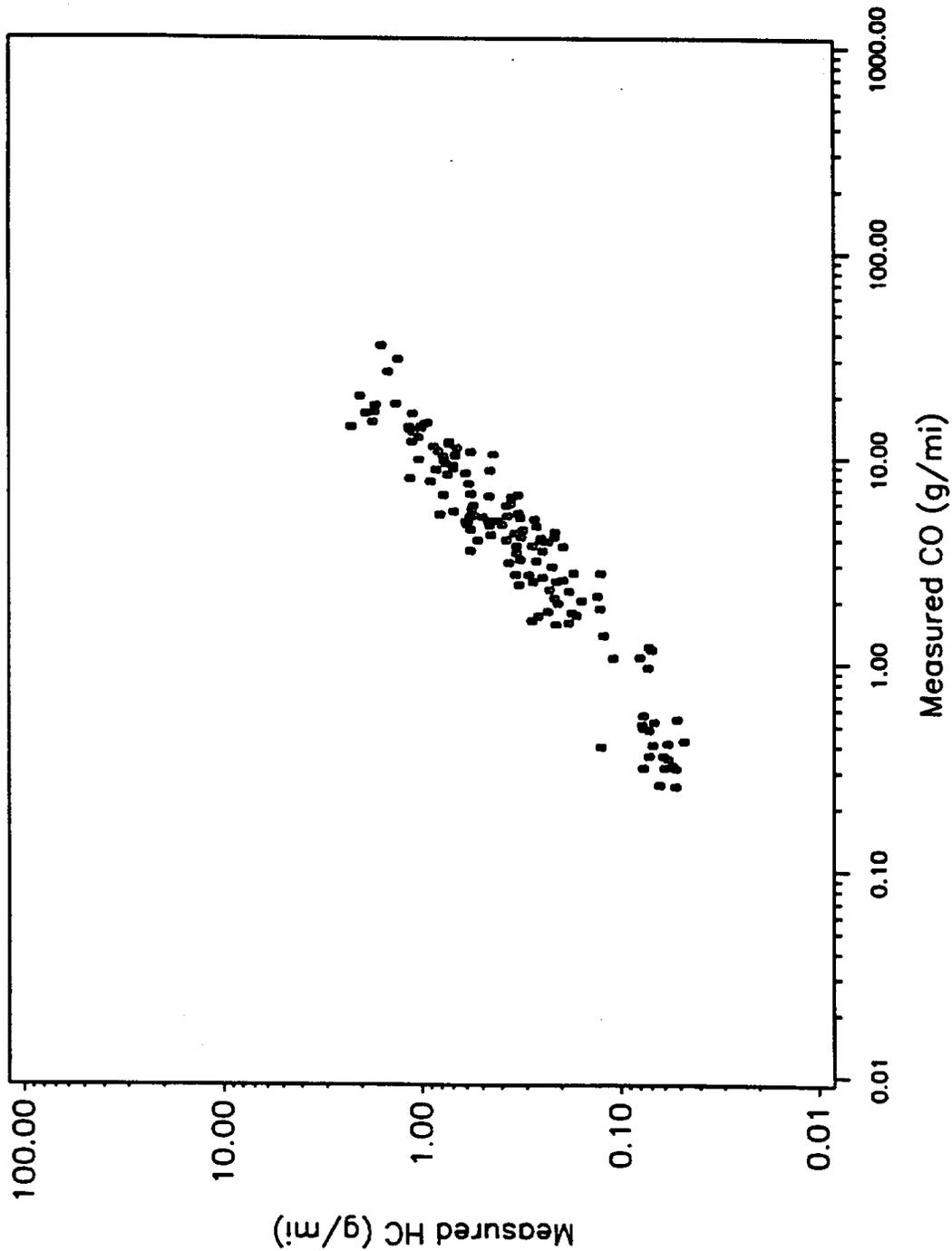


Figure 5-20
Correlation Plot of Exhaust HC and CO

VEHID=9 FUELSYS=ThrottleBody EMSTECH=3wayAdaptive

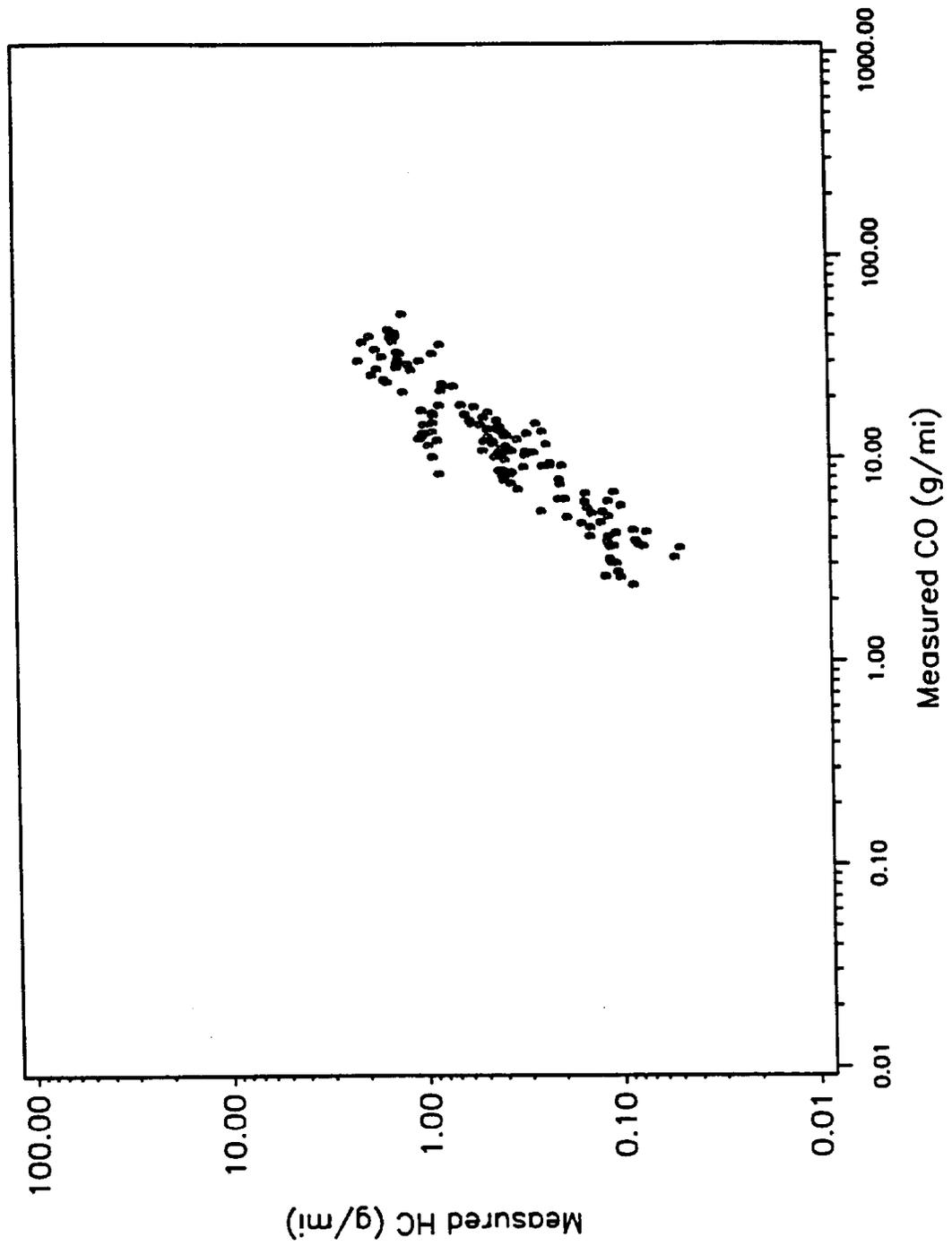


Figure 5-21
Correlation Plot of Exhaust HC and CO

VEHID= 10 FUELSYS= Carburetted EMSTECH= Oxycatalyst

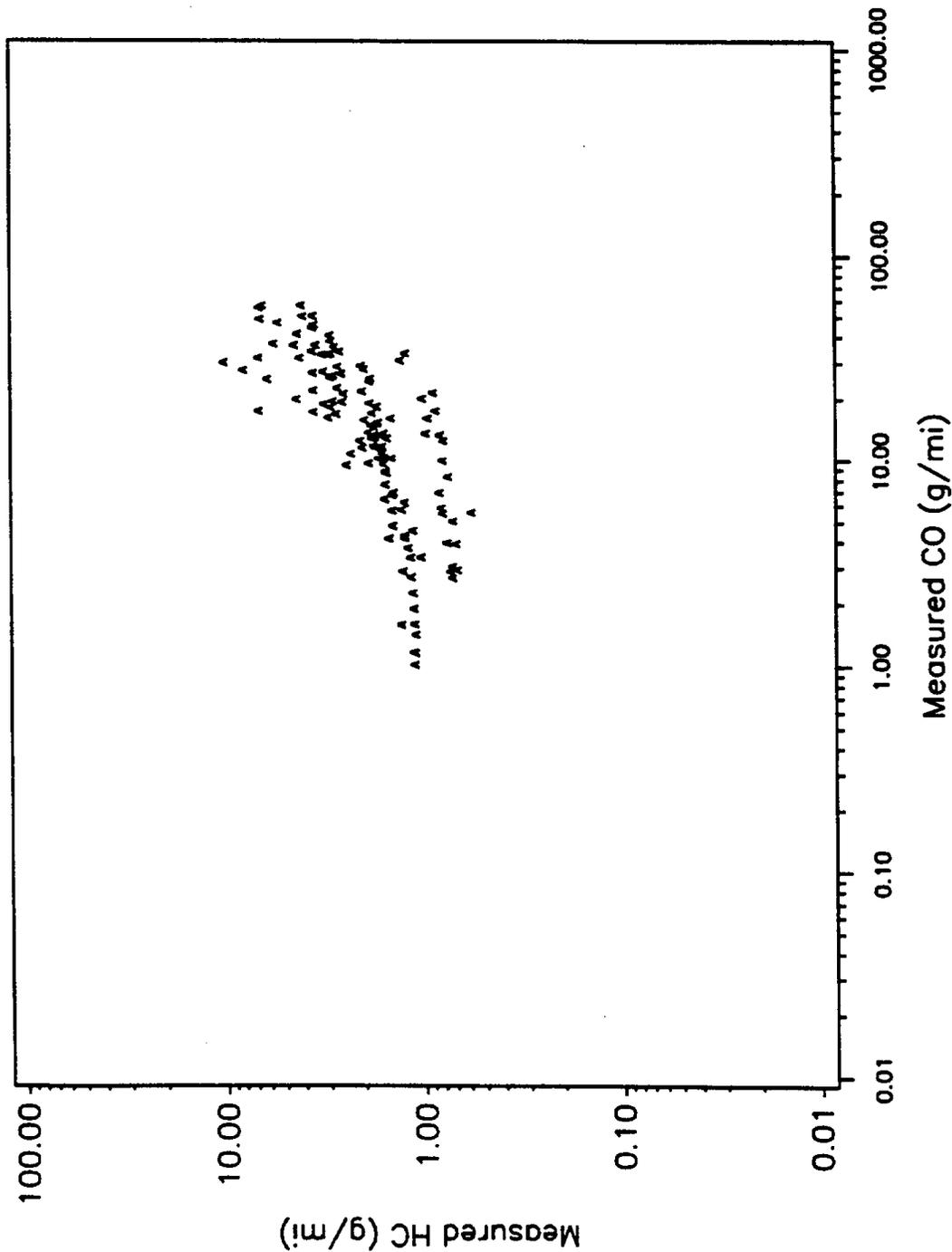


Figure 5-22 Correlation Plot of Exhaust HC and CO

VEHID=11 FUELSYS=Carburetted EMSTECH=3wayNonadapt

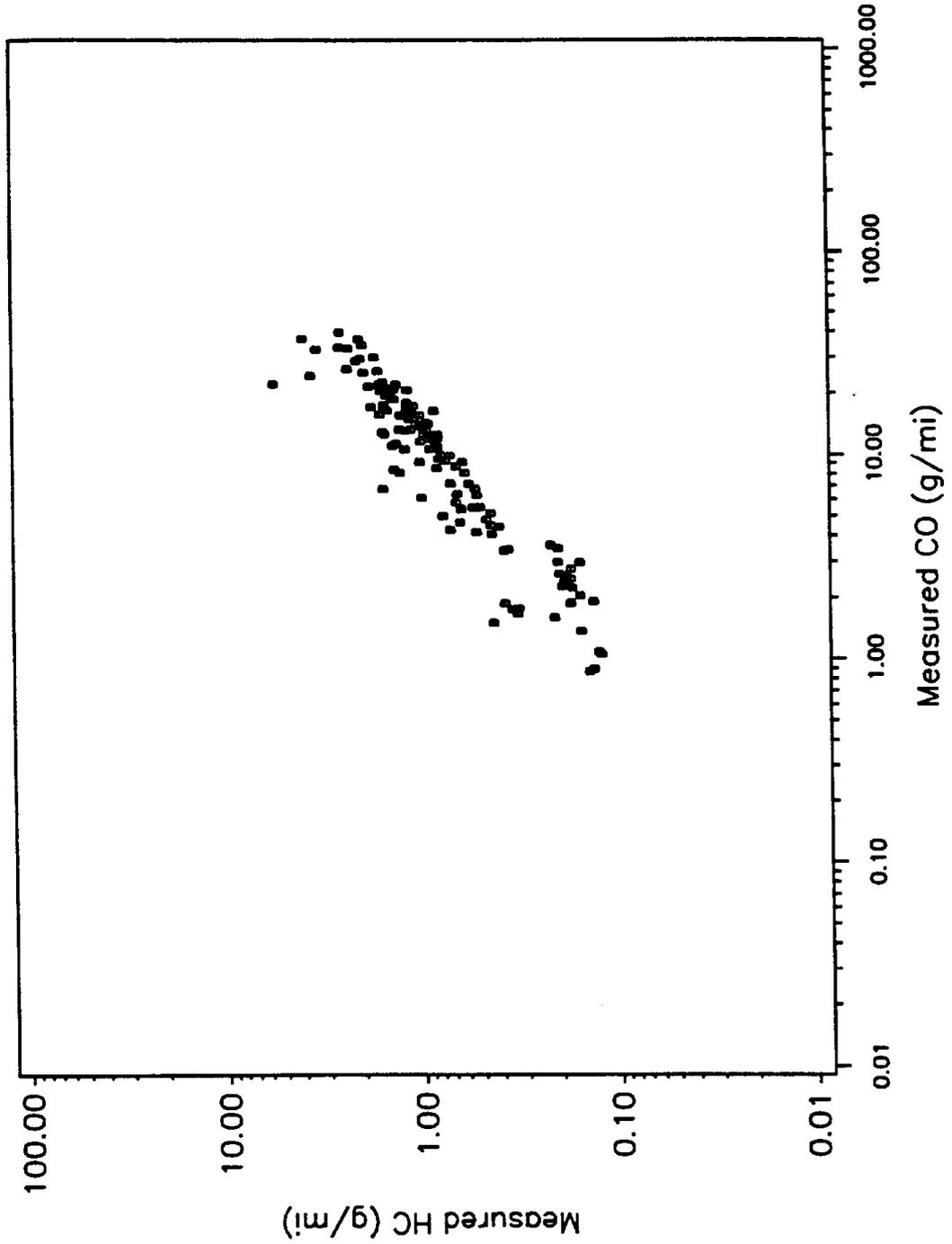


Figure 5-23 Correlation Plot of Exhaust HC and CO

VEHID=12 FUELSYS=Carburetted EMSTECH=Oxycatalyst

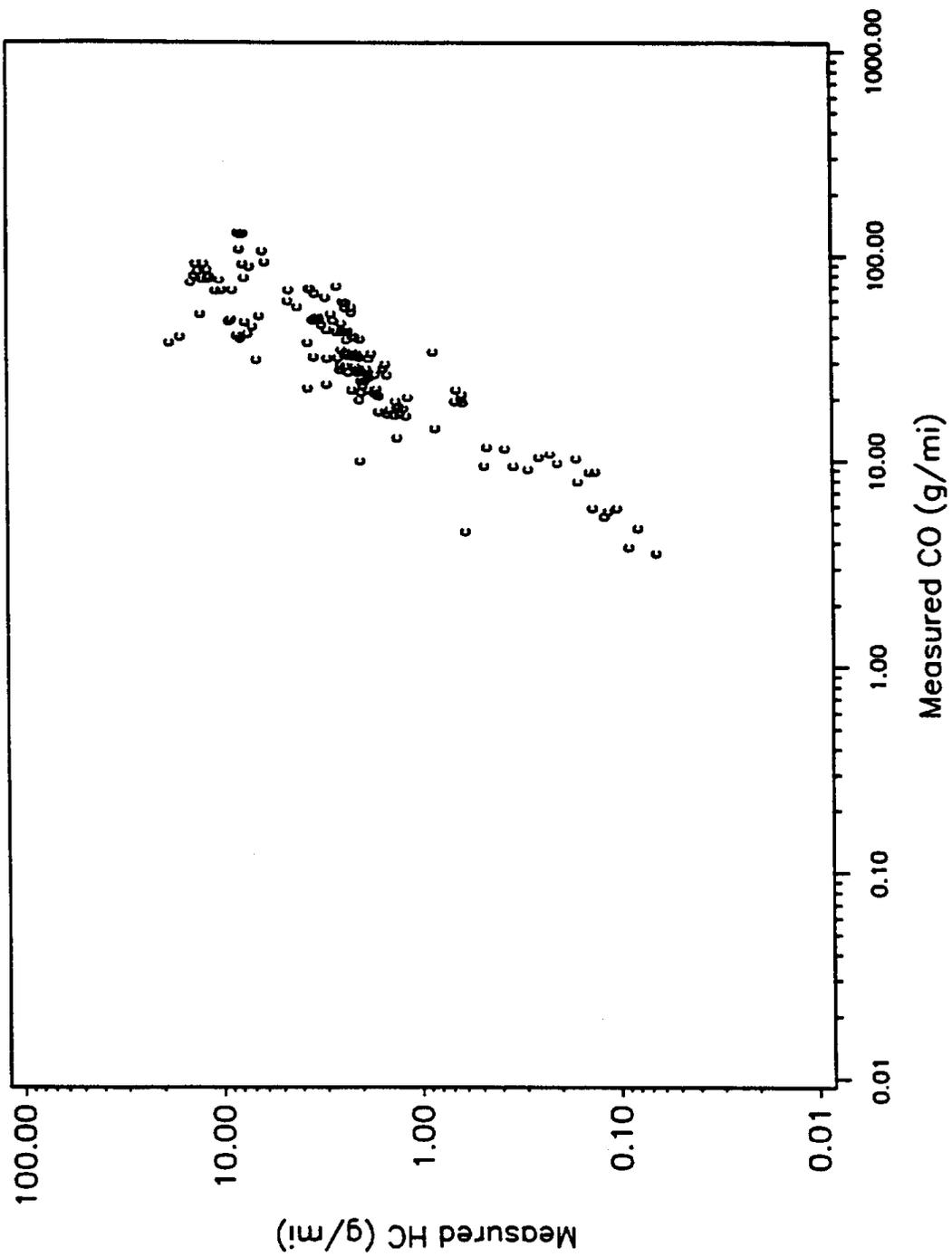
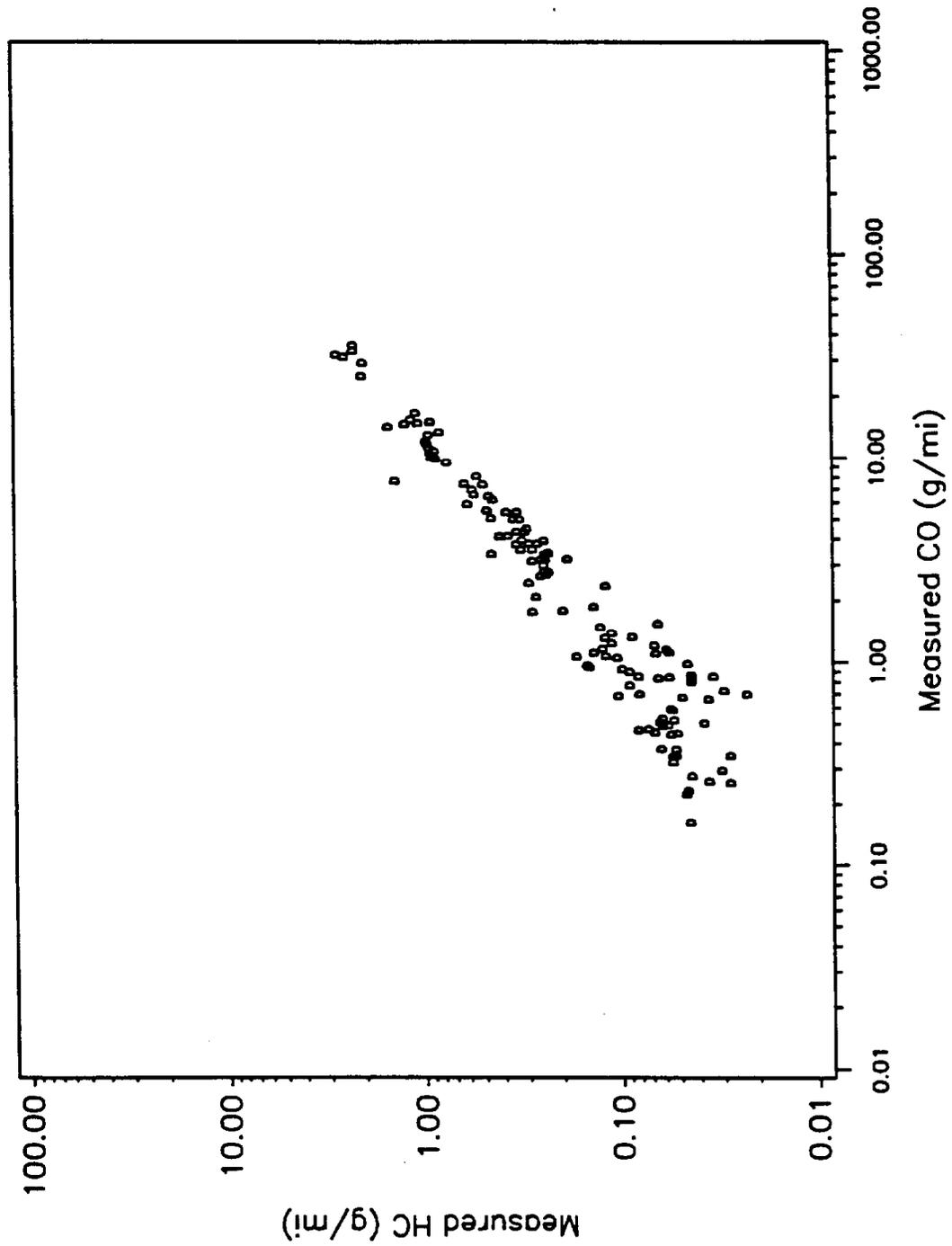


Figure 5-24
Correlation Plot of Exhaust HC and CO

VEHID=13 FUELSYS=MultiPoint EMSTECH=3wayAdaptive



13 individual vehicles on separate plots. These individual plots show that, with the exception of Vehicle 10, in general, conditions which produce reductions in the exhaust CO also produce reduced exhaust HC emissions. In the case of Vehicle 10, this also occurs up to a point. There, conditions which produce measured CO values below 10 grams per mile are characterized by measured HC emissions which do not go much below 1 gram per mile.

The following preliminary class regression statement was used to evaluate the main effects of the five parameters in the absence of any interactions:

$$\ln HC = \text{VEHID} \quad \text{CYCLE} \quad \text{BLENDTYP} \quad \text{TEMP} \quad \text{SEASON}$$

This analysis of variance indicated that the five parameters had the following order of magnitude effect on the $\ln HC$:

$$\text{CYCLE} > \text{VEHID} \gg \text{TEMP} > \text{SEASON} > \text{BLENDTYP}$$

Evaluation of the transformation to be used for the HC emissions was made by regressions against the following combination of effects:

$$\text{VEHID} \quad \text{VEHID} * \text{CYCLE} \quad \text{VEHID} * \text{BLENDTYP} \quad \text{CYCLE} * \text{TEMP} \quad \text{SEASON}$$

Both the HC emissions and the natural log of the HC emissions were regressed against these parameters and the residuals were examined for homogeneity. The regression using linear HC resulted in a funnel shaped residual pattern; the natural log of the HC emissions produced a homogeneous residual pattern. Therefore, the log of the HC emissions was the transformation chosen. In the process of doing these regressions, no outliers were found. All 1751 HC observations were used for subsequent analyses.

Then, a long series of regressions was used to try to discover the best model statement which would describe the HC emissions. The continuous oxygen concentration OXY was brought into the model statement as the interaction with $\text{VEHID} * \text{BLENDTYP}$. In the process of performing these regressions, several observations were made:

- The cycle had a strong effect on the HC emissions.
- The individual vehicle had a strong effect on the HC emissions.
- There was a strong interaction between cycle and vehicle. That is, vehicles responded differently to different cycles.
- There was a significant, but relatively weak, interaction between vehicle and blend type. In other words, vehicles responded slightly differently to a given blend type.
- The interaction between cycle and blend type was not significant. This indicates that a given blend type produced about the same size of HC emission change in one cycle as it did in another cycle.
- Blend season and temperature were difficult to examine because of the small size of the effects they produced, which tended to be buried in the noise of the data.
- Comparison of the HC responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel Y was significantly different from Fuel N, but Fuel X was not significantly different from Fuel N. Therefore, observations with Fuel Y were dropped from further considera-

tion for HC effects, and Fuels X and N were considered the same fuel for further HC regressions. This left 1667 HC observations.

The best overall model which described the emissions of the individual vehicles was given by:

$$\ln HC = \text{VEHID} * \text{CYCLE} \quad \text{CYCLE} * \text{TEMP} \quad \text{SEASON} \quad \text{VEHID} * \text{BLENDTYP} * \text{OXY}$$

The regression fit the measured CO values with a standard deviation of about 37%, the r^2 was 0.935, and the model F was 188. The SAS output and parity plot of the regression are given in Appendix K.

To assist in the assignment of general vehicle technology behavior factors, the vehicles which have similar behavior can be classified together. Classifications were made by performing alternative regressions by substitution of technology parameters for vehicle parameters in the above equation. The VEHID in VEHID*BLENDTYP*OXY was replaced with technology candidate parameters for emission control technology (EMSTECH), fuel induction system (FUELSYS), canister bottom type (CNSTR), or engine displacement (DISP). The VEHID in VEHID*CYCLE was retained for these regressions, since the emissions performance of individual vehicles within the same technology grouping will vary considerably due to the idiosyncrasies of each individual vehicle.

The overall results of this exercise indicated that EMSTECH provided the best technology grouping. The EMSTECH groups were Non-Catalyst, Oxy-Catalyst, TWC/NAL, and TWC/AL. The best exhaust HC regression model using EMSTECH groupings was found to be:

$$\ln HC = \text{VEHID} * \text{CYCLE} \quad \text{CYCLE} * \text{TEMP} \quad \text{SEASON} \quad \text{EMSTECH} * \text{BLENDTYP} * \text{OXY}$$

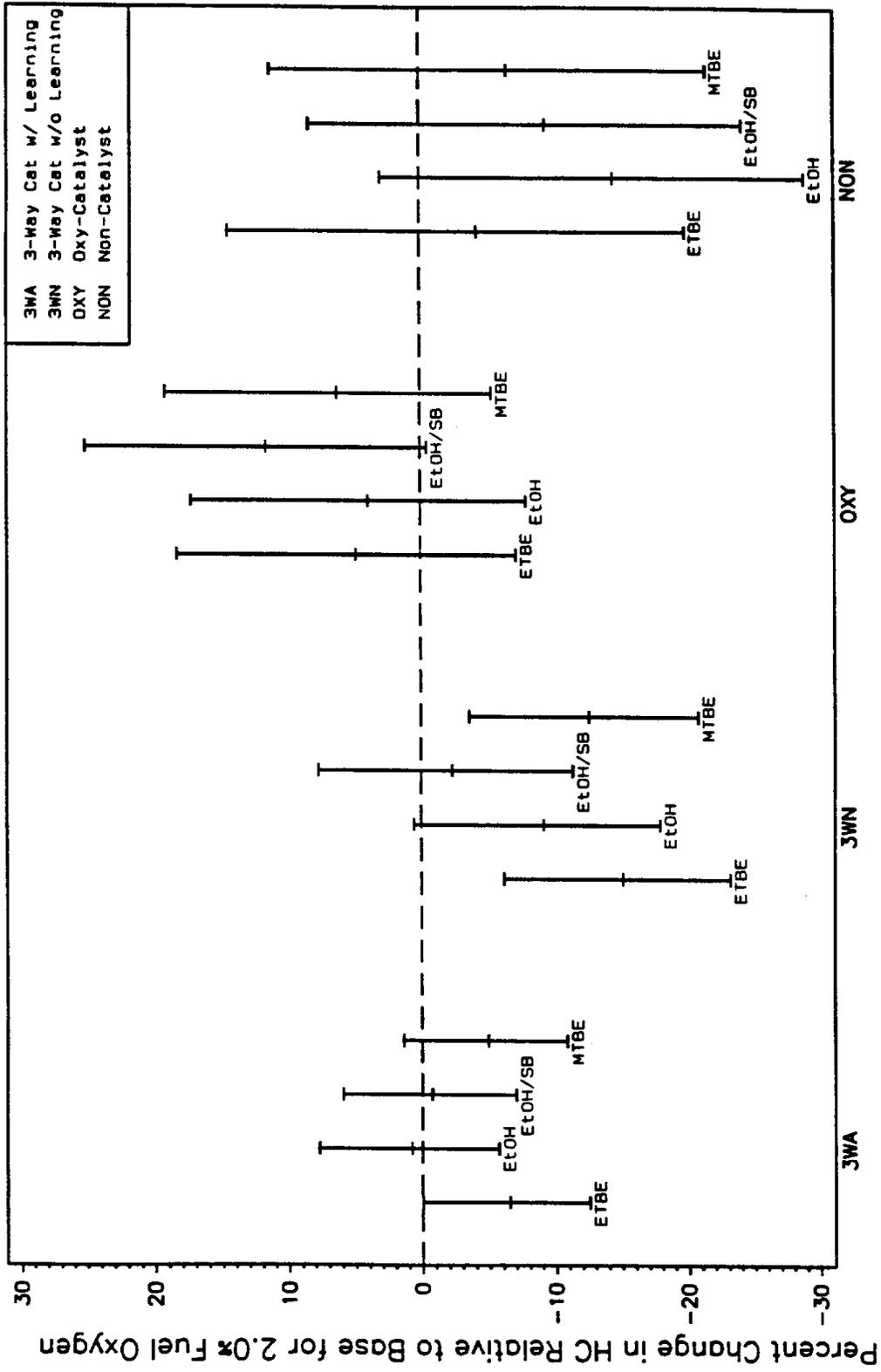
The SAS output listing and the parity plot from this final technology-based regression are given in Appendix K. From this regression, the effects on HC emissions relative to the combined base fuels (Base and LowRVPBase) for the four EMSTECH groups are shown in Figure 5-25. Note that the vertical axis is the percent change in HC with respect to the combined Base fuels for an oxygenated fuel blend with 2.0% oxygen. The expected effects for 2.7% oxygen fuel would be about 27/20 times the effects shown in the figure. The error bars give the 95% confidence limits on the mean value.

The plot shows that for the TWC/AL, ETBE produced significant reductions of exhaust hydrocarbon emissions relative to the combined base fuels, but the other blends did not. Also, ETBE has significantly lower HC than EtOH. For TWC/NAL vehicles, ETBE and MTBE blends produced significant reductions in hydrocarbon emissions and were significantly lower than EtOH/SB. EtOH and EtOH/SB did not produce significant HC reductions relative to the base fuels. For the two oxy-catalyst vehicles and the non-catalyst vehicle, the uncertainty in the reductions was great enough that for all blend types the reductions were not statistically significant. Note for the first two technologies, the HC emissions response with respect to blend type: ETBE and MTBE tended to produce the lower HC than EtOH and EtOH/SB, but this tendency was not always statistically significant.

The regression also indicated that the summer blends produced 9 percent lower HC emissions than the winter blends, and this difference was significant at the 95% confidence level. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

Effect of Blend Type on HC Emissions

Model: lnHC = vehid*cycle*temp*season*emstech*blendtyp*oxy



Exhaust Emission Control Technology

4. *Exhaust Total Nitrogen Oxides (NO_x)*. The results of the exhaust NO_x measurements are given in the table in Appendix E. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The NO_x emissions in grams per mile are listed as a function of vehicle (VEHID), blend season (SEASON), temperature (TEMP), blend type (BLENDTYP), and driving cycle (CYCLE). Test date (TESTDATE) is used in the table to make the distinction between results from replicate tests.

Just as for exhaust HC, exhaust NO_x can be compared with the exhaust CO measurements. For all of the observations, this is done in Figure 5-26. This plot looks different than the plot between HC and CO measurements. Instead of a relatively linear correlation between the two parameters, the NO_x versus CO plot is much more scattered. To help better visualize the relationships between NO_x and CO, the plots for the data taken on individual vehicles are shown in Figures 5-27 to 5-39. Three general trends with the data can be seen. For Vehicles 2, 3, 7, 10, and 12, the relationship between NO_x and CO is flat. That is, as CO is reduced, NO_x remains about the same. For Vehicles 1, 5, 8, 11, and 13, as the measured CO drops, the measured NO_x drops slightly. For Vehicles 4, 6, and 9, as the measured CO drops, the measured NO_x drops a great deal. Vehicle 4 showed the greatest reduction in NO_x with respect to the reduction in CO.

The following preliminary class regression statement was used to evaluate the main effects of the five parameters on NO_x in the absence of any interactions:

$$\ln \text{NO}_x = \text{VEHID} \text{ CYCLE} \text{ BLENDTYP} \text{ TEMP} \text{ SEASON}$$

This analysis of variance indicated that the five parameters had the following order of magnitude effect on the $\ln \text{NO}_x$:

$$\text{VEHID} > \text{CYCLE} \gg \text{TEMP} > \text{BLENDTYP} > \text{SEASON}$$

Evaluation of the transformation to be used for the NO_x emissions was made by regressions against the following combination of effects:

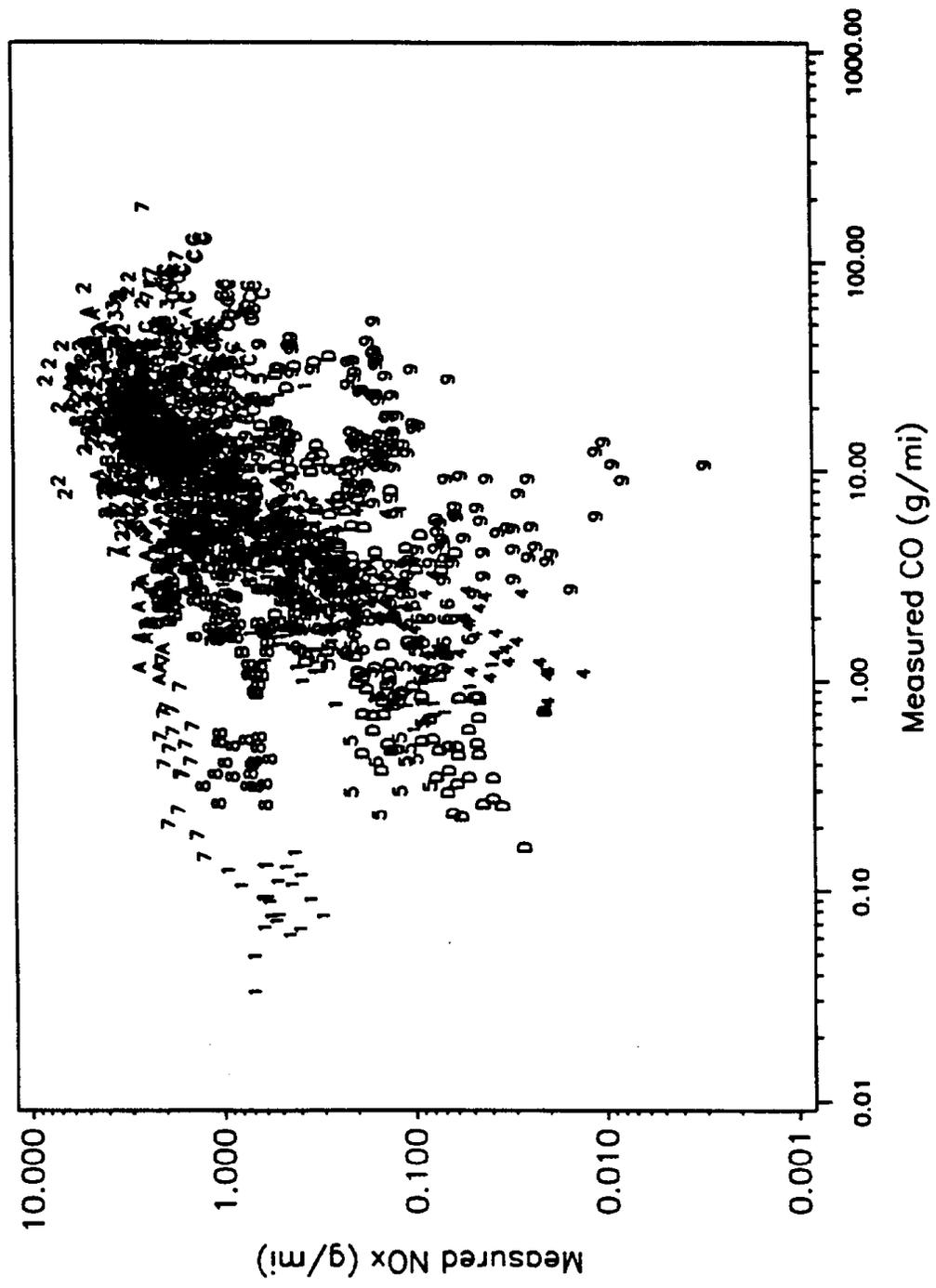
$$\text{VEHID} \quad \text{VEHID} * \text{CYCLE} \quad \text{TEMP} \quad \text{VEHID} * \text{BLENDTYP}$$

The NO_x emissions, the natural log of the NO_x emissions, and NO_x^{0.2} were regressed against these parameters and the residuals were examined for homogeneity. The regression using linear NO_x produced a funnel shaped residual pattern opening to the right; the natural log of the NO_x emissions produced a funnel shaped residual pattern opening to the left, and the NO_x^{0.2} produced a homogeneous residual pattern. Therefore, the NO_x^{0.2} was the transformation chosen. In the process of doing these regressions, three data points were found to be outliers and were removed from further regressions: Vehicle 6/75°/Fuel N/NYCC on 18MAR92 = 0.125 g/mi, Vehicle 13/95°/Fuel U/NYCC on 21AUG92 = 1.348 g/mi, and Vehicle 6/95°/Fuel M/NYCC on 5MAY92 = 5.39 g/mi. This left 1748 data points to be analyzed.

Then, a long series of regressions was used to try to discover the best model statement which would describe the NO_x emissions. The continuous oxygen concentration OXY was brought into the model statement as the interaction with VEHID*BLENDTYP. In the process of performing these regressions, several observations were made:

- The individual vehicle had a strong effect on the NO_x emissions.
- The cycle had a strong effect on the NO_x emissions.

Figure 5-26
 Correlation Plot of Exhaust NOx and CO



VEHD	111	1	222	2	333	3	444	4	555	5	666	6	777	7	888	8	999	9	AAA	10	BBB	11	CCC	12	DDD	13
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Figure 5-27
Correlation Plot of Exhaust NOx and CO

VEHID=1 FUELSYS=Multipoint EMSTECH=3wayAdaptive

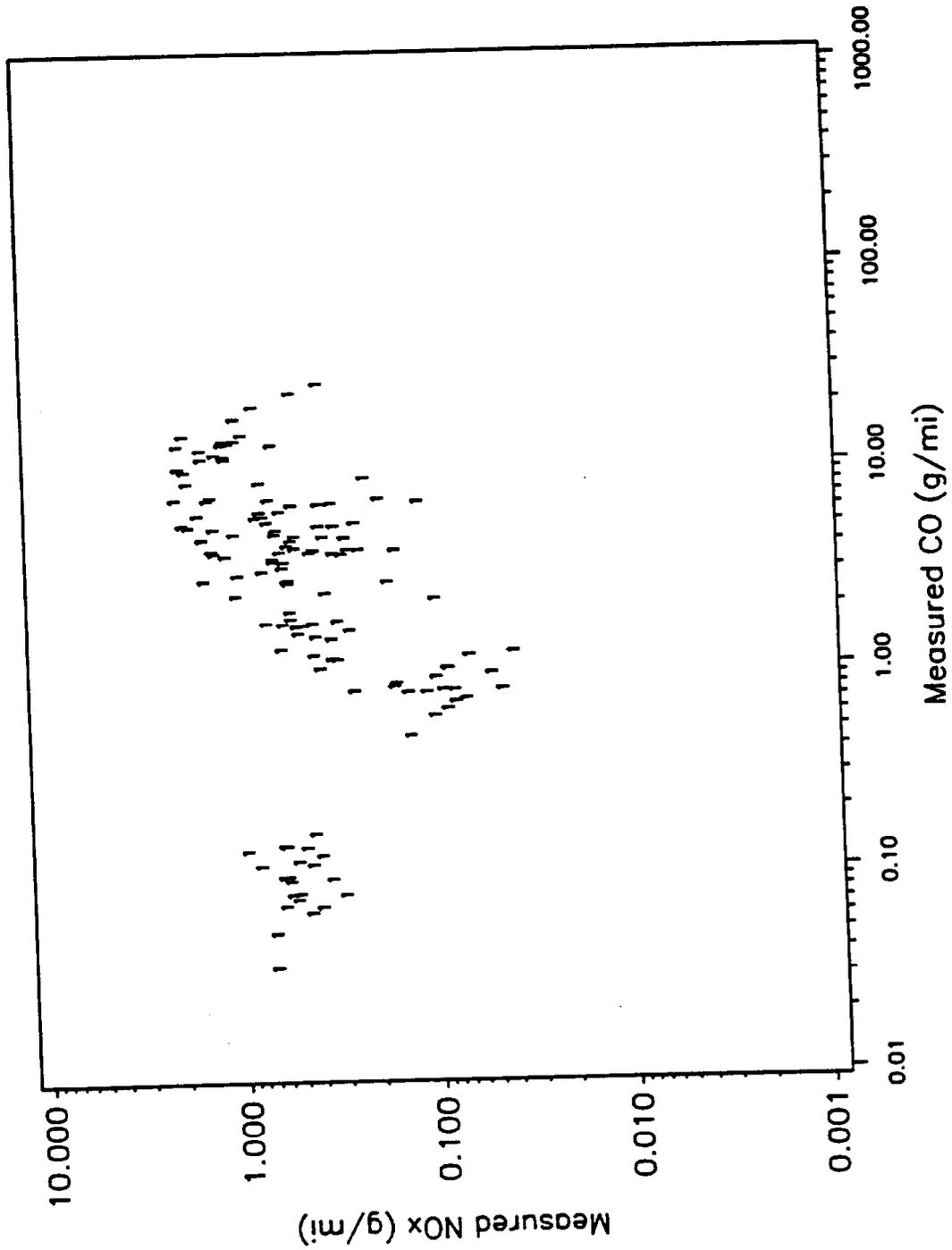


Figure 5-28
Correlation Plot of Exhaust NOx and CO

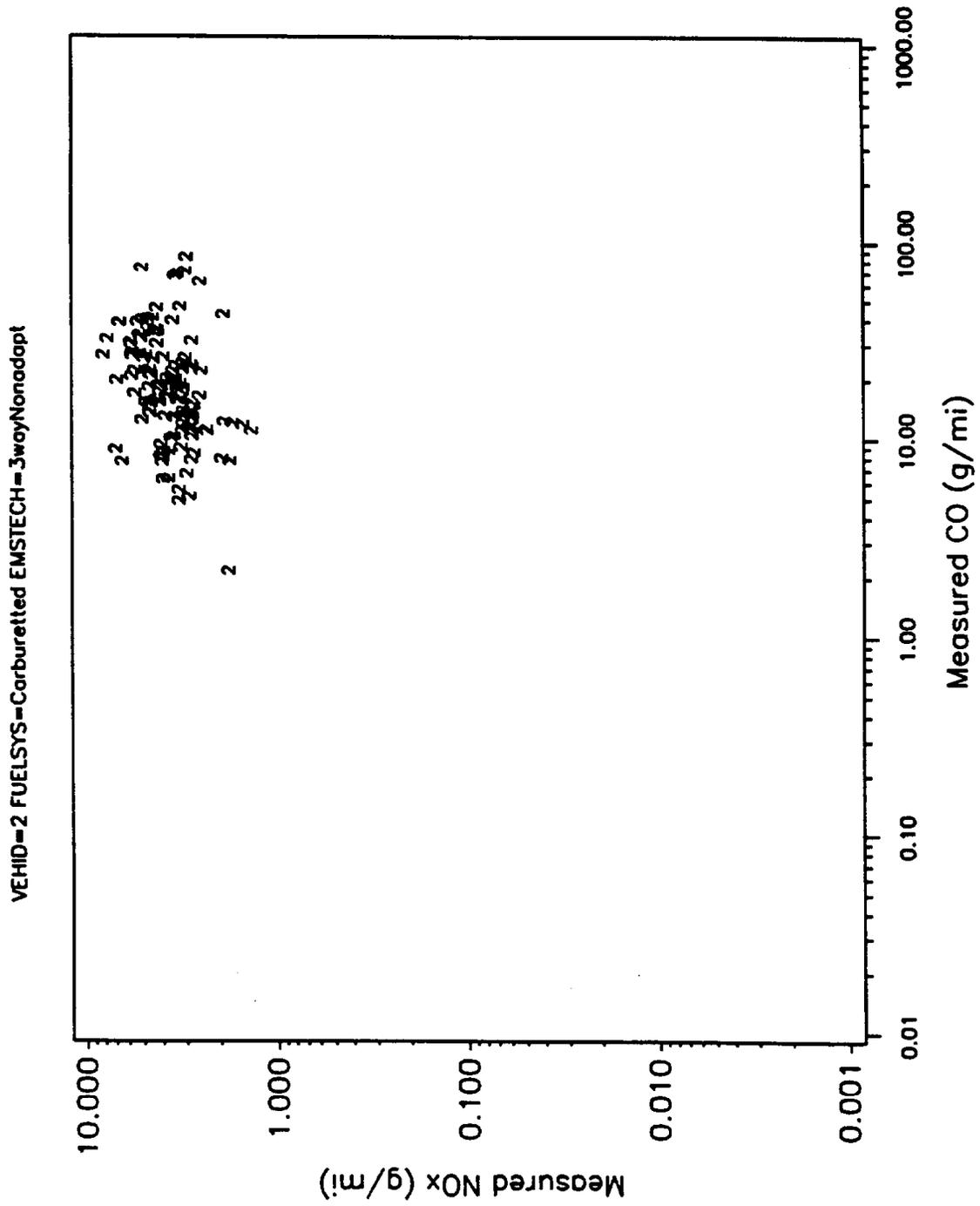


Figure 5-29
Correlation Plot of Exhaust NOx and CO

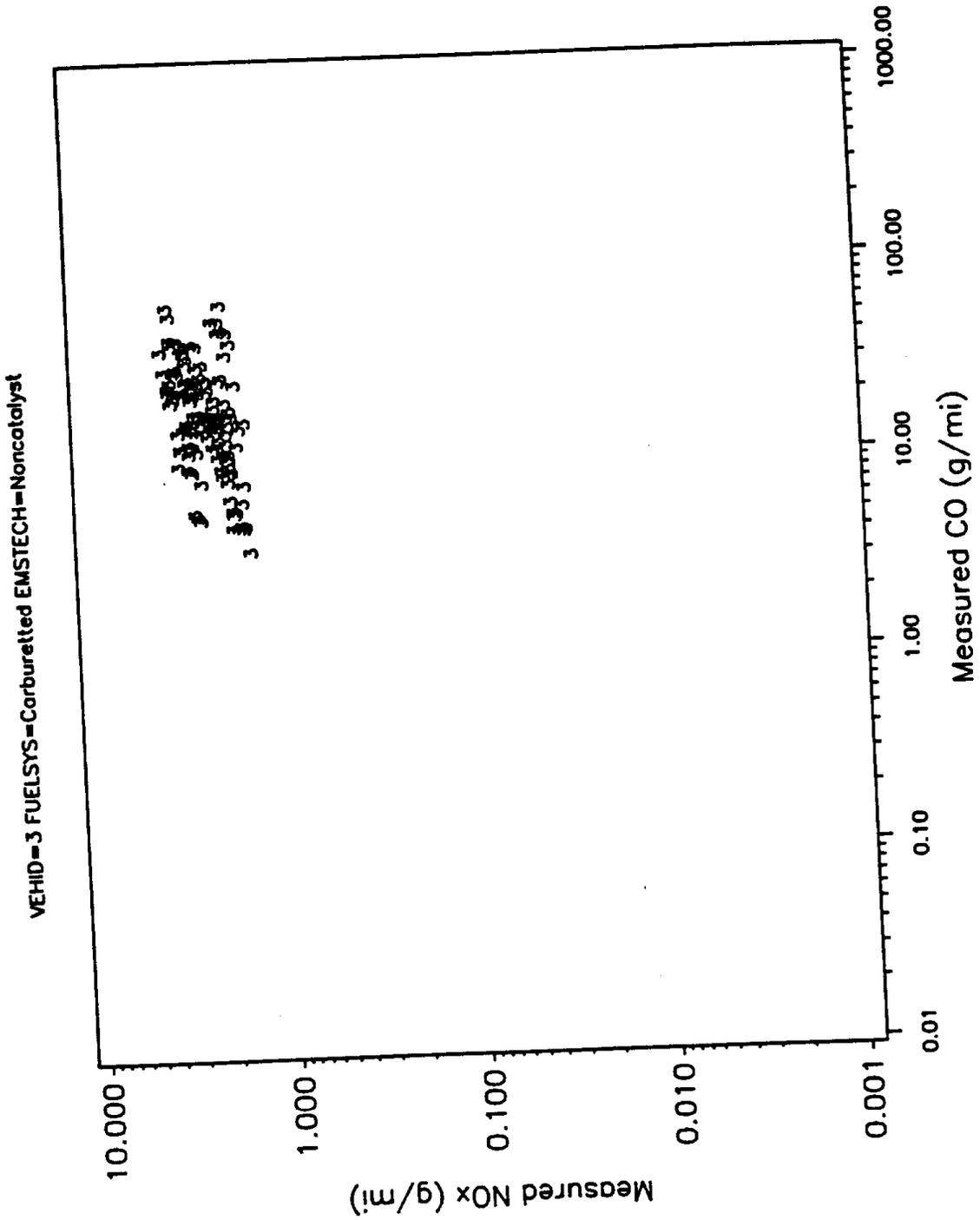


Figure 5-30
Correlation Plot of Exhaust NOx and CO

VEHID=4 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

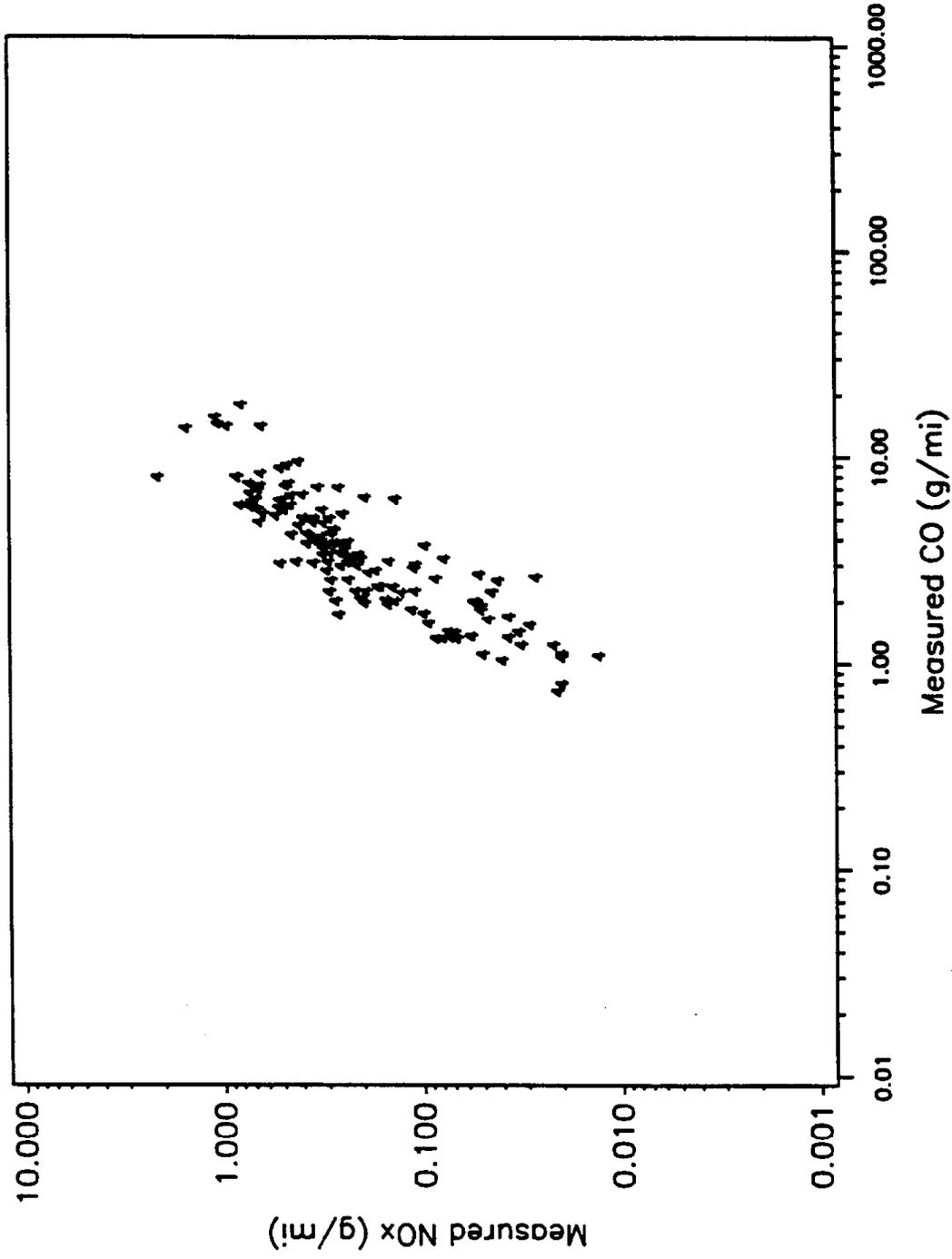


Figure 5-31
Correlation Plot of Exhaust NOx and CO

VEHID=5 FUELSYS=MultiPoint EMSTECH=3wayAdaptive

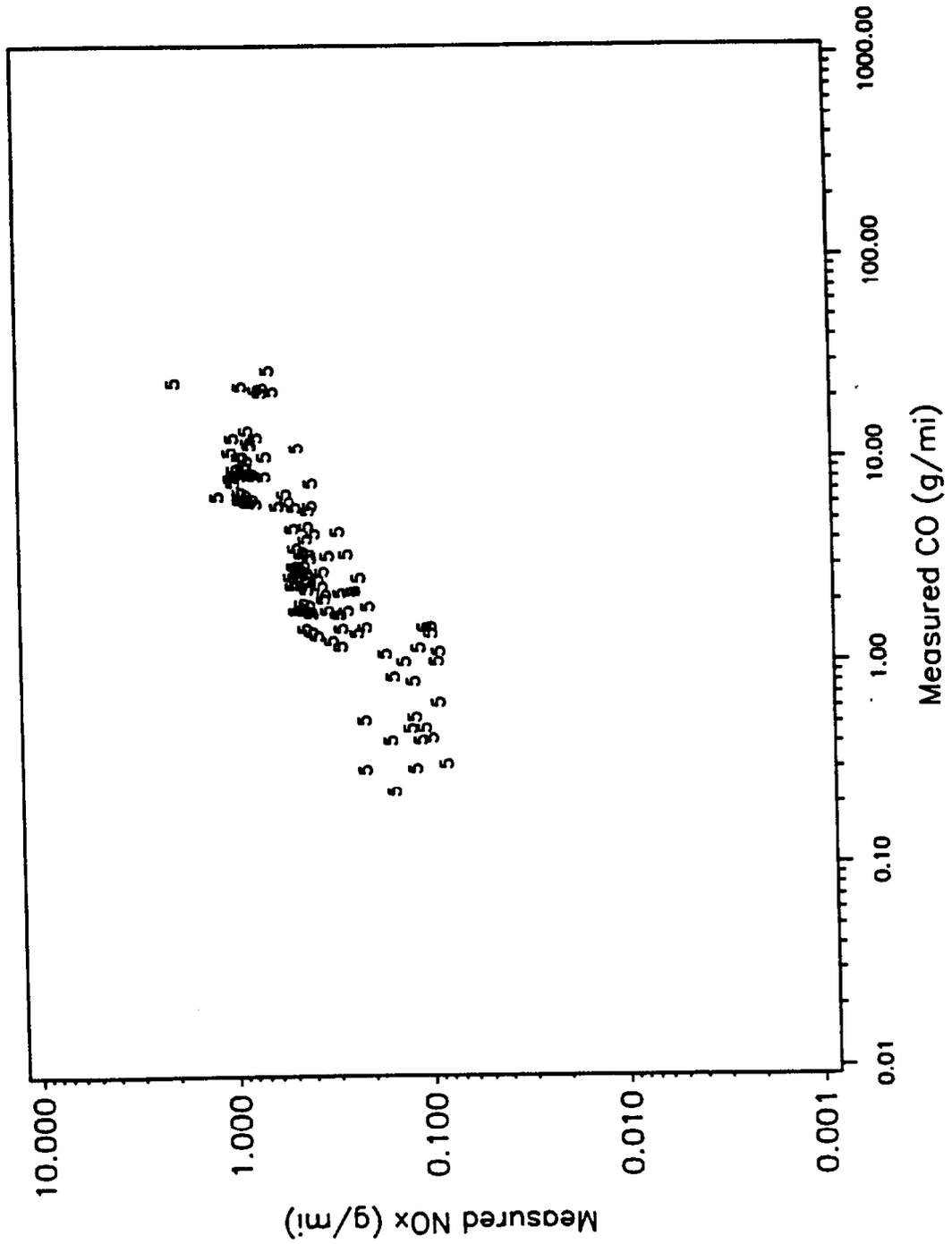


Figure 5-32 Correlation Plot of Exhaust NOx and CO

VEHID=6 FUELSYS=MultiPoint EMSTECH=JwayAdaptive

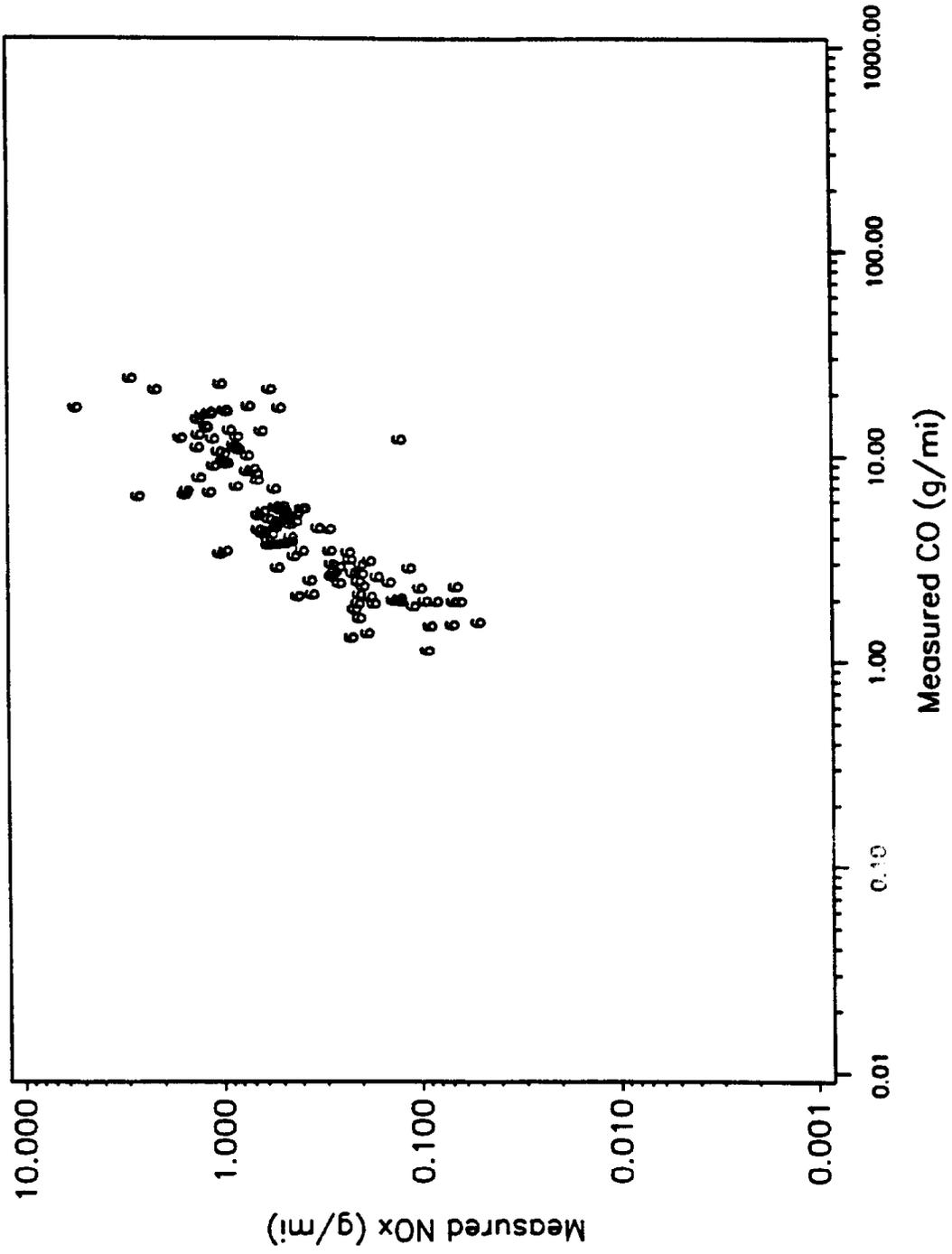


Figure 5-33
Correlation Plot of Exhaust NOx and CO

VEHID=7 FUELSYS=Carburetted EMSTECH=3wayNonodapt

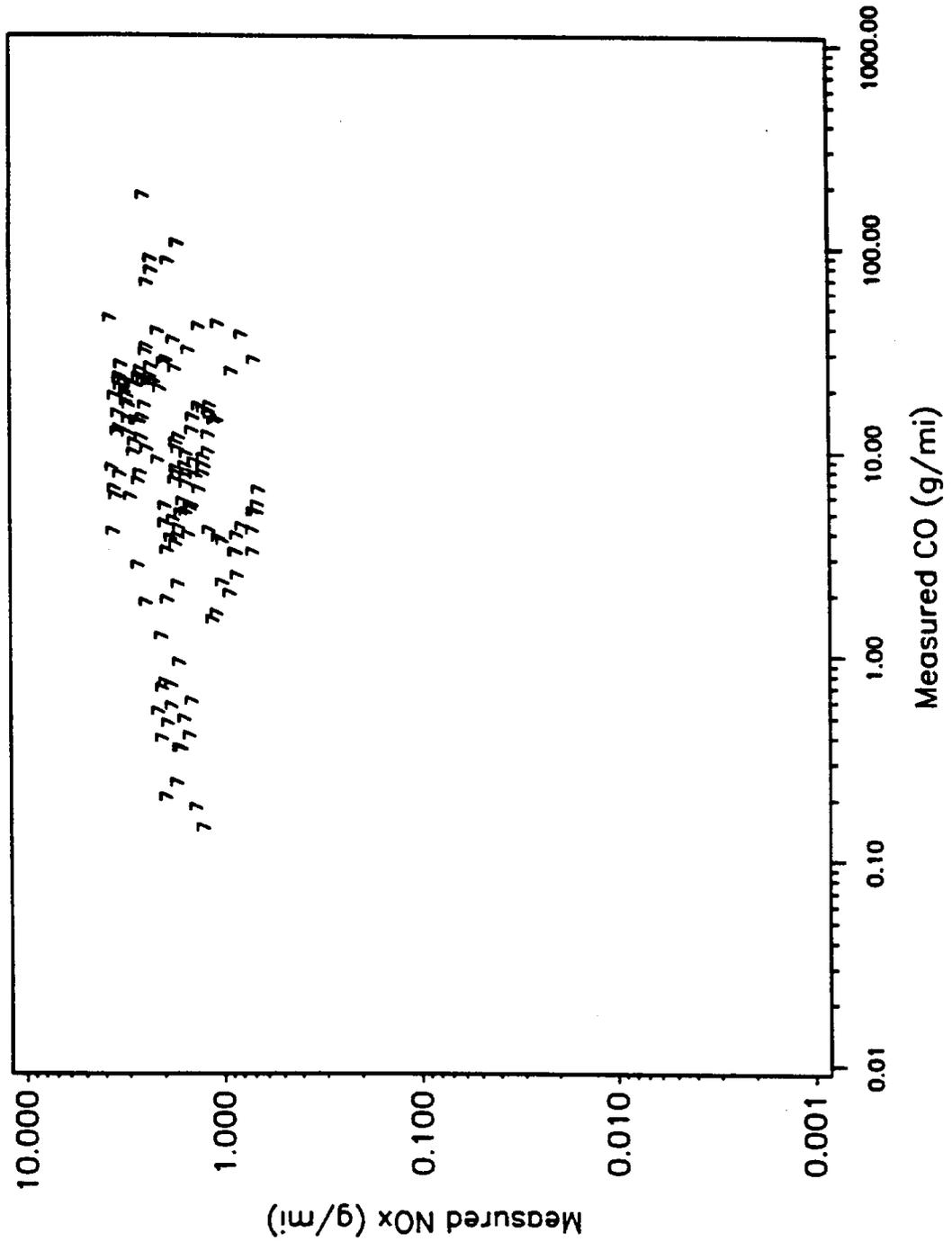


Figure 5-34
Correlation Plot of Exhaust NOx and CO

VEHID=8 FUELSYS=MultiPoint EMSTECH=JwoyAdaptive

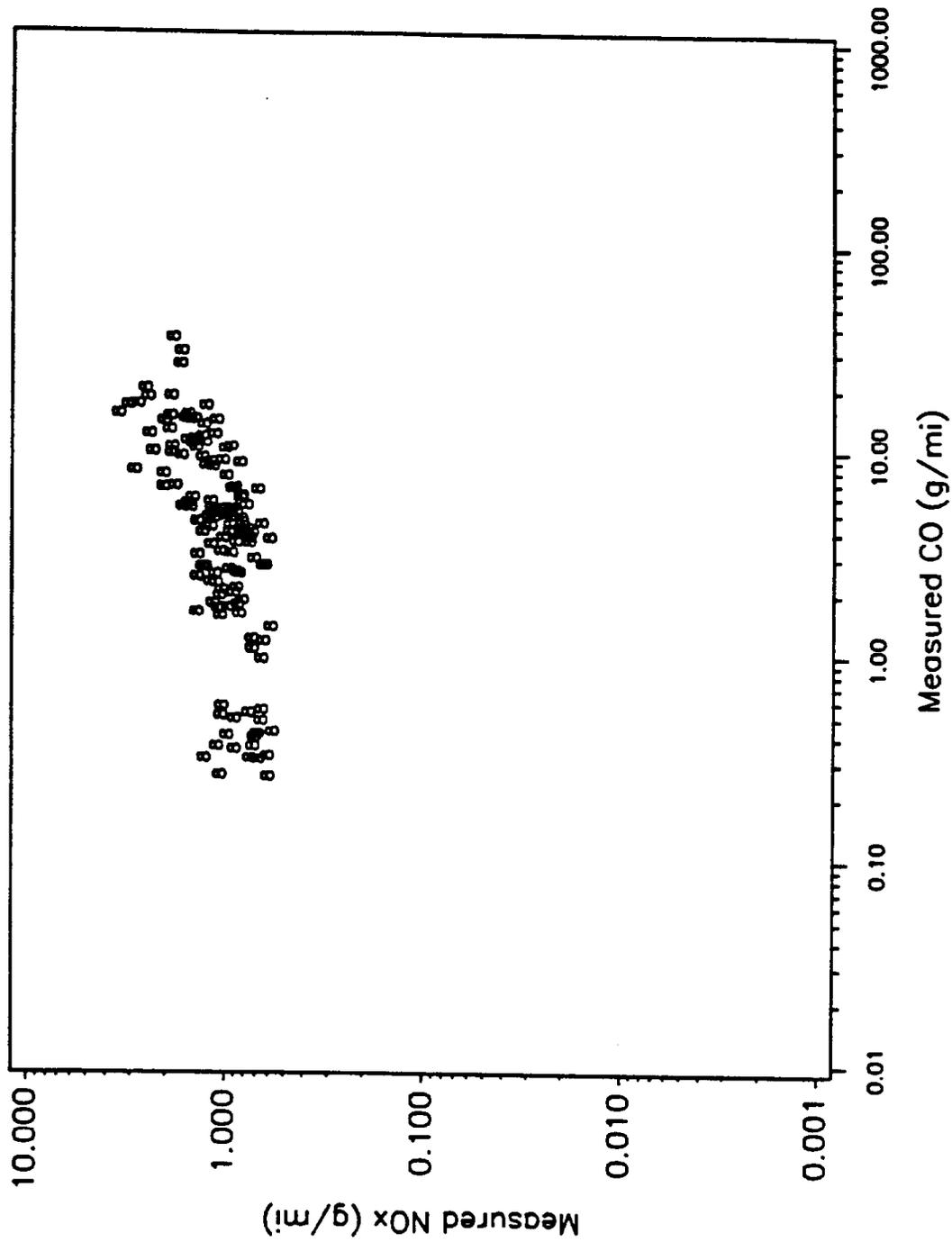


Figure 5-35
Correlation Plot of Exhaust NOx and CO

VEHID=9 FUELSYS=ThrottleBody EMSTECH=JwayAdaptive

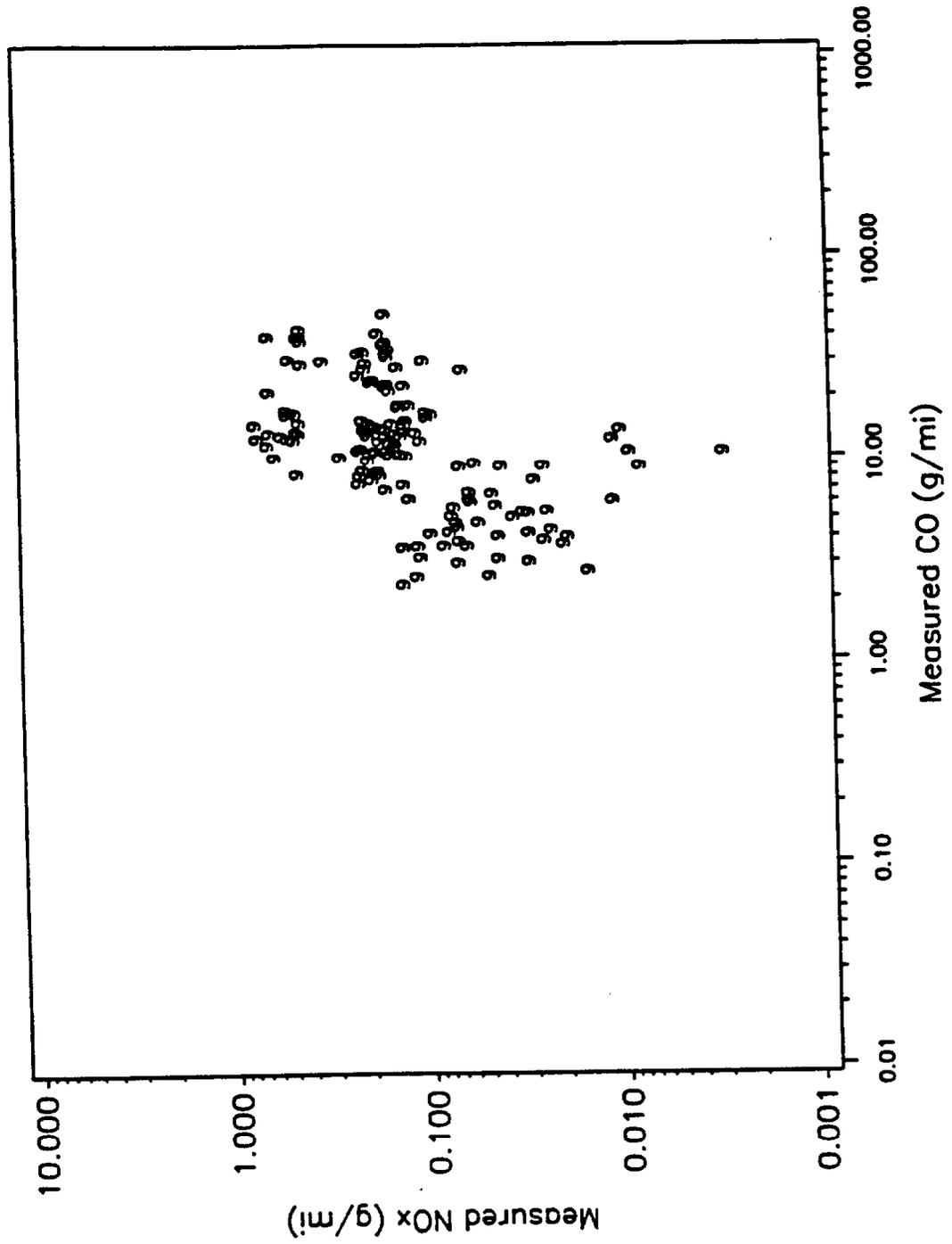


Figure 5-36
Correlation Plot of Exhaust NOx and CO

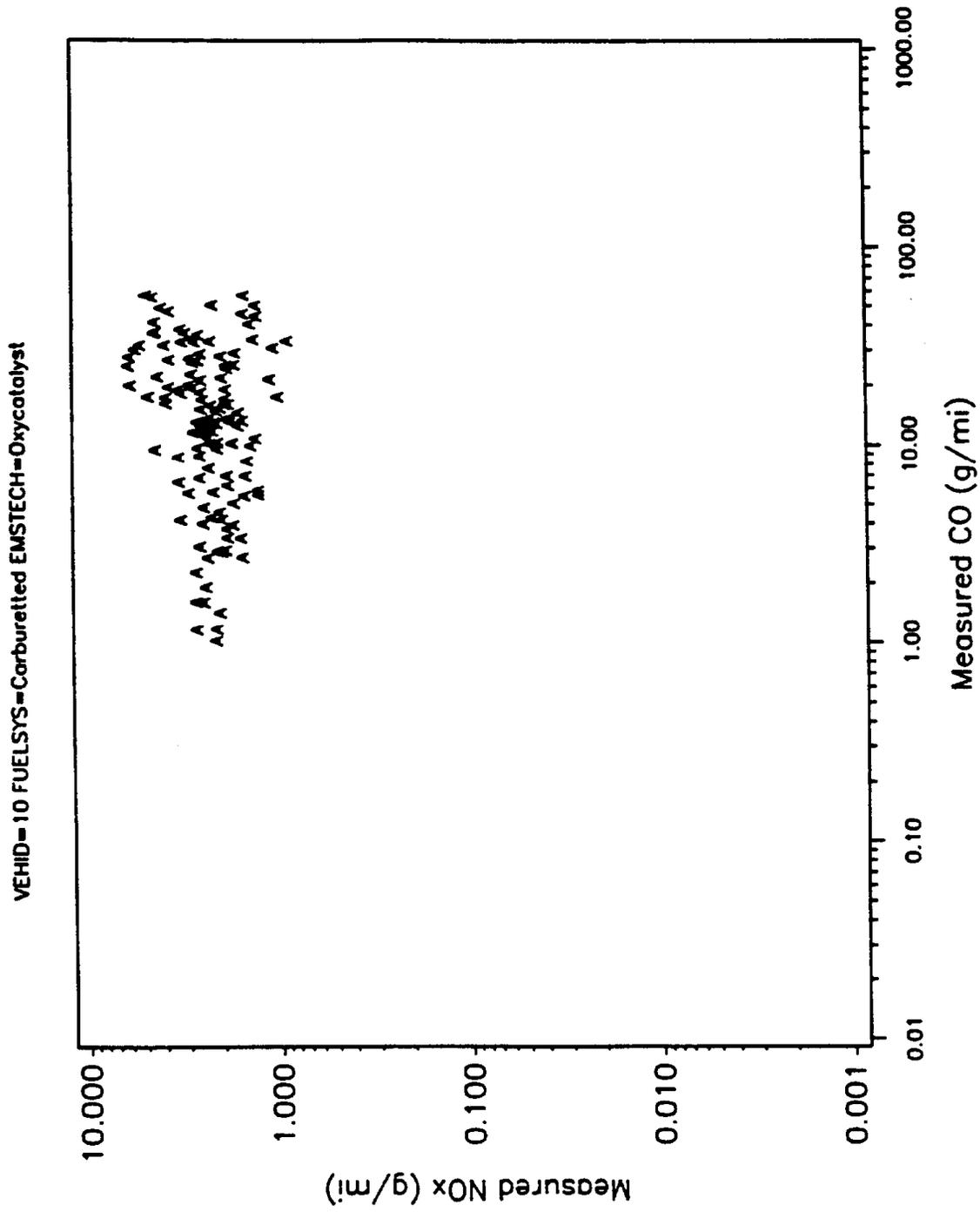


Figure 5-37
Correlation Plot of Exhaust NOx and CO

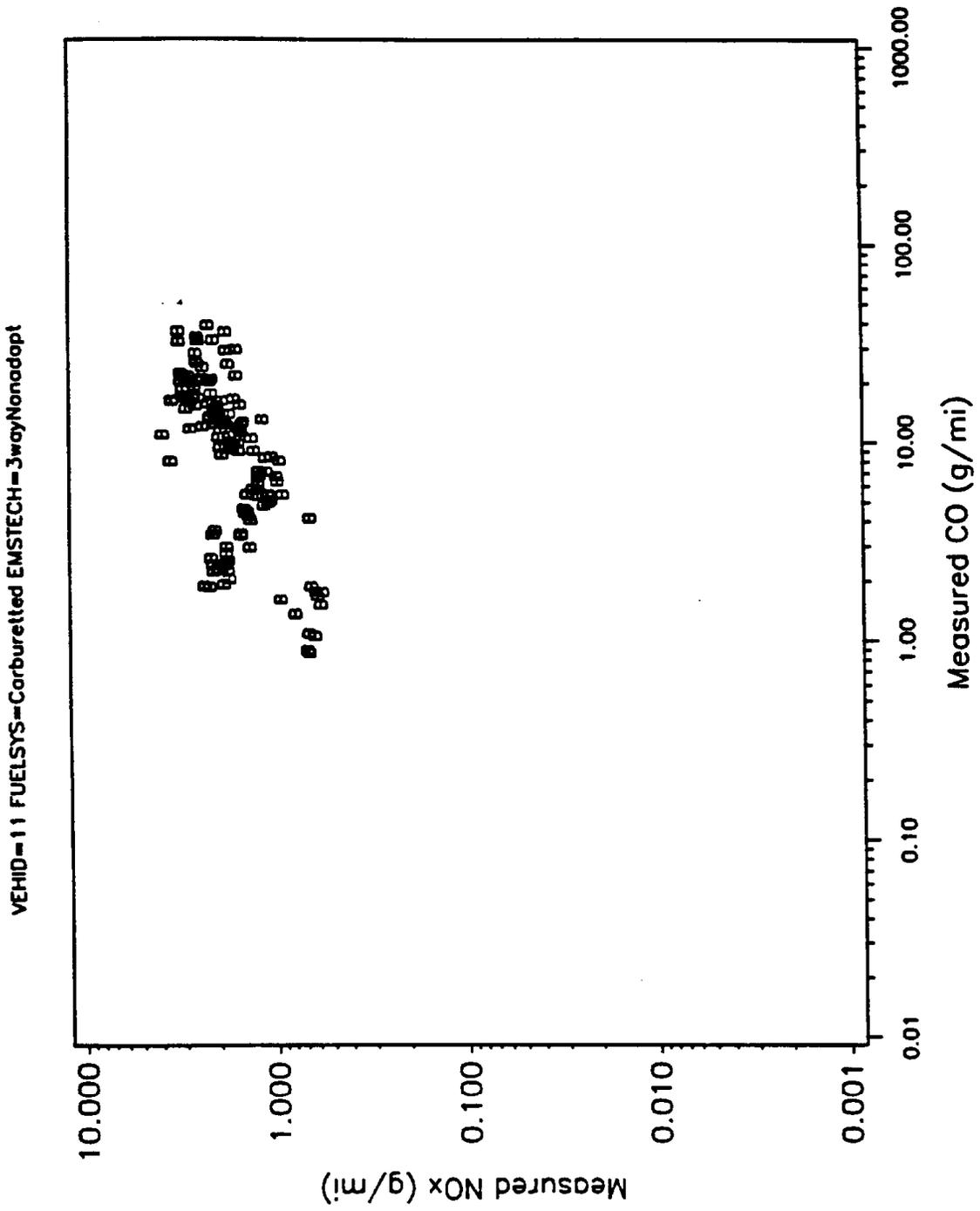


Figure 5-38
Correlation Plot of Exhaust NOx and CO

VEHID= 12 FUELSYS=Carburetted EMSTECH=Oxycatalyst

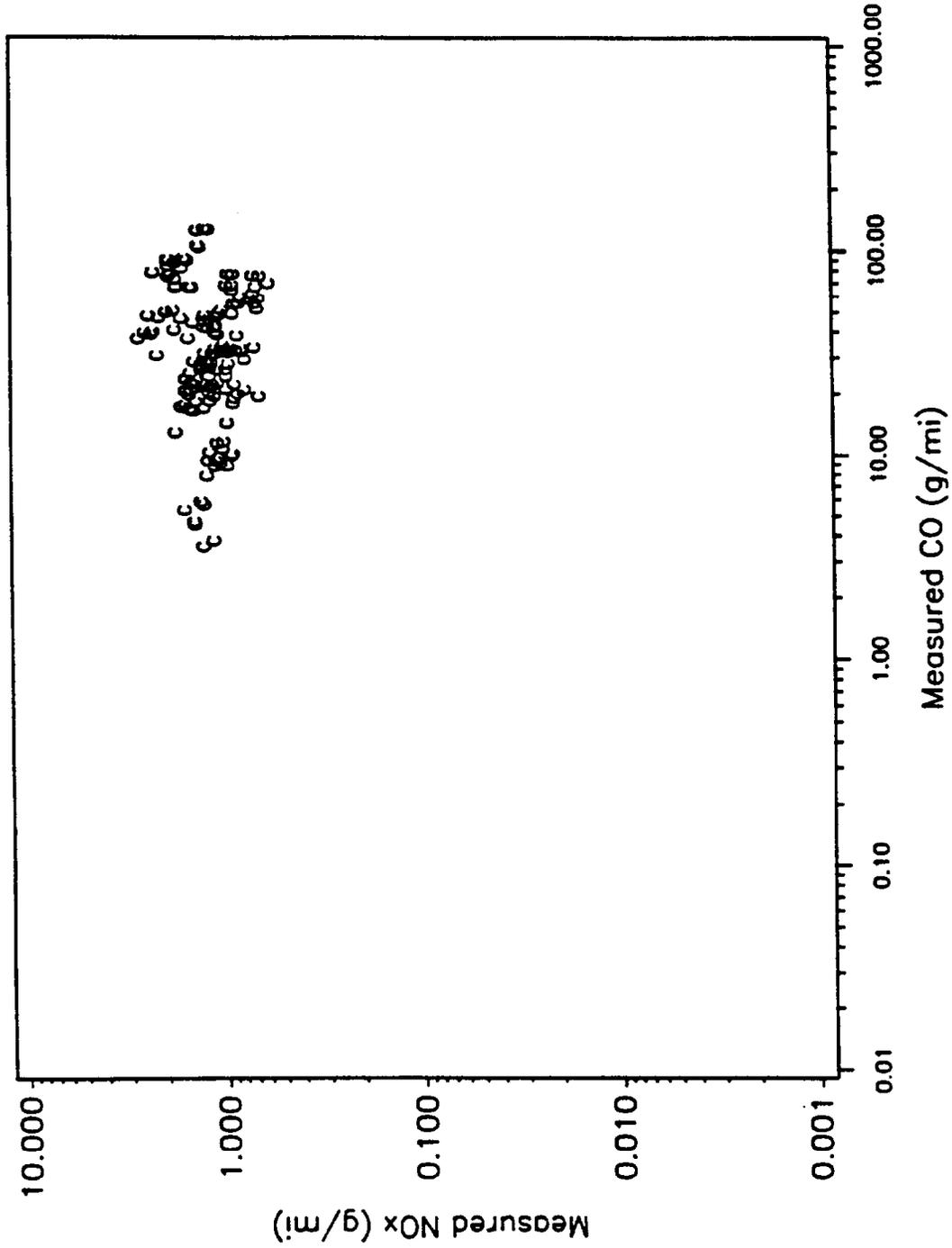
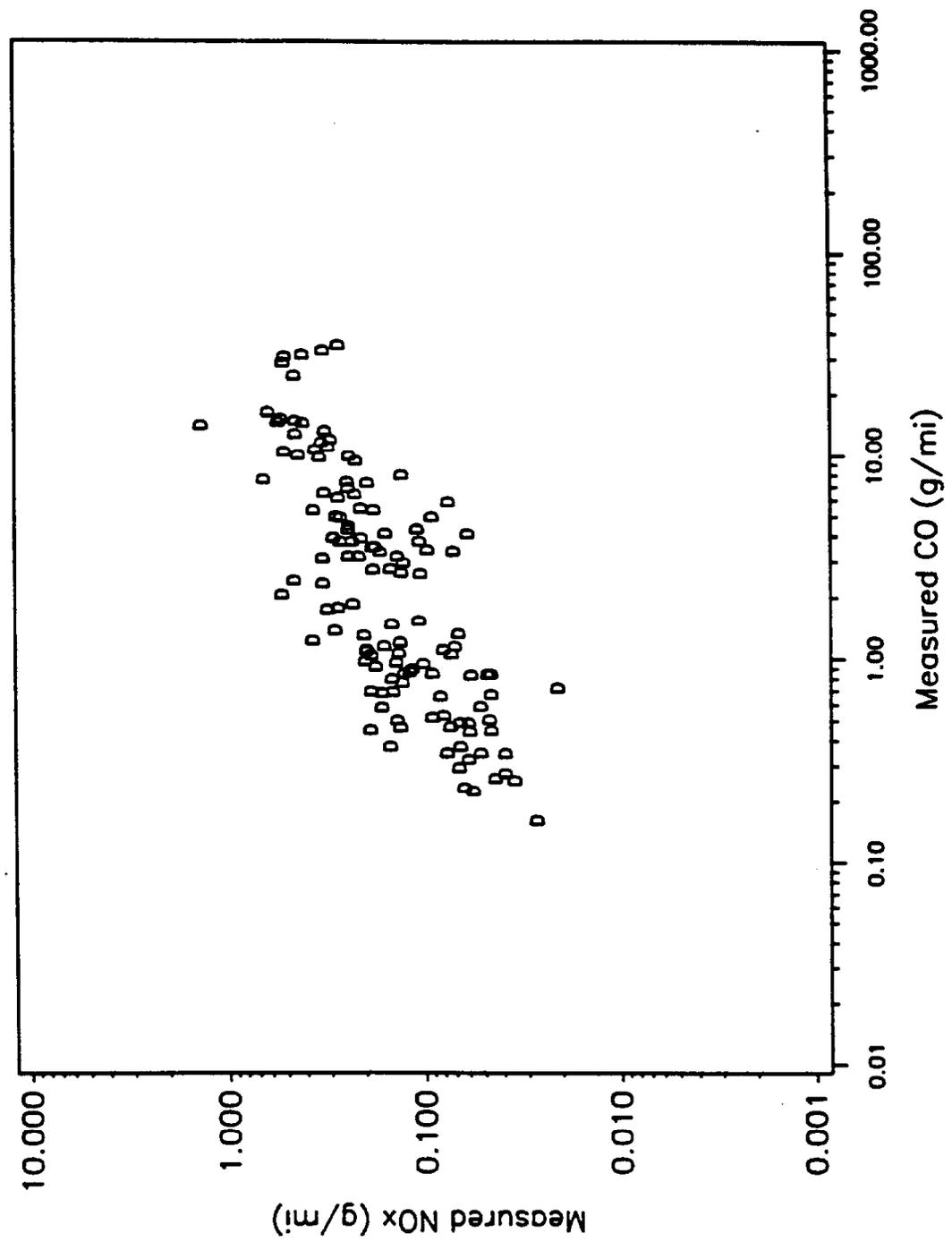


Figure 5-39
Correlation Plot of Exhaust NOx and CO

VEHID=13 FUELSYS=MultiPoint EMSTECH=3wayAdaptive



- There was a strong interaction between cycle and vehicle. That is, vehicles responded differently to different cycles.
- There was a significant, but relatively weak, interaction between vehicle and blend type. In other words, vehicles responded slightly differently to a given blend type.
- The interaction between cycle and blend type was not significant. This indicates that a given blend type produced about the same size of NO_x emission change in one cycle as it did in another of the cycles tested.
- Blend season produced no significant effects on NO_x in any of the regressions tested.
- Comparison of the NO_x responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel Y was significantly different from Fuel N, but Fuel X was not significantly different from Fuel N. Therefore, observations with Fuel Y were dropped from further consideration for NO_x effects, and Fuels X and N were considered the same fuel for further NO_x regressions. This left 1664 NO_x observations.

The best overall model which described the emissions of the individual vehicles was given by:

$$\text{NO}_x^{0.2} = \text{VEHID} \text{ VEHID}*\text{CYCLE} \text{ VEHID}*\text{TEMP} \\ \text{VEHID}*\text{BLENDTYP}*\text{OXY}$$

The regression fit the measured NO_x^{0.2} values with a standard deviation of about 0.047, the r² was 0.960, and the model F was 4828. The SAS output and parity plot of the regression are given in Appendix K.

To assist in the assignment of general vehicle technology behavior factors, the vehicles which have similar behavior can be classified together. Classifications were made by performing alternative regressions by substitution of technology parameters for vehicle parameters in the model statement above. The VEHIDs in the three interactions were sequentially replaced with technology parameters for emission control technology (EMSTECH), fuel induction system (FUELSYS), canister bottom type (CNSTR), or engine displacement (DISP). The main effect of VEHID was retained for these regressions, since the emissions performance of vehicles within the same technology grouping will vary considerably due to the idiosyncrasies of each individual vehicle.

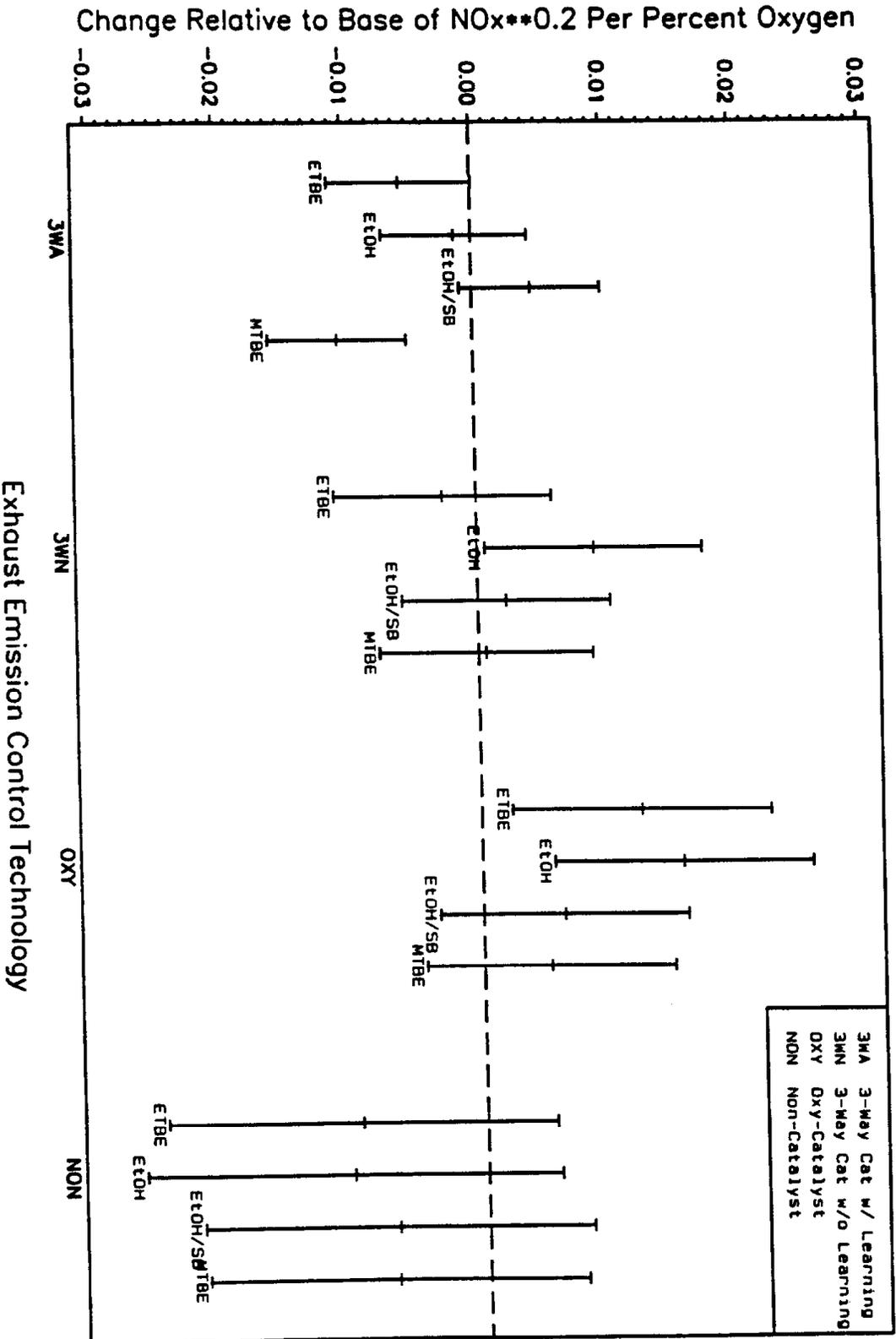
The overall results of this exercise indicated that EMSTECH provided the best technology grouping. The EMSTECH groups were Non-Catalyst, Oxy-Catalyst, TWC/NAL, and TWC/AL. Then, the best exhaust NO_x regression model using EMSTECH groupings was found to be:

$$\text{NO}_x^{0.2} = \text{VEHID} \text{ EMSTECH}*\text{CYCLE} \text{ EMSTECH}*\text{TEMP} \\ \text{EMSTECH}*\text{BLENDTYP}*\text{OXY}$$

The SAS output listing and the parity plot from this final technology-based regression are given in Appendix K. From this regression, the effects on NO_x emissions relative to the combined base fuels (Base and LowRVPBase) for the four EMSTECH groups are shown in Figure 5-40. Note that the vertical axis is the change per percent oxygen with respect to the combined Base fuels of NO_x measured in grams per mile and raised to the 0.2 exponent. The error bars give the 95% confidence limits on the mean value.

Figure 5--4U Effect of Blend Type on NOx Emissions

Model: NOx**0.2 = vehid emstech*cycle emstech*temp emstech*blendtyp*oxy



Because the magnitude of effects in $\text{NO}_x^{0.2}$ by the blends are difficult to visualize in terms of untransformed NO_x , Figure 5-41 is provided. Reductions in $\text{NO}_x^{0.2}$ cannot be expressed as a constant reduction in NO_x or as a constant percent reduction in NO_x . Therefore, the figure shows the percent reduction in NO_x relative to a base fuel emission level of 1 g/mi for each blend type with a 2.0% oxygen content. The percent reductions for other base fuel emission levels and other oxygen contents can be calculated using the regression results given in Appendix E.

From Figure 5-41 several observations can be made. For the TWC/AL vehicles, ETBE and MTBE produced significant reductions in NO_x , and EtOH/SB produced significantly higher NO_x than all three other blend types. For the TWC/NAL vehicles, EtOH produced a significant increase in NO_x , but EtOH/SB did not. ETBE and MTBE produced significantly lower NO_x than EtOH. The two oxy-catalyst vehicles showed significant increases in NO_x for ETBE and EtOH and no significant changes for the other blends. The non-catalyst vehicle did not show significant changes in NO_x for any of the blends.

Other regressions indicated that the summer blends and the winter blends had no difference in NO_x emissions. While the oxygen contents of the blends were different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

5. *Estimated Photochemical Reactivity of Exhaust Hydrocarbons.* The results of the exhaust estimated ozone production (EOP) calculations are given in the table in Appendix F. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The EOP for each test condition was determined by calculating the scalar product of the Carter reactivity factors (MIR) and the speciation results for volatile organic compounds (VOC) for each test. For exhaust emissions, the speciation results are in grams of VOC per mile and the MIR values are in grams of ozone per gram of VOC; therefore, the EOP for each test is in grams of ozone per mile. The EOP is listed as a function of vehicle, blend season, temperature, blend type, and driving cycle. Test date is used in the table to make the distinction between results from replicate tests. EOP results are available only for vehicles 1, 2, 3, 4, 5, 9, and 12, because speciations were performed on emissions from only these vehicles.

The estimated ozone production can be compared with the measured VOC emissions for each test to determine how the effective reactivity of the hydrocarbon emissions changes for different emission levels for the test vehicles. This comparison is provided in Figure 5-42. The estimated ozone production is plotted on the vertical axis in grams of ozone per mile. The horizontal axis shows the total VOC emissions which were calculated by summing the speciated results for each test. Also plotted in the figure are two lines which represent where the data points would fall if the overall reactivity factor for each test was 1 and 4. When the data points are compared with these two lines, it can be seen that, for VOC emission levels in this test program above 1 gram per mile, the overall effective Carter reactivity factor was about 4. For vehicles and test conditions which produced VOC emissions lower than 1 gram per mile, the effective Carter reactivity factor for the hydrocarbon emissions as a whole dropped. In addition, at the lower VOC levels, there is increased scatter in the data. This may be due to experimental error in the speciation measurements; however, other factors related to vehicle emission control systems could also be causing values to disperse.

Figure 5-41
Effect of Blend Type on NOx Emissions

Percent Changes Shown Are for a Baseline NOx Level of 1 g/mi

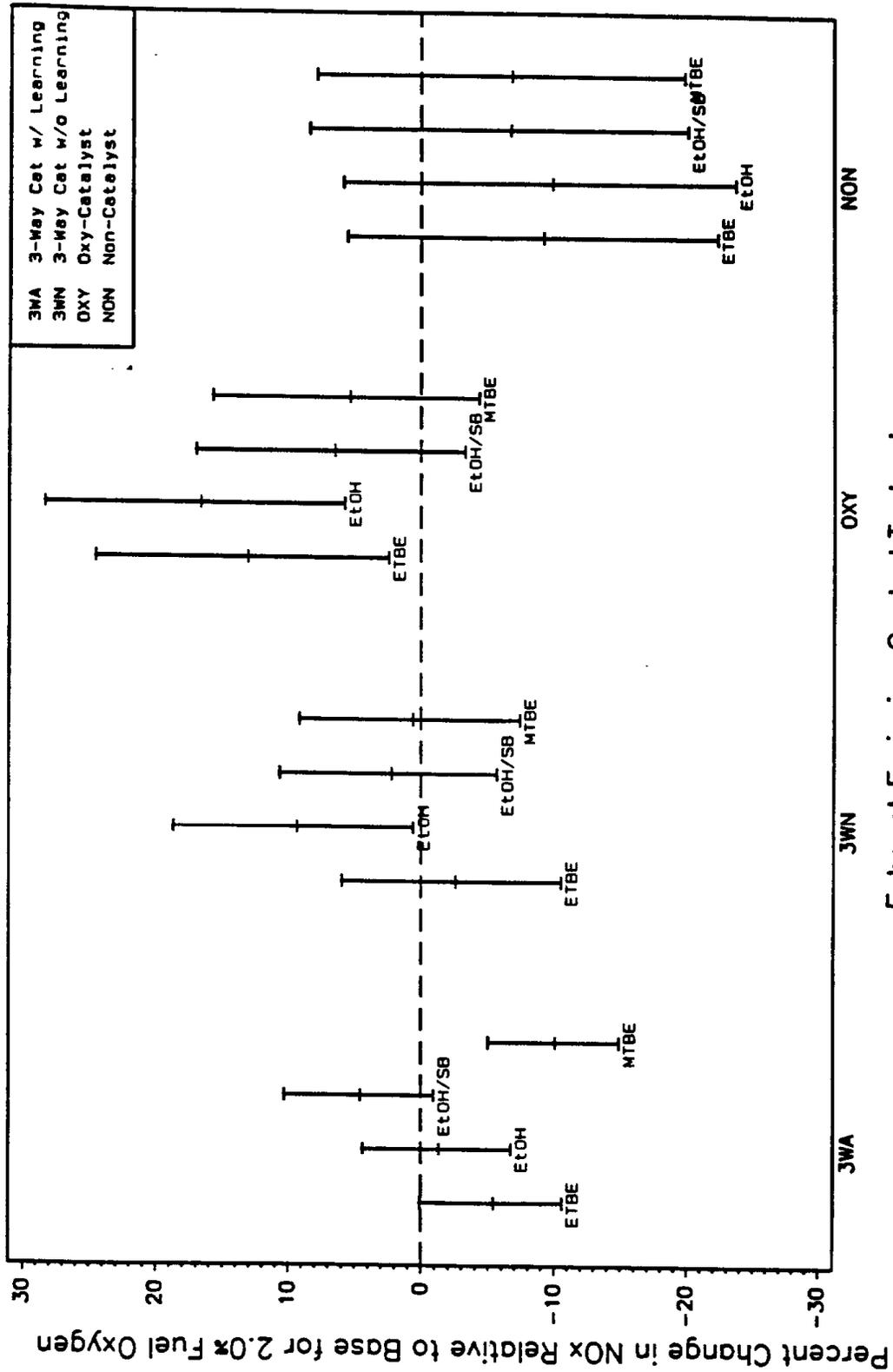
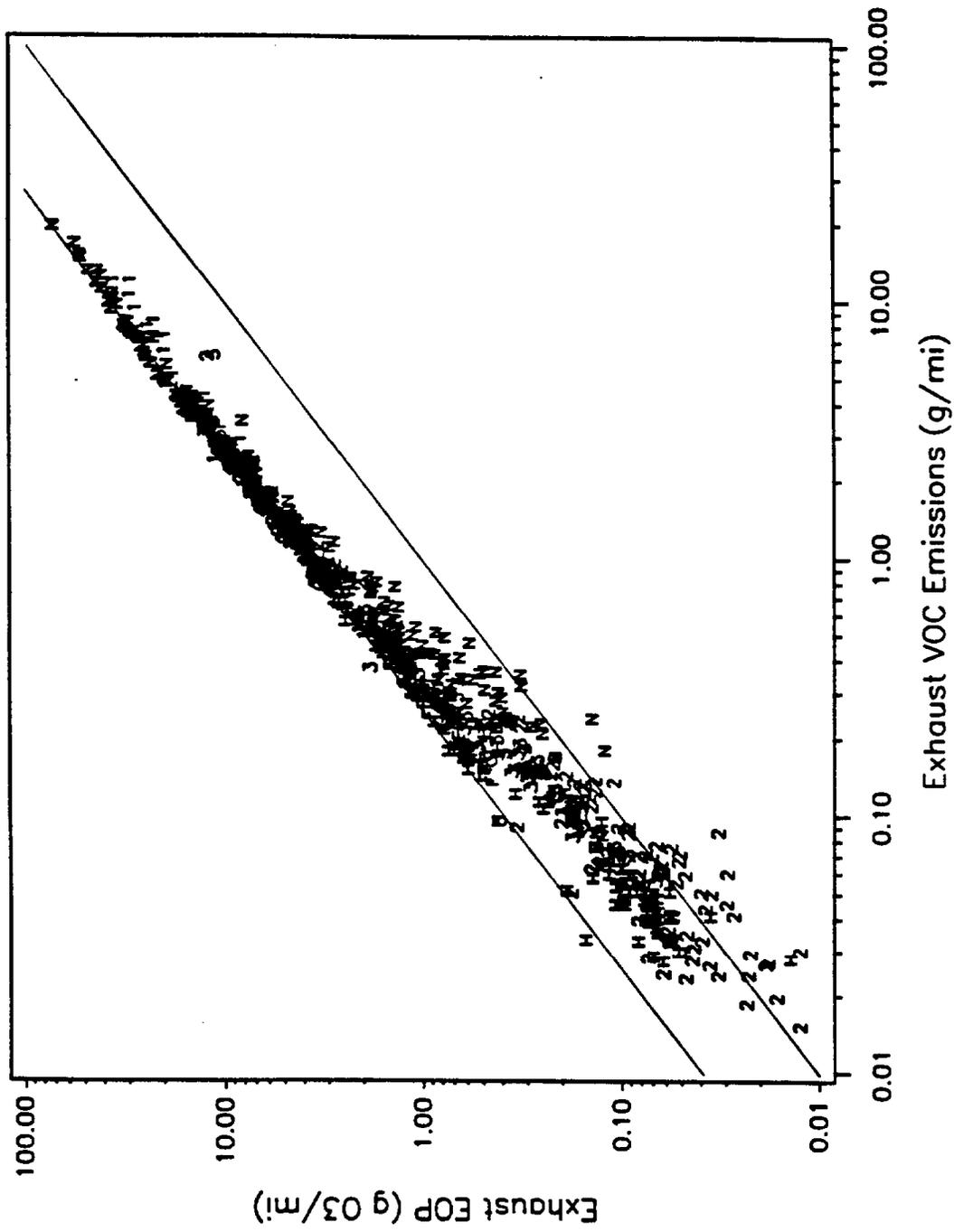


Figure 5-42
 Comparison of Exhaust Estimated Ozone Production
 and Exhaust VOC Emissions



The following preliminary class regression statement was used to evaluate the main effects of the five parameters on the exhaust estimated ozone production (EXEOP) in the absence of any interactions:

$$\ln \text{EXEOP} = \text{CYCLE} \text{ VEHID} \text{ BLENDTYP} \text{ TEMP} \text{ SEASON}$$

This analysis of variance indicated that the five parameters had the following order of magnitude effect:

$$\text{VEHID} > \text{CYCLE} \gg \text{BLENDTYP} > \text{TEMP} > \text{SEASON}$$

The evaluation of the transformation to be used for the EOP levels was made by regressions against the following combination of effects:

$$\text{VEHID} \text{ VEHID*CYCLE} \text{ TEMP} \text{ SEASON} \text{ BLENDTYP}$$

Both the EOP and the natural log of the EOP were regressed against these parameters and the residuals were examined for homogeneity. The regression using linear EOP resulted in a funnel-shaped residual pattern; the natural log of the EOP produced a homogeneous residual pattern. Therefore, the log of the EOP was the transformation chosen. In the process of doing these regressions, three data points were found to be outliers and were removed from further regressions: Vehicle 5/50°F/Fuel Y/NYCC on 11AUG92 = 9.444 g O₃/mi, Vehicle 5/75°F/Fuel O/Bag3 on 10FEB92 = 2.503 g O₃/mi, and Vehicle 2/75°F/Fuel Q/Bag2 on 20FEB92 = 0.180 g O₃/mi. This left 857 observations left for subsequent analyses.

Then, a long series of regressions was used to try to discover the best model statement which would describe the exhaust EOP. The continuous oxygen concentration OXY was brought into the model statement as the interaction with VEHID*BLENDTYP. In the process of performing these regressions, several observations were made:

- The individual vehicle and the driving cycle had an almost overwhelming effect on the exhaust EOP.
- There was a strong interaction between cycle and vehicle; that is, vehicles responded differently to different cycles.
- There was a significant interaction between vehicle and blend type; in other words, vehicles responded differently to a given blend type.
- The interaction between cycle and blend type was not significant. This indicates that a given blend type produced about the same size of exhaust EOP change in one cycle as it did in another cycle.
- Blend season was not found to be important in any of the regressions that were attempted.
- Comparison of the exhaust EOP responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel X and Fuel Y were not significantly different from Fuel N. Therefore, observations with Fuels X, Y, and N were considered the same base fuel for further exhaust EOP regressions.

The best overall model which described the exhaust EOP for individual vehicles was given by:

$$\ln\text{EXEOP} = \text{VEHID}*\text{CYCLE} \quad \text{CYCLE}*\text{TEMP} \quad \text{VEHID}*\text{BLENDTYP}*\text{OXY} \quad \text{SEASON}$$

Blend season was not found to be significant, but was included in the regression because it was significant in the HC emissions regression. The SAS output listing and the parity plot from this regression are given in Appendix K.

To assist in the assignment of general vehicle technology behavior factors, the vehicles which have similar behavior can be classified together. Classifications were made by performing alternative regressions by substitution of technology parameters for vehicle parameters in the above equation. The VEHID in VEHID*BLENDTYP*OXY was replaced with technology candidate parameters for emission control technology, fuel induction system, canister bottom type, or engine displacement. The VEHID in VEHID*CYCLE was retained for these regressions since the emissions performance of individual vehicles within the same technology grouping will vary considerably due to the idiosyncrasies of each individual vehicle.

The overall results of this exercise indicated that FUELSYS provided the best technology grouping; however, EMSTECH, which provided the best technology grouping for total hydrocarbon exhaust emissions, was a very close second. Therefore, we chose to use EMSTECH as the regression technology grouping since it was found to be best for exhaust CO, HC, and NO_x emissions. It should also be noted that only the EMSTECH category level of TWC/AL has more than one vehicle (1, 4, 5, 9); the other category levels have only one vehicle each. Therefore, using EMSTECH*BLENDTYP*OXY instead on VEHID*BLENDTYP*OXY really only indicates pooled results for TWC/AL vehicles. Thus, the good exhaust EOP regression model was found to be:

$$\ln\text{EXEOP} = \text{VEHID}*\text{CYCLE} \quad \text{EMSTECH}*\text{BLENDTYP}*\text{OXY} \quad \text{CYCLE}*\text{TEMP} \quad \text{SEASON}$$

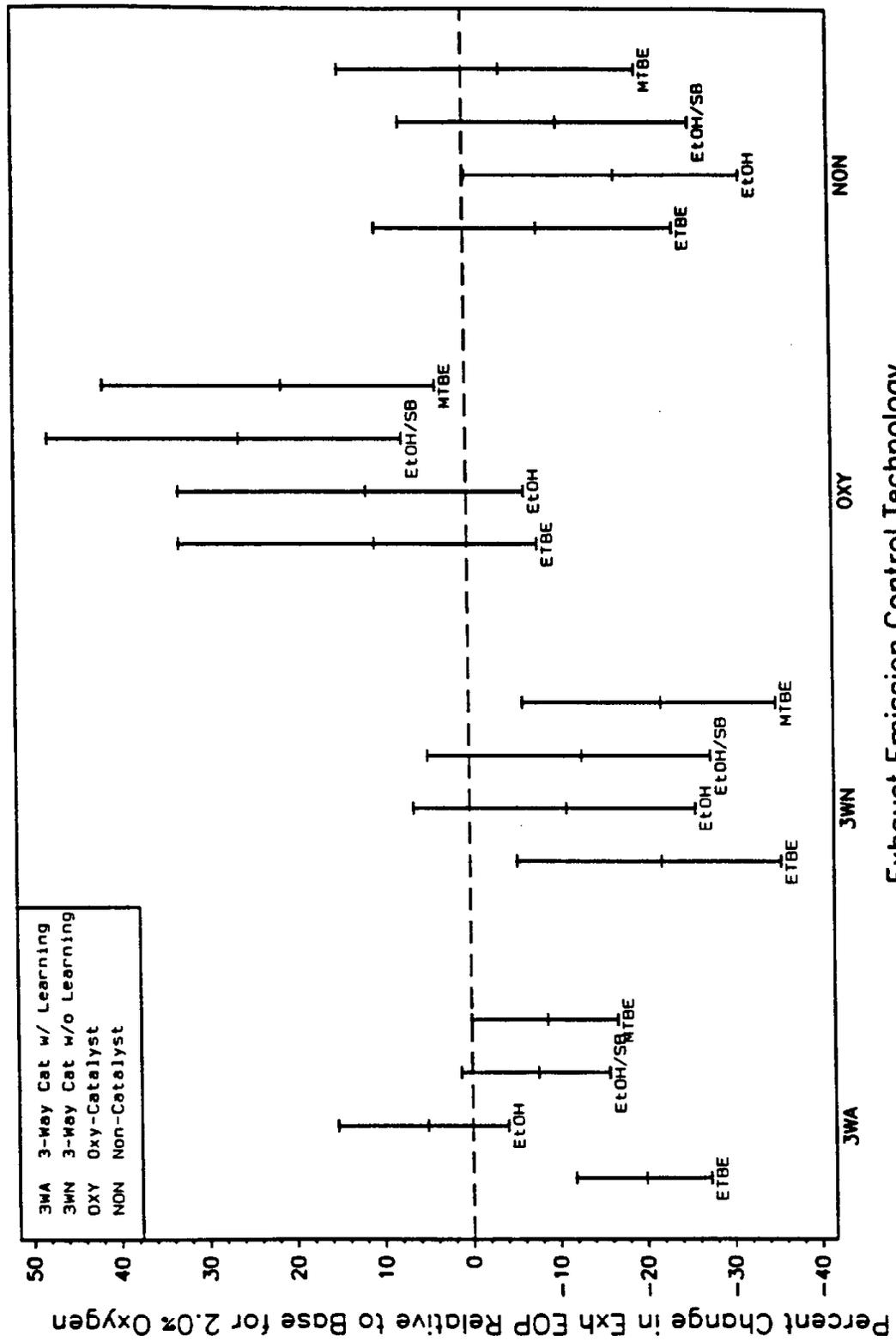
The SAS output listing and the parity plot from this final technology-based regression are given in Appendix K. From this regression, the effects of the four blend types on the exhaust EOP of the four technology groups relative to the combined base fuels are shown in Figure 5-43. This plot shows significant reductions in the exhaust estimated ozone production of the TWC/AL and TWC/NAL vehicles for the ETBE and MTBE blends relative to the combined bases. Also, ETBE produced significantly lower exhaust EOP than the other three blends for the TWC/AL vehicles. EtOH for the non-catalyst vehicle showed a significant reduction. The EtOH/SB and MTBE produced a significant increase for the oxy-catalyst vehicle. Other effects relative to the base fuel were not significant.

The regression also indicated that the summer blends produced 8 percent lower exhaust estimated ozone production levels than the winter blends, and this difference was significant at the 95% confidence level. Note that the summer and winter blends had volatility differences of 2 psi and had different base blending stocks. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

6. *Exhaust Toxics.* There are four exhaust toxics of concern in this study: benzene, formaldehyde, acetaldehyde, and 1,3-butadiene. Each of these is examined in a separate section below.

Figure 5-43
Effect of Blend Type on Exhaust EOP

Model: lnEXEOP = vehid•cycle cycletemp season emstech•blendtyp•oxy



a. Exhaust Benzene Emissions--The exhaust benzene emission values are given in Appendix I. They are listed as a function of vehicle, blend season, temperature, blend type, and test date. Only ten of the exhaust benzene values are less than or equal to 0.0000 grams per mile. These low values occurred for some test conditions for Bag 2 of the FTP on Vehicles 1 and 5.

The regression of the exhaust benzene (EXHBZ) values was performed using the individual vehicle model that was found to be best for the total hydrocarbon exhaust emissions:

$$\ln\text{EXHBZ} = \text{VEHID} * \text{CYCLE} \text{ CYCLE} * \text{TEMP} \text{ SEASON} \text{ VEHID} * \text{BLENDTYP} * \text{OXY}$$

A linear transformation of the exhaust benzene values was attempted and the log transformation was found to be much superior in terms of the homogeneity of the residuals. In the process of performing the regressions, no outlier values were detected. All 849 observations were used for subsequent analyses.

Comparison of the exhaust benzene responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel Y was significantly different from Fuel N, but Fuel X was not significantly different from Fuel N. Therefore, observations with Fuel Y were dropped from further consideration for exhaust benzene effects, and Fuels X and N were considered the same fuel for further exhaust benzene regressions. This left 808 exhaust benzene observations.

The results of this model indicated that all four terms of the regression statement had significant effects on the exhaust benzene levels. The SAS output and parity plot of the regression are given in Appendix K. Because this regression contained only seven vehicles, an attempt to justify the grouping of vehicles by a particular technology parameter was not attempted. Instead, the same technology parameter as was used for the total exhaust hydrocarbon emissions was used. Thus, the final regression statement became:

$$\ln\text{EXHBZ} = \text{VEHID} * \text{CYCLE} \text{ CYCLE} * \text{TEMP} \text{ SEASON} \text{ EMSTECH} * \text{BLENDTYP} * \text{OXY}$$

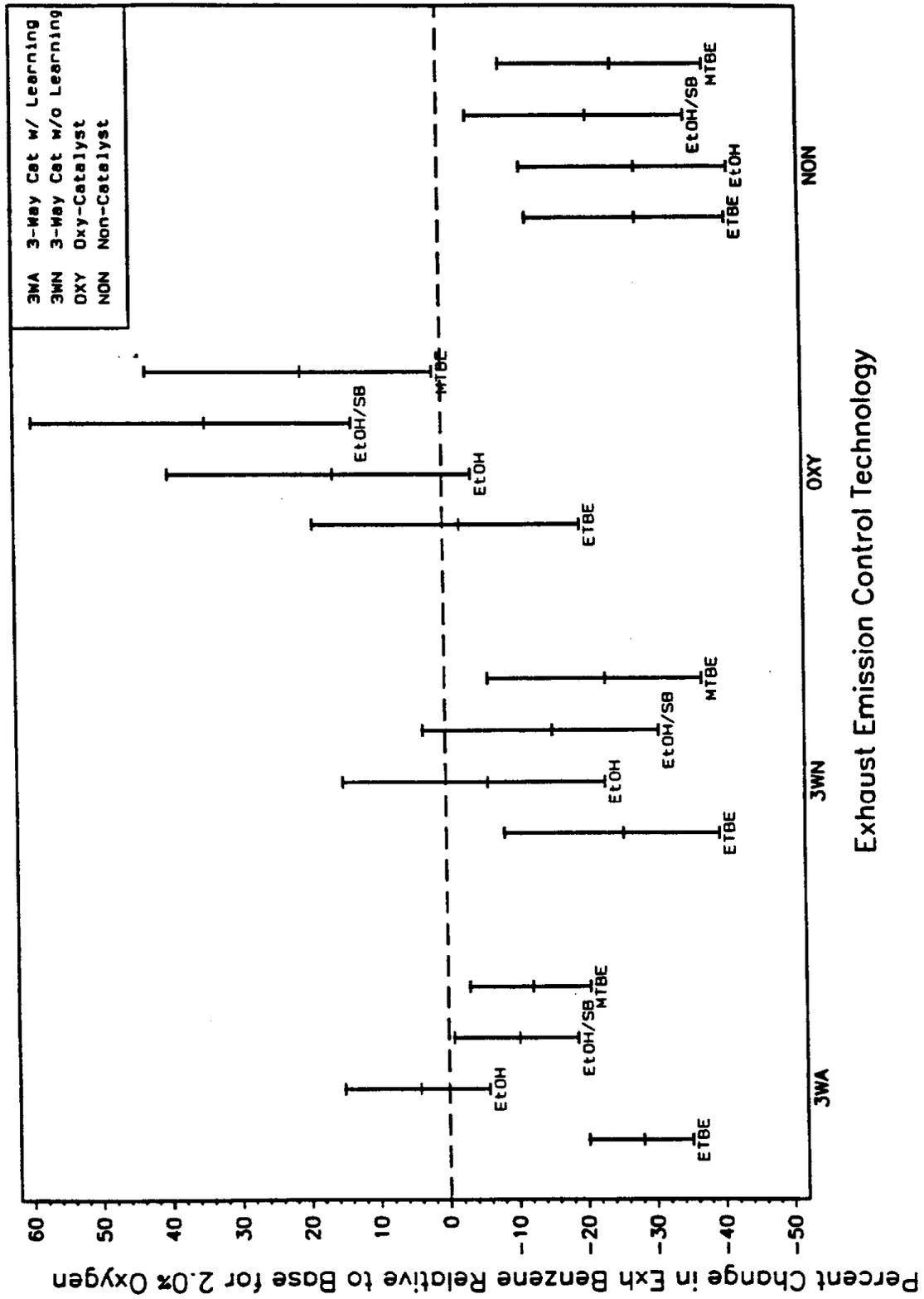
This regression fit the data with an r^2 of 0.919 and an error on the exhaust benzene values of about 41%. Every term in the regression was significant. The SAS output and parity plot of the regression are given in Appendix K. The effect of BLENDTYP on the four categories of EMSTECH is shown in Figure 5-44. It is important to note that the TWC/AL category is represented in this data by Vehicles 1, 4, 5, and 9. However, the other three categories are represented by one vehicle each: TWC/NAL by Vehicle 2, oxy-catalyst by Vehicle 12, and non-catalyst by Vehicle 3.

The figure shows that for TWC/AL vehicles, ETBE, MTBE, and EtOH/SB blends produced, relative to the base, significant reductions in the exhaust benzene, and the EtOH blend did not produce a significant reduction. In addition, it can be seen that ETBE produced reductions significantly larger than all of the other three blends. The TWC/NAL vehicle also responded with significant reductions for ETBE and ETBE. Also, ETBE and MTBE had benzene emissions that were significantly lower than for EtOH blends. The oxy-catalyst vehicle showed benzene increases relative to the base for EtOH/SB and MTBE. For the non-catalyst vehicle, all oxygenated blends gave significant benzene reductions.

The regression also indicated that the summer blends produced 8 percent higher exhaust benzene emissions than the winter blends, but this difference was not significant at the 95% confi-

Figure 5-44
Effect of Blend Type on Exhaust Benzene Emissions

Model: lnBzn = vehid*cycle*temp season emstech*blendtyp*oxy



dence level. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

b. Exhaust Formaldehyde Emissions--The exhaust formaldehyde emissions data is presented in Appendix I. Of all the values that are there, only 39 are less than or equal to 0.0000 grams per mile. As a result of the regressions that were performed on the data, seven data points were found to be outliers: Vehicle 4/50°F/Fuel P/Bag1 on 21AUG91 = 0.8138 g/mi, Vehicle 1/75°F/-Fuel P/NYCC on 17JAN92 = 0.0263 g/mi, Vehicle 3/50°F/Fuel R/HFET on 9SEP91 = 0.0014 g/mi, Vehicle 4/50°F/Fuel P/Bag3 on 21AUG91 = 0.2254 g/mi, Vehicle 4/75°F/Fuel T/NYCC on 24FEB92 = 0.0089 g/mi, Vehicle 5/50°F/Fuel Y/NYCC on 11AUG92 = 0.0115 g/mi, and Vehicle 9/75°F/Fuel V/NYCC on 5AUG92 = 0.0124 g/mi. These outliers were not considered in subsequent examination of the formaldehyde data. This left 804 formaldehyde observations left for subsequent analyses.

Modeling of the exhaust formaldehyde emissions was performed using the same model as for the individual vehicles for the total hydrocarbon emissions. Several different transformations were attempted to find the most homogeneous residual pattern. The best was to raise the formaldehyde concentrations to an exponent of 0.2. However, the result which was obtained in terms of regression results was close to that which was obtained using a log transformation. Therefore, the log transformation was used for simplicity of interpretation.

Comparison of the formaldehyde responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel X and Fuel Y were not significantly different from Fuel N. Therefore, observations with Fuels X, Y, and N were considered the same base fuel for further formaldehyde regressions.

For the final model, VEHD was replaced on BLENDTYP using EMSTECH, which is the technology parameter which was found to be best for the total hydrocarbon emission regression. Thus, the final technology-based emission regression model for exhaust formaldehyde (EXHFORM) was:

$$\ln \text{EXHFORM} = \text{VEHD} * \text{CYCLE} * \text{TEMP} * \text{SEASON} * \text{EMSTECH} * \text{BLENDTYP} * \text{OXY}$$

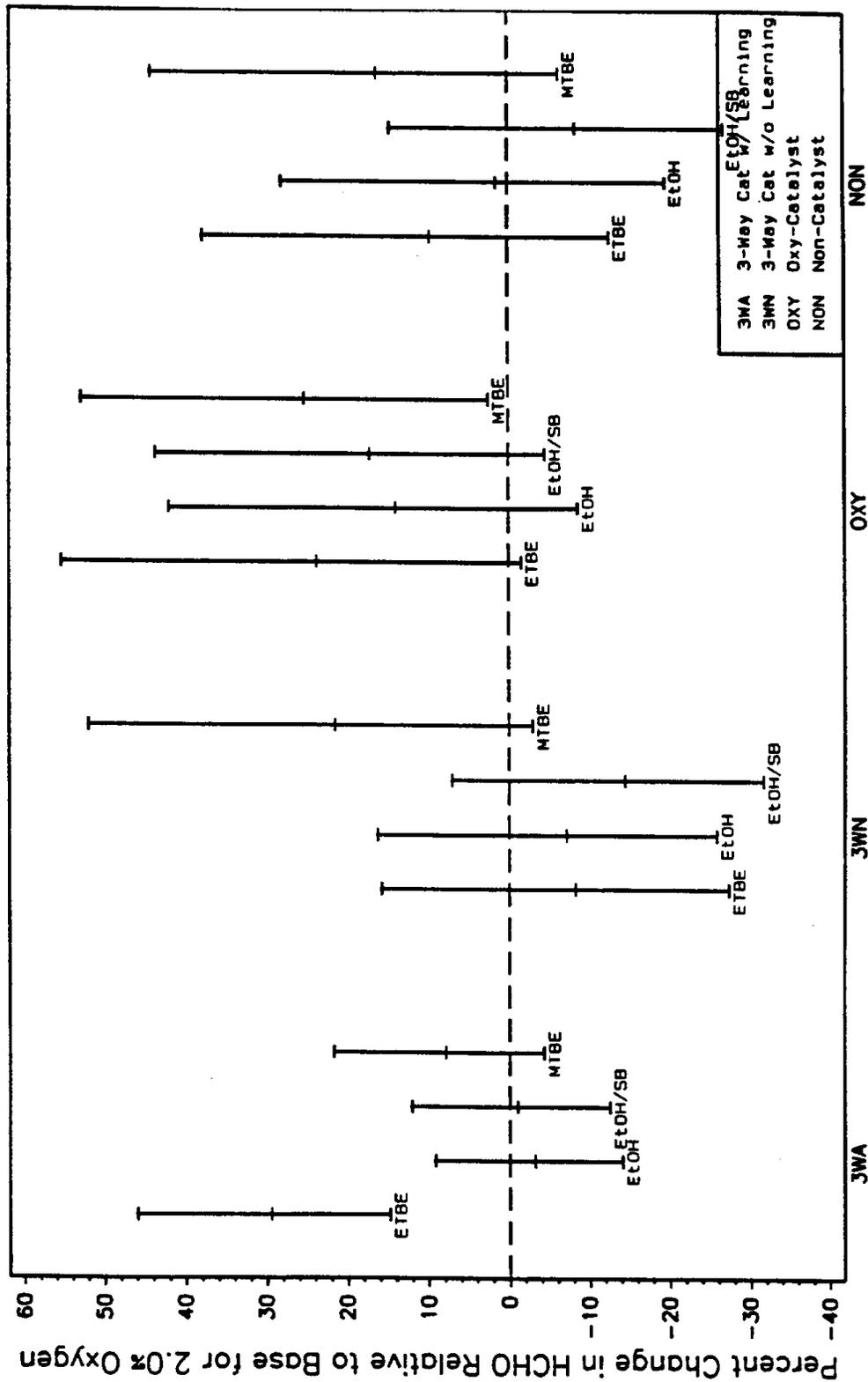
The effects of BLENDTYP on the exhaust formaldehyde emissions as found by this regression are shown in Figure 5-45. The SAS output and parity plot of the regression are given in Appendix K. It is important to remember that the TWC/AL category is represented by four vehicles, but the other three categories are each based on measurements from only one vehicle.

The figure shows that the only significant effects were increases in formaldehyde and were found for TWC/AL vehicles for ETBE and for the oxy-catalyst vehicle for MTBE blends. The other effects relative to the combined base fuels were not significant.

The overall trend in the response of exhaust formaldehyde to the four blend types seems to be inverted compared with the CO, HC, NO_x, and benzene emissions. That is, in general, ETBE and MTBE produced higher formaldehyde emissions than did the EtOH and EtOH/SB blends; however, most of these trends are not statistically significant. The regression also indicated that the summer blends produced 14 percent lower formaldehyde emissions than the winter blends, and this difference was significant at the 95% confidence level. While the oxygen content of the

Figure 5-45
Effect of Blend Type on Formaldehyde Emissions

Model: Inform = vehid*cycle*temp season emstech*blendtyp*oxy



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blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLEND-TYP*OXY term of the regression.

c. Exhaust Acetaldehyde Emissions--The exhaust acetaldehyde emission values as a result of the speciated emission measurements are shown in Appendix I. Forty-one of the values shown have values less than or equal to 0.0000 grams per mile. As a result of the regressions examining this data, one outlier was identified: Vehicle 3/50°F/Fuel R/HFET on 9SEP91 = 0.0010 g/mi. This outlier was not considered in subsequent examination of the acetaldehyde data. This left 805 observations to be analyzed.

Regression analysis of the exhaust acetaldehyde (EXHACET) data began with the same regression model statement as that for the total exhaust hydrocarbon emissions, the exhaust benzene emissions, and the exhaust formaldehyde emissions. Various transformations of the acetaldehyde data were tried to find the best transformation which produced the most homogeneous residuals. This was found to be an exponent of 0.3. The result of this transformation was noticeably different from the log and linear transformations and, it was retained for the remainder of the analysis.

Comparison of the exhaust acetaldehyde responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel Y was significantly different from Fuel N, but Fuel X was not significantly different from Fuel N. Therefore, observations with Fuel Y were dropped from further consideration for exhaust acetaldehyde effects, and Fuels X and N were considered the same fuel for further exhaust acetaldehyde regressions. This left 764 exhaust acetaldehyde observations.

For the best individual vehicle model, the interactions VEHID*CYCLE, CYCLE*TEMP, and VEHID*BLENDTYP*OXY were found to be significant. SEASON was not significant, but was retained in the regression to estimate the size of the SEASON effect. The SAS output and parity plot of the individual regression are given in Appendix K. Then, the interaction VEHID*BLENDTYP*OXY was replaced with EMSTECH*BLENDTYP*OXY to measure the effect of blend type for the different technologies. Thus, the final regression statement became:

$$\text{EXHACET}^{0.3} = \text{VEHID*CYCLE CYCLE*TEMP SEASON EMSTECH*BLENDTYP*OXY}$$

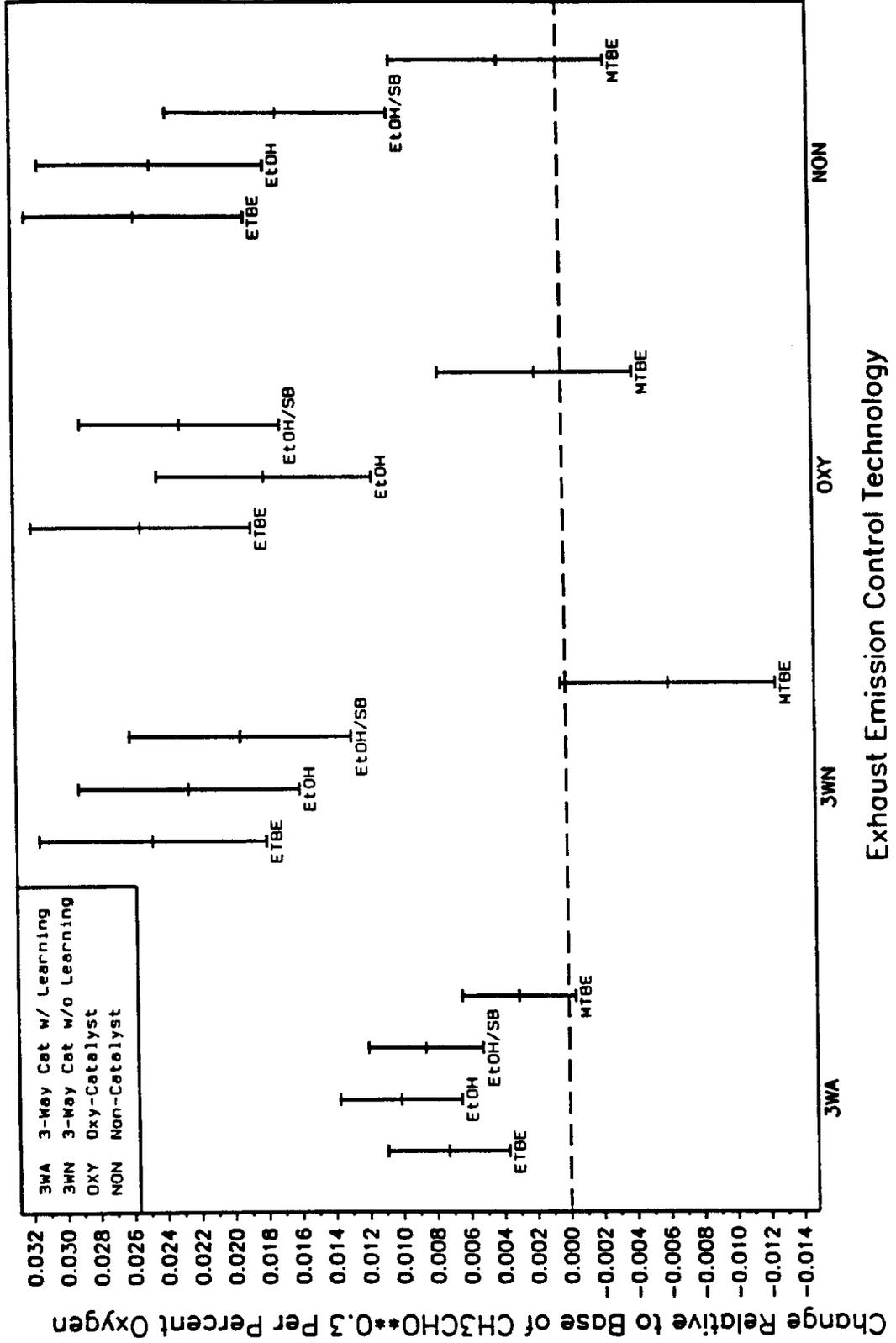
This produced an r^2 of 0.945 and predicted the EXHACET^{0.3} levels with a standard deviation of about 0.027. The SAS output and parity plot of the regression are given in Appendix K.

The effect of BLENDTYP on the exhaust EXHACET^{0.3} is shown in Figure 5-46. Because the magnitude of effects in EXHACET^{0.3} by the blends are difficult to visualize in terms of untransformed EXHACET, Figure 5-47 is provided. Reductions in EXHACET^{0.3} cannot be expressed as a constant reduction in acetaldehyde or as a constant percent reduction in acetaldehyde. Therefore, Figure 5-47 shows the percent reduction in acetaldehyde relative to a base fuel emission level of 10 mg/mi for each blend type with a 2.0% oxygen content. The percent reductions for other base fuel emission levels and other oxygen contents can be calculated using the regression results given in Appendix K.

Figure 5-47 shows significant increases in the acetaldehyde emissions were produced relative to the Base by ETBE, EtOH, and EtOH/SB for all four vehicle technology groups. On the other hand, no difference was seen for MTBE for any of the technologies. Also, the figure indicates that TWC/AL technology vehicles produced significantly lower acetaldehyde emissions than the

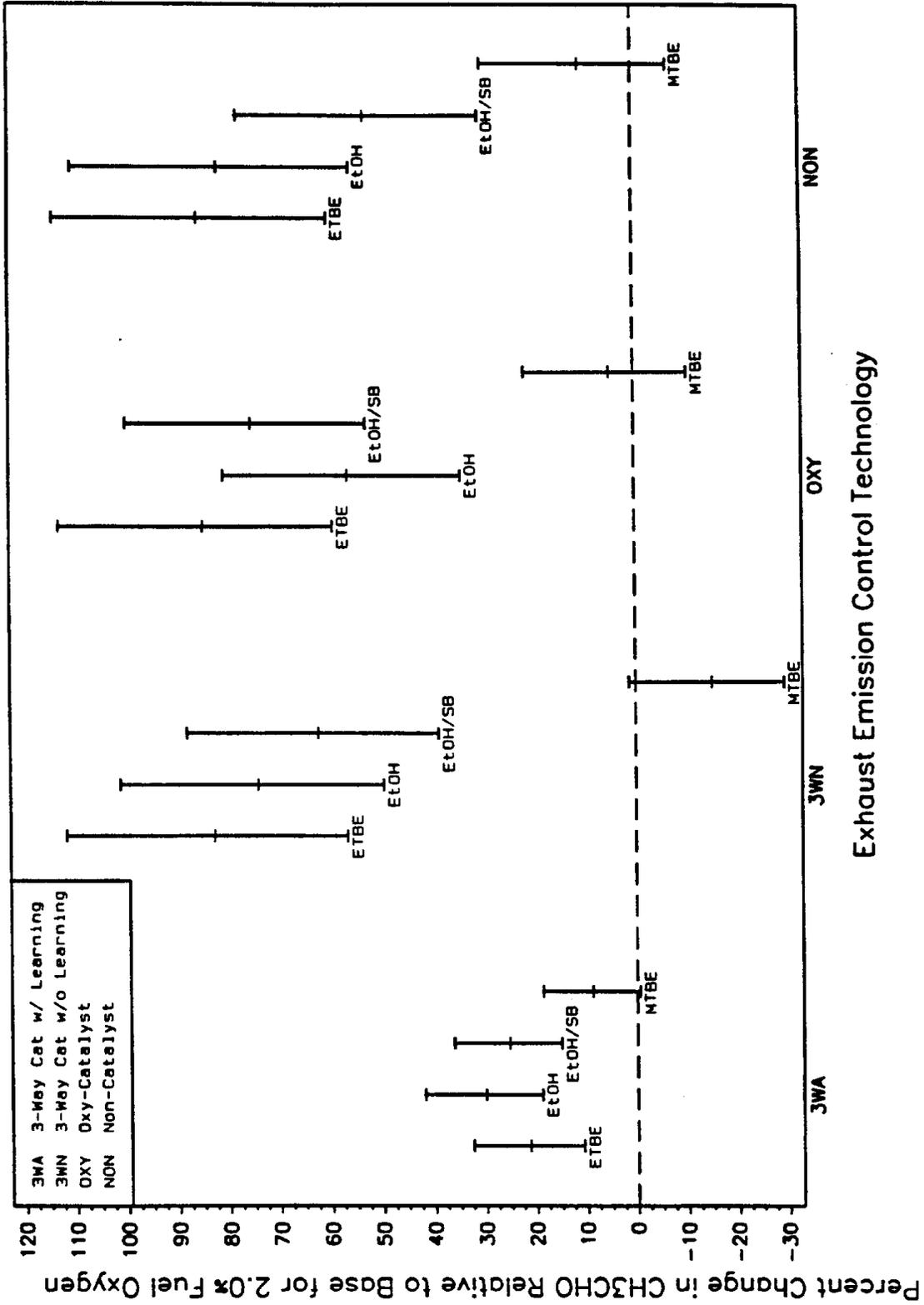
Figure 5-46
Effect of Blend Type on Acetaldehyde Emissions

Model: Acet**0.3 = vehid*cycle emstech*blendtyp*oxy cycle*temp season



Effect of Blend Type on Acetaldehyde Emissions

Percent Changes Shown Are for a Baseline Acetaldehyde Level of 10 mg/mi



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older technologies; however, it is important to remember that the older technologies are represented by one vehicle each. At the conditions used to create Figure 5-47, ETBE, EtOH, and EtOH/SB blends produced acetaldehyde increases of about 20% for TWC/AL vehicles and increases of about 80% for the other three, older technologies.

The regression also indicated that the summer blends and winter blends had no difference in acetaldehyde emissions. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

d. Exhaust 1,3-Butadiene Emissions--The exhaust 1,3-butadiene emission measurements are shown in Appendix I. Of all the values shown, a large number, 242, of the values are less than or equal to 0.0000 grams per mile. In fact, for Vehicles 1, 4, and 5, virtually all of the measured 1,3-butadiene values for Bag 2, Bag 3, HFET, and NYCC are 0.0000 grams per mile. These three vehicles have TWC/AL technology on multipoint fuel-injection systems. They are the only vehicles in the speciated test group which have this combination of technologies. Vehicle 9, which has TWC/AL and a throttle body fuel-injection system, also had Bag 2 with 0.0000 grams per mile for 1,3-butadiene emission values.

The same initial regression model statement as was used for the total exhaust hydrocarbon emissions, exhaust benzene, exhaust formaldehyde, and exhaust acetaldehyde was used. Various transformations of the 1,3-butadiene measurement values were used to search for homogeneous residuals. It was found that the 0.3 exponent transformation EXH13BUT^{0.3} provided the best description. As a result of the regression of this data, no outliers were found. All 627 observations were used for subsequent analyses.

Comparison of the 1,3-butadiene responses of Fuel X (LowRVPWinterBase) and Fuel Y (NewStockWinterBase) with Fuel N (WinterBase) by regression indicated that Fuel X and Fuel Y were not significantly different from Fuel N. Therefore, observations with Fuels X, Y, and N were considered the same base fuel for further 1,3-butadiene regressions.

The SAS output and parity plot of the best individual vehicle regression are given in Appendix K. The model statement had the following form:

$$\text{EXHBUT}^{0.3} = \text{VEHID} * \text{CYCLE} \quad \text{CYCLE} * \text{TEMP} \quad \text{SEASON} \\ \text{VEHID} * \text{BLENDTYP} * \text{OXY}$$

For the final model, the VEHID*BLENDTYP*OXY interaction was replaced with EMSTECH*BLENDTYP*OXY, as was used in the total hydrocarbon emissions regression. This produced a regression with an r² of 0.920 and predicted the measured EXH13BUT^{0.3} values with an error of 0.026. It should be noted that the predicted values for those conditions for Vehicles 1, 4, 5, and 9, which had measured values of 0, were not always close to 0. The reason for this is that when an exponentiation transformation is performed, measured values of 0 do not get transformed by SAS into the new data space. Therefore, these values cannot be used to estimate regression coefficients. Consequently, the regression for exhaust 1,3-butadiene may be less reliable than those of the other exhaust toxic compounds which were investigated in this section.

The predicted effects of the blend types on the four vehicle technology categories of EXH13BUT^{0.3} are shown in Figure 5-48. Note that each of the four technologies is represented by a single vehicle for these results. Because the magnitude of effects in EXH13BUT^{0.3} by the blends are difficult to visualize in terms of untransformed EXH13BUT, Figure 5-49 is provided. Reduc-

Effect of Blend Type on 1,3-Butadiene Emissions

Model: But**0.3 = vehid*cycle emstech*blendtyp*oxy cycle*temp season

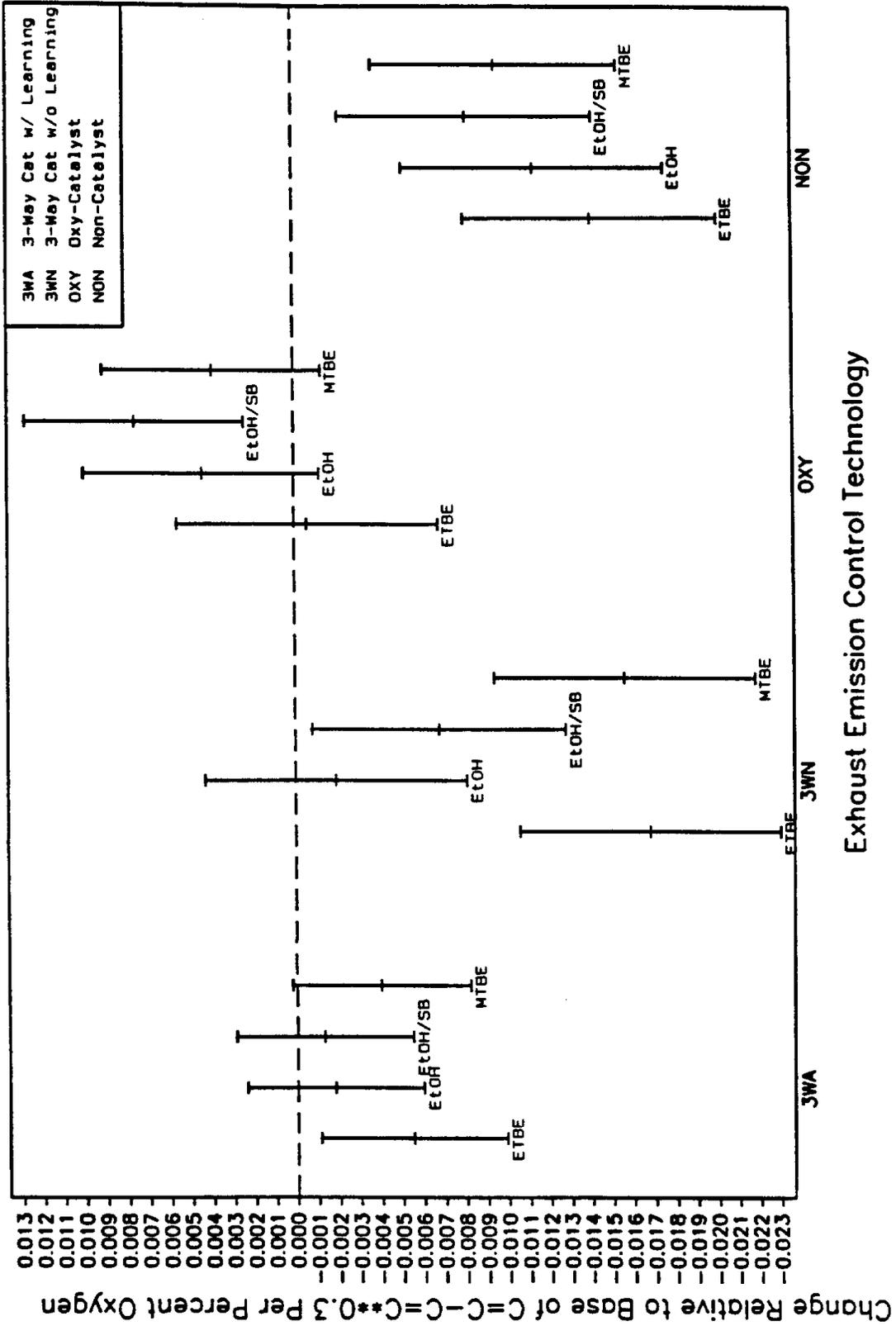
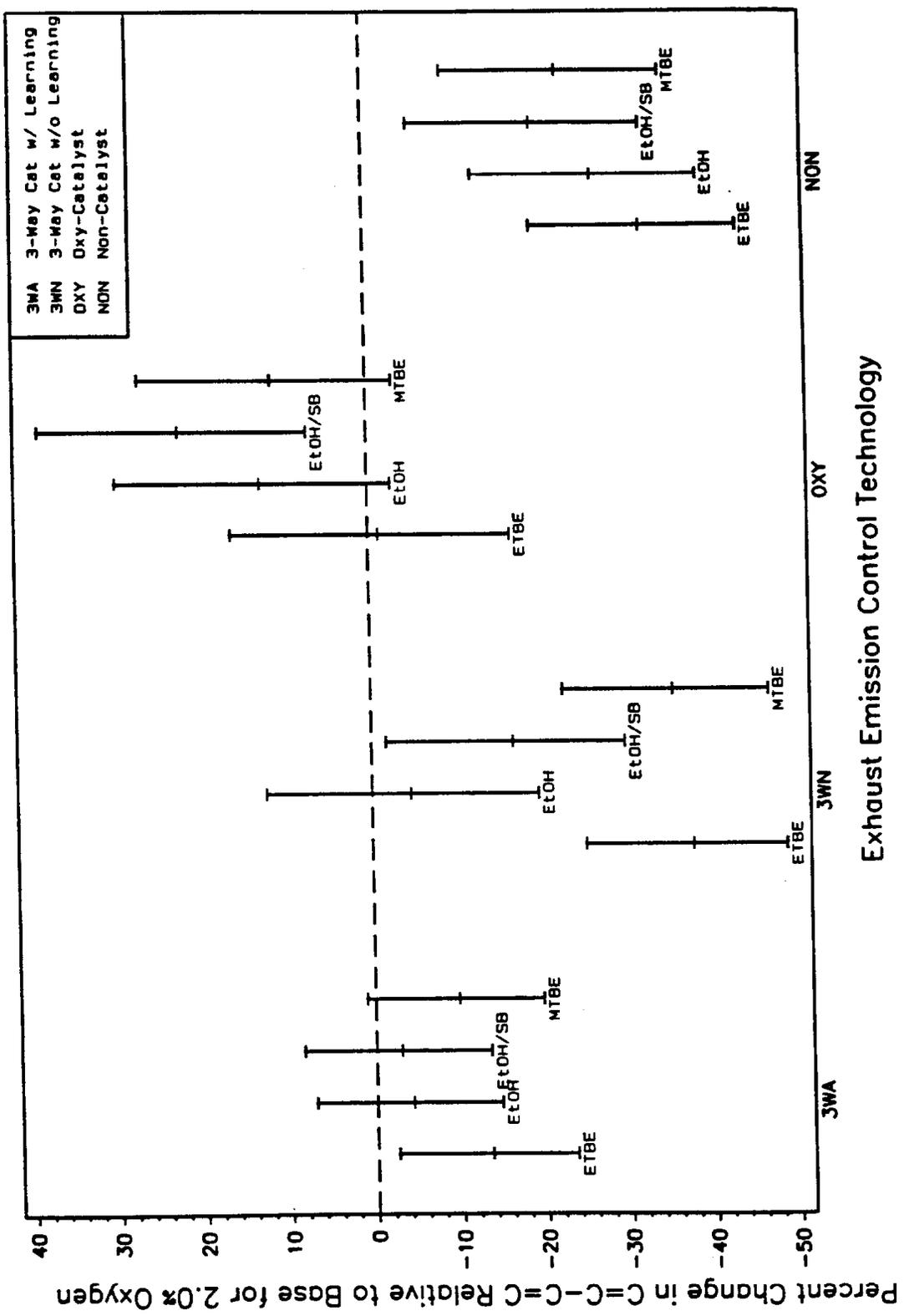


Figure 5-49
 Effect of Blend Type on 1,3-Butadiene Emissions

Percent Changes Shown Are for a Baseline 1,3-Butadiene Level of 10 mg/mi



tions in EXH13BUT^{0.3} cannot be expressed as a constant reduction in 1,3-butadiene or as a constant percent reduction in 1,3-butadiene. Therefore, Figure 5-49 shows the percent reduction in 1,3-butadiene relative to a base fuel emission level of 10 mg/mi for each blend type with a 2.0% oxygen content. The percent reductions for other base fuel emission levels and other oxygen contents can be calculated using the regression results given in Appendix I.

The results in Figure 5-49 show that for the TWC/AL vehicle, ETBE produced significantly lower exhaust 1,3-butadiene emissions, and MTBE was almost significant. For the TWC/NAL vehicle, the ETBE, EtOH/SB, and MTBE blends produced significantly lower exhaust 1,3-butadiene emissions than the combined base fuels. The oxy-catalyst vehicle showed a significant increase in 1,3-butadiene for EtOH/SB with respect to the base blends. The non-catalyst vehicle produced significant reductions of 1,3-butadiene for all oxygenated blends. Note that there was a general trend for ETBE and MTBE to produce lower 1,3-butadiene emissions than EtOH and EtOH/SB; however, these trends were not always statistically significant.

The regression also indicated that the summer blends produced 10 percent lower 1,3-butadiene emissions than the winter blends, and this difference was significant at the 95% confidence level. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the EMSTECH*BLENDTYP*OXY term of the regression.

E. EVALUATION OF EVAPORATIVE EMISSIONS

Tables 5-15 and 5-16 show the test matrices for the reference fuels and for the oxygenated fuels, respectively. The reference fuels were tested to provide a baseline against which the results of the oxygenated and base fuels could be compared.

The oxygenated fuels test matrix shown in Table 5-16 shows the structure of the experimental design used to measure the effects on evaporative emissions. All 13 test vehicles were planned to be tested at each of the five blend types, for both blend seasons, and at a low and high temperature for the summer blends, and at only 75°F for the winter blends. Running loss tests were performed only for the summer blends at 95°F. Speciation of hydrocarbon emissions for seven of the vehicles which underwent diurnal and hot soak testing was planned for all test conditions. Alcohol speciation of the evaporative emissions was performed only in those cases where Ethanol (EtOH) or Ethanol Splash Blend (EtOH/SB) was the test fuel and aldehyde speciation was not performed on any of the evaporative emissions tests, since these compounds are only produced by combustion and, therefore, would not be present in evaporative emissions.

1. Evaporative Emission Responses to Reference Fuels. The responses of the vehicles to the evaporative emission testing with Indolene® (FUELID E) and industry average fuel (FUELID A) are shown in Table 5-17 for diurnal, hot soak, and running loss evaporative emissions.

A comparison of the responses of the diurnal and hot soak emissions for the thirteen vehicles using the Summer Base fuel (Fuel M), the Winter Base fuel (Fuel N), and the Industry Average fuel (Fuel A) are shown in Figures 5-50 and 5-51. The three fuels have different blending stocks and have nominal RVPs of 7.7 psi for M, 8.5 psi for A, and 9.7 psi for N. The data plotted in the figures were all taken at 75°F. The measured emissions are plotted with a log scale because of the large range of data values. The horizontal scale denotes the nine different combinations of fuel

Table 5-15. Reference Fuel Test Design for Evaporative Emissions

RVP (psi)	Temp (F)	Fuel	Diurnal			Hot-Soak			Running Loss					
			HC	Speciation	ROH RCHO	HC	Speciation	ROH RCHO	HC	Speciation	ROH RCHO			
9.0	75	RF-A	13	7	0	0	13	7	0	0	6	6	0	0
	95	RF-A												
9.0	95	Indolene	1	1	0	0	1	1	0	0	1	1	0	0
	75	Indolene	1	1	0	0	1	1	0	0	0	0	0	0
	50	Indolene	0	0	0	0	0	0	0	0	0	0	0	0

13 denotes VEHIDs 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
 7 denotes VEHIDs 1, 2, 3, 4, 5, 9, 12
 6 denotes VEHIDs 1, 2, 3, 6, 9, 12
 1 denotes VEHID 1

Table 5-16. Oxygenated Fuel Test Design for Evaporative Emissions

SEASON	TEMP	BLENDTYP	Diurnal			Hot-Soak			Running Loss			
			HC	Speciation	HC	HC	Speciation	HC	Speciation	HC	Speciation	
			HC	ROH	FCO	HC	ROH	FCO	HC	ROH	FCO	
Summer	75	Base	13	7	0	0	13	7	0	0	0	0
		MTBE	13	7	0	0	13	7	0	0	0	0
		ETBE	13	7	0	0	13	7	0	0	0	0
		EIOH	13	7	7	0	13	7	7	0	0	0
		EIOH-SB	13	7	7	0	13	7	7	0	0	0
Summer	95	Base	13	7	0	0	13	7	0	0	0	0
		MTBE	13	7	0	0	13	7	0	0	0	0
		ETBE	13	7	0	0	13	7	0	0	0	0
		EIOH	13	7	7	0	13	7	7	0	6	6
		EIOH-SB	13	7	7	0	13	7	7	0	6	6
Winter	50	Base										
		MTBE										
		ETBE										
		EIOH										
		EIOH-SB										
Winter	75	Base	13	7	0	0	13	7	0	0	0	0
		MTBE	13	7	0	0	13	7	0	0	0	0
		ETBE	13	7	0	0	13	7	0	0	0	0
		EIOH	13	7	7	0	13	7	7	0	7	7
		EIOH-SB	13	7	7	0	13	7	7	0	7	7

13 denotes VEHIDS 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
 7 denotes VEHIDS 1, 2, 3, 4, 5, 9, 12
 6 denotes VEHIDS 1, 2, 3, 6, 9, 12
 1 denotes VEHID 1

Table 5-17. Total Evaporative Emissions for Reference Fuels

Vehicle Id	Temperature (F)	Test Date	Fuel Id	Fuel Description	Diurnal (g)	Hot Soak (g)	Running Loss (g)
1	50	09/13/91	E	Indolene	.	.	.
1	50	12/05/91	E	Indolene	.	.	.
1	75	11/21/91	E	Indolene	0.633	1.980	.
1	75	01/14/92	A	Industry Ave.	0.331	0.626	.
1	95	08/19/91	A	Industry Ave.	.	.	2.170
1	95	12/18/91	E	Indolene	.	.	1.350
1	95	04/23/92	E	Indolene	6.507	11.478	.
2	75	01/20/92	A	Industry Ave.	0.696	0.634	.
2	75	08/06/92	A	Industry Ave.	.	.	.
2	95	08/16/91	A	Industry Ave.	.	.	7.110
3	75	01/23/92	A	Industry Ave.	3.482	8.535	.
3	95	08/20/91	A	Industry Ave.	0.985	1.700	4.300
4	75	12/09/91	A	Industry Ave.	.	.	.
4	75	08/06/92	A	Industry Ave.	.	.	.
5	75	01/03/92	A	Industry Ave.	0.212	0.150	.
6	75	12/11/91	A	Industry Ave.	5.774	0.221	.
6	75	08/06/92	A	Industry Ave.	0.330	0.584	.
6	95	08/27/91	A	Industry Ave.	.	.	1.480
7	75	01/03/92	A	Industry Ave.	1.823	6.873	.
8	75	12/09/91	A	Industry Ave.	0.412	0.227	.
9	75	12/11/91	A	Industry Ave.	0.196	0.585	.
9	95	08/16/91	A	Industry Ave.	.	.	2.580
10	75	01/15/92	A	Industry Ave.	8.262	13.365	.
11	75	02/13/92	A	Industry Ave.	0.337	1.612	.
12	95	08/20/91	A	Industry Ave.	.	.	3.480
13	75	03/25/92	A	Industry Ave.	0.280	0.360	.

Comparison of Diurnal Emissions of the 13 Test Vehicles (1, 2, 3, 4, 5, 6, 7, 8, 9, 10(A), 11(B), 12(C), 13(D)) for Industry Average and Base Fuels at 75 F

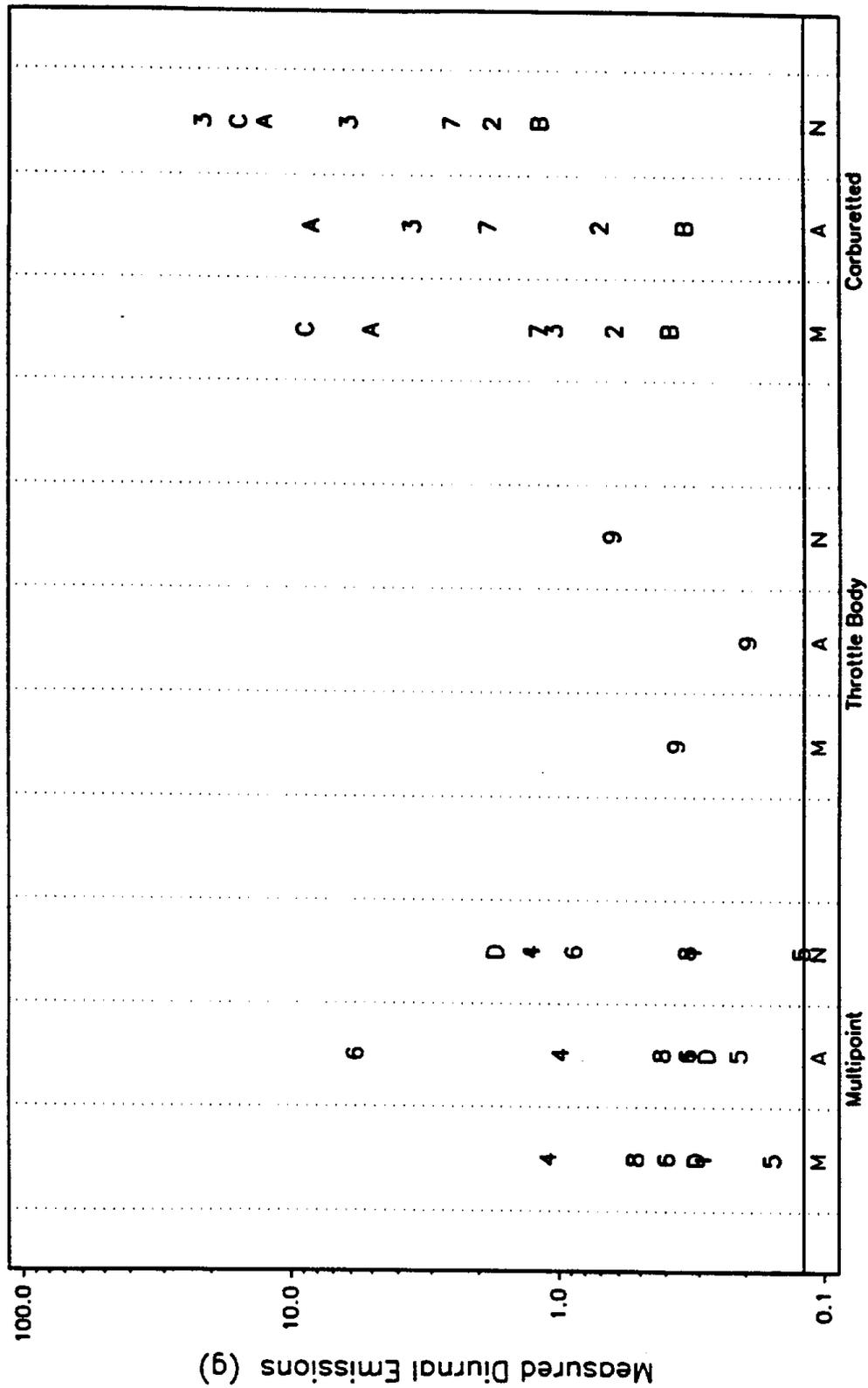
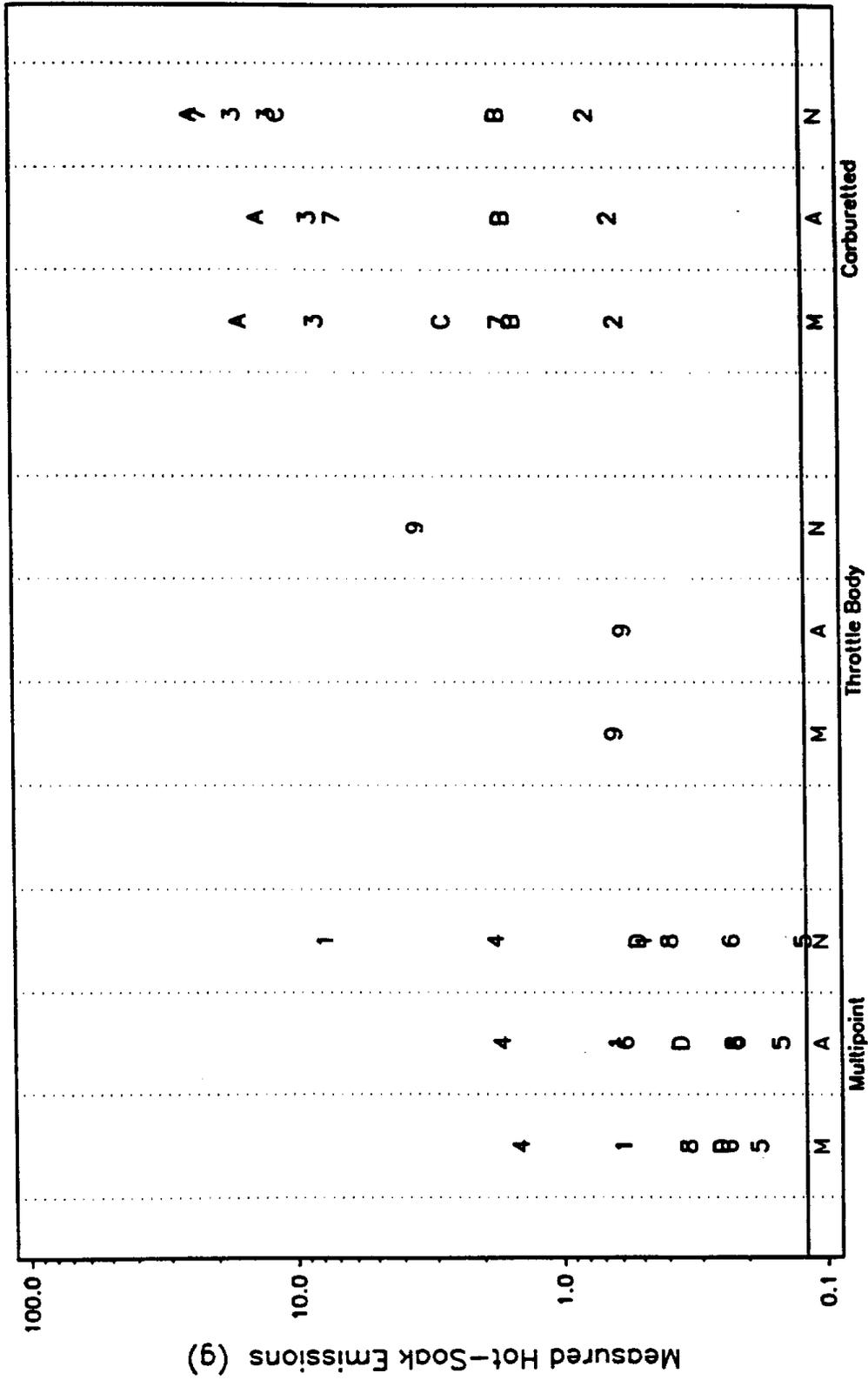


Figure 5-51
Comparison of Hot-Soak Emissions of the 13 Test Vehicles
 (1, 2, 3, 4, 5, 6, 7, 8, 9, 10(A), 11(B), 12(C), 13(D))
for Industry Average and Base Fuels at 75 F



induction system type and fuel. Within each of these nine bands, the data for each test is plotted using a symbol which denotes the vehicle identity number as shown in the figure titles.

The figures provide a visual comparison of the Industry Average (Fuel A) with the Summer and Winter Base (Fuels M and N) under different test conditions. In general, the figures show that while test results varied among the fuels, the measured values were similar. For diurnal and hot soak emissions, the carburetted vehicles produced higher emissions on the average than the fuel-injected vehicles. Within fuel induction system type, emissions showed a tendency to be higher at higher fuel volatility ($M < A < N$). From this, it is apparent that the Summer and Winter Base fuels produce evaporative emissions behavior that are similar to that produced by an Industry Average fuel. The figures show that the differences in emissions responses caused by these unoxxygenated test fuels were smaller than differences produced by individual vehicles and fuel induction system technology.

2. *Total Diurnal Emissions (DI)*. The results of the evaporative diurnal emissions measurements are given in the table in Appendix G. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The DI emissions in grams are listed as a function of vehicle, blend season, temperature, and blend type. Driving cycle was not a parameter which was investigated. Test date is used in the table to make the distinction between results from replicate tests.

The following preliminary class regression statement was used to evaluate the main effects of the four parameters in the absence of any interactions:

$$\ln DI = \text{VEHID BLENDTYP TEMP SEASON}$$

This analysis of variance indicated that the four parameters had the following order of magnitude effects on the $\ln DI$:

$$\text{TEMP} > \text{VEHID} > \text{SEASON} > \text{BLENDTYP}$$

Graphical and tabular examination and preliminary regressions of the data indicated that VEHID, VEHID*TEMP, and VEHID*SEASON had significant effects on DI emission levels, but the interaction VEHID*BLENDTYP was weak. This indicates that vehicles are responding differently to temperature and blend season, but are responding in the same way to the different fuel blends. Therefore, evaluation of the transformation to be used for the DI emissions was made by regression against the following combination of effects:

$$\text{VEHID VEHID*TEMP VEHID*SEASON BLENDTYP}$$

Additional regressions indicated that the natural log of the diurnal emissions was a reasonable transformation to be used. In addition, five data points seem to be outliers in the regression: Vehicle 1/95°/Fuel U on 20OCT92 = 5.234 grams, Vehicle 1/75°/Fuel N on 10AUG92 = 1.262 grams, Vehicle 3/75°/Fuel O on 27FEB92 = 14.719 grams, Vehicle 3/75°/Fuel N on 12OCT92 = 21.158 grams, and Vehicle 8/75°/Fuel V on 21JAN92 = 1.069 grams. These diurnal test results appear to be outliers, both in terms of the regression and in terms of examination of the data in Appendix G. The values were left out of further examination of the data. This left 200 observations on 13 vehicles to be analyzed.

A series of regressions was used to try to discover the best model statement which would describe the DI emissions. The continuous oxygen concentration OXY was brought into the model

statement as the interaction with VEHID*BLENDTYP. In the process of performing these regressions, several observations were made:

- The individual vehicle had a strong effect on the DI emissions.
- The higher emitting vehicles tended to be more sensitive to TEMP and SEASON than the lower emitting vehicles.
- Vehicles which tended to be more sensitive to temperature changes were also found to be more sensitive to blend season changes.

The best overall model which described the emissions of the individual vehicles was given by:

$$\ln DI = \text{VEHID} + \text{VEHID} * \text{TEMP} + \text{VEHID} * \text{SEASON} + \text{VEHID} * \text{BLENDTYP} * \text{OXY}$$

The regression fit the measured DI values with a standard deviation of about 40%, the r^2 was 0.954, and the model F was 26. The SAS output and parity plot of the regression are given in Appendix K.

To assist in the assignment of general vehicle technology behavior factors, the vehicles which have similar behavior can be classified together. Classifications were made by performing alternative regressions by substitution of technology parameters for vehicle parameters. The VEHID in the equation above for VEHID*TEMP, VEHID*SEASON, and VEHID*BLENDTYP was replaced with technology candidate parameters for a carburetted/fuel-injected parameter (CARBFI) and canister bottom type (CNSTR), which are the only two technology parameters which could affect evaporative emissions. The VEHID main effect parameter was retained for these regressions, since the emissions performance of individual vehicles within the same technology grouping will vary considerably due to the idiosyncrasies of each vehicle.

The overall results of this exercise indicated that CARBFI provided the best technology grouping. The CARBFI groups were carburetted and fuel-injected.

Finally, the best DI regression model using CARBFI groupings was found to be:

$$\ln DI = \text{VEHID} + \text{CARBFI} * \text{TEMP} + \text{CARBFI} * \text{SEASON} + \text{CARBFI} * \text{BLENDTYP} * \text{OXY}$$

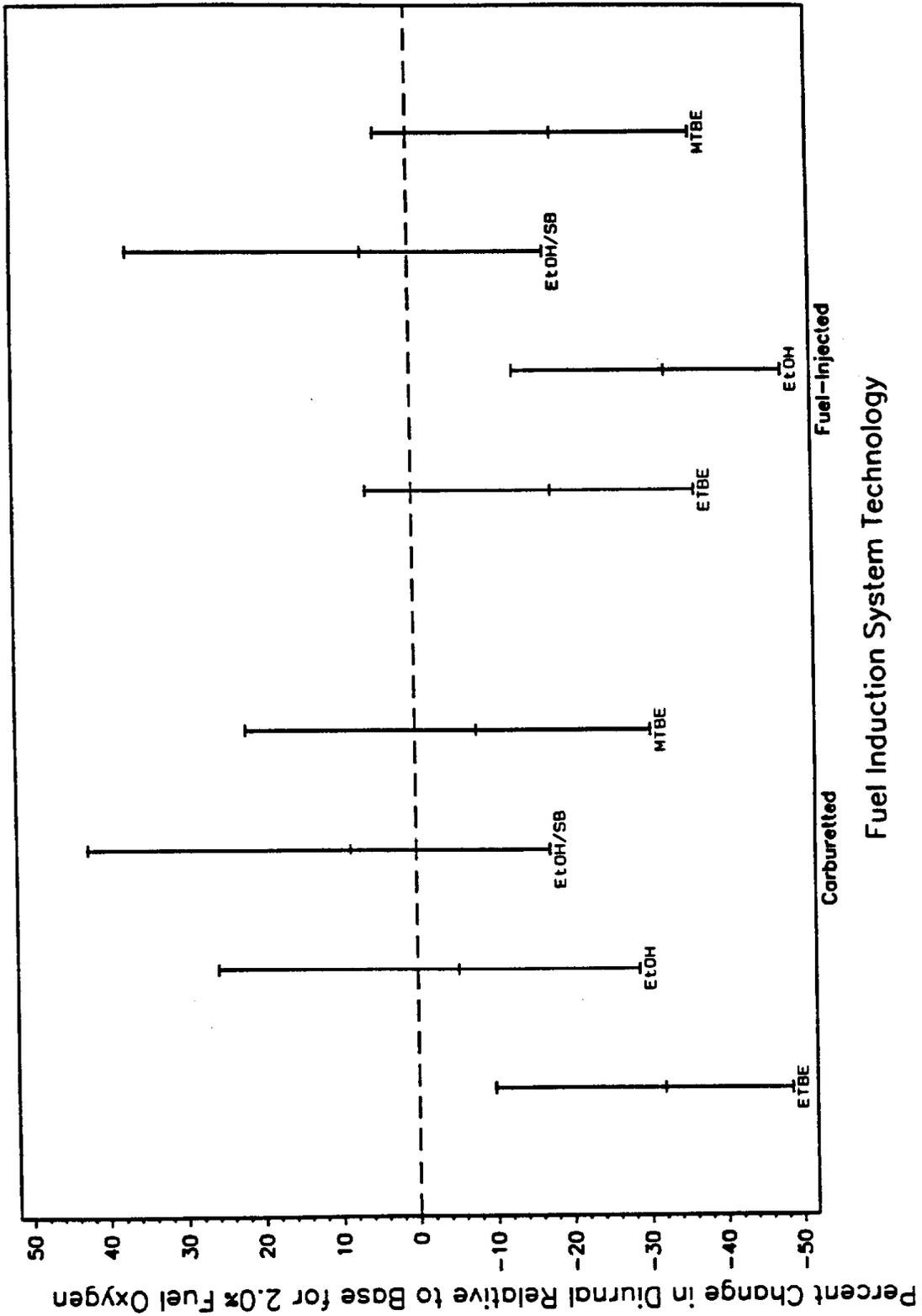
The SAS output and parity plot of the regression are given in Appendix K. From this regression, the effects on DI emissions of the four blend types relative to the Base for the two CARBFI groups are shown in Figure 5-52. The figures shows that for the carburetted vehicles, only ETBE produced a significant reduction with respect to the base fuel; ETBE also had significantly lower diurnal emissions than the EtOH, EtOH/SB, and MTBE blends. The only significant reduction for the fuel-injected vehicles was by the EtOH. The EtOH/SB blends had significantly higher diurnal emissions than ETBE, EtOH, and MTBE blends for fuel-injected technologies.

The regression also indicated that the summer blends produced 57 percent lower diurnal emissions than the winter blends for carburetted vehicles and 24 percent lower diurnal emissions than the winter blends for fuel-injected vehicles, and these differences were significant at the 95% confidence level. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the CARBFI*BLENDTYP*OXY term of the regression.

The regression also indicated that 75°F produced 75 percent lower diurnal emissions than 95°F for carburetted vehicles and 61 percent lower diurnal emissions than 95°F for fuel-injected vehicles, and these differences were significant at the 95% confidence level.

Effect of Blend Type on Diurnal Evaporative Emissions

Model: lnDI = vehid carbfi*temp carbfi*season carbfi*blendtyp*oxy



3. *Estimated Photochemical Reactivity of Diurnal Emissions.* The results of the evaporative diurnal estimated ozone production (EOP) measurements are given in the table in Appendix H. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The diurnal EOP in grams is listed as a function of vehicle, blend season, temperature, and blend type. Driving cycle was not a parameter which was investigated. Test date is used in the table to make the distinction between replicate results.

A comparison of the diurnal EOP is made with the diurnal total VOC emissions in Figure 5-53. The total diurnal emissions were calculated by summing the individual speciations for each test condition. The plot shows a linear trend between the diurnal EOP and the total diurnal emissions. The ratio of these two quantities at any given point on the plot provides an estimate of the effective reactivity (MIR) value for the vehicle test condition combination. The effective MIR values range from 2 to 4.

The following preliminary class regression statement was used to evaluate the main effects of the four parameters on diurnal estimated ozone production (DIEOP) in the absence of any interactions:

$$\ln \text{DIEOP} = \text{VEHID TEMP SEASON BLENDTYP}$$

This analysis of variance indicated that the four parameters had the following order of magnitude effects on the $\ln \text{DIEOP}$:

$$\text{VEHID} > \text{TEMP} > \text{SEASON} > \text{BLENDTYP}$$

Graphical and tabular examination and preliminary regressions of the data indicated that VEHID, VEHID*TEMP, and VEHID*SEASON had significant effects on the diurnal EOP levels, but the interaction VEHID*BLENDTYP was weak. This indicates that vehicles were responding differently to temperature and season but responding in the same way to the different fuel blends. Therefore, evaluation of the transformation to be used for the diurnal EOP levels was made by regression against the following combination of effects:

$$\text{VEHID VEHID*TEMP VEHID*SEASON BLENDTYP}$$

Additional regressions indicated that the natural log of the diurnal EOP was a reasonable transformation to be used. A series of regressions was used to try to discover the best model statement which would describe the diurnal EOP. The continuous oxygen concentration OXY was brought into the model statement as the interaction with VEHID*BLENDTYP. In the process of performing these regressions, several observations were made:

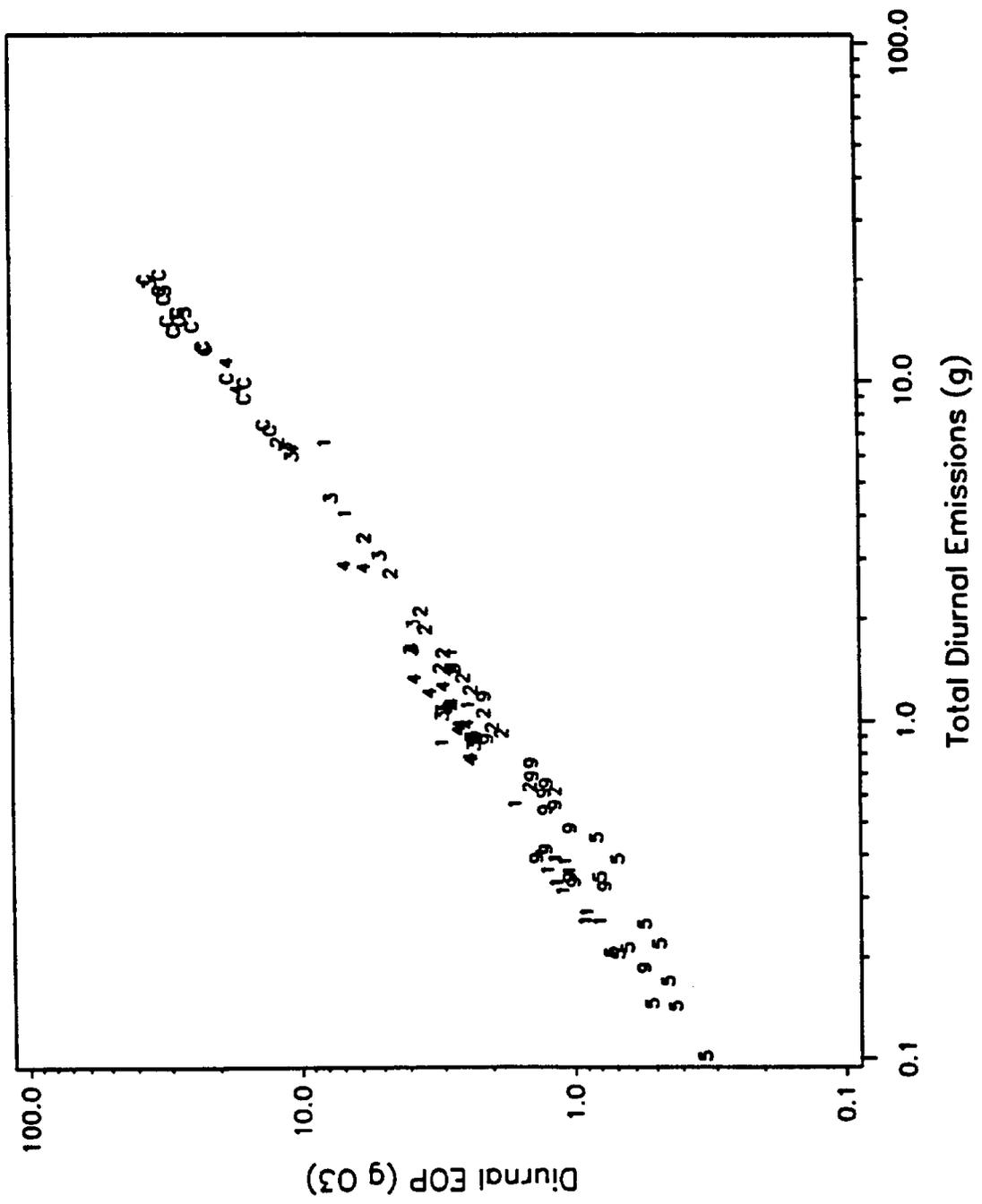
- The individual vehicle had the strong effect on the diurnal EOP levels.
- The interaction between vehicle and blend type was not significant; however, the effect of blend type on the diurnal EOP for the vehicle group as a whole was significant.

The best overall model which described the emissions of the individual vehicles were determined for carburetted and fuel-injected vehicles separately and were given by:

$$\ln \text{DIEOP} = \text{VEHID VEHID*TEMP VEHID*SEASON BLENDTYP*OXY}$$

The SAS output and parity plot of the regression are given in Appendix K. The regressions fit the measured DIEOP with standard deviations of about 40% and with r^2 of about 0.87.

Comparison of Diurnal EOP and Total Diurnal Emissions



VEHID 1 1 1 1 2 2 2 2 3 3 3 3 4 4 4 4 5 5 5 5 9 9 9 9 C C C 12

Because the regressions indicated that there was no significant VEHID*BLENDTYP interaction, assignment of general vehicle technology behavior factors to the regression was not attempted. Instead, it was assumed that the separate models for carburetted and fuel-injected vehicles as a group were adequate to describe the behavior. Thus, the technology-based model for DIEOP had the form:

$$\ln\text{DIEOP} = \text{VEHID TEMP SEASON BLENDTYP*OXY}$$

and separate regressions were used for carburetted and fuel-injected technologies. The SAS output and parity plot of the two regressions are given in Appendix K.

From these regressions, the effects of blend types for the two fuel induction technologies on diurnal EOP, relative to the base fuel, are shown in Figure 5-54. Only ETBE and MTBE showed a significant reduction in the diurnal EOP levels for carburetted vehicles. In addition, ETBE produced significantly lower DIEOP levels than EtOH and EtOH/SB for the carburetted vehicles. For fuel-injected vehicles, all blend types were not significantly different from the base fuel. EtOH/SB was significantly higher than EtOH and MTBE.

The regressions also indicated that the summer blends produced 51 percent lower (significant) DIEOP levels than the winter blends for carburetted vehicles and 13 percent lower (not significant) DIEOP levels than the winter blends for fuel-injected vehicles. Note that the summer and winter blends had volatility differences of 2 psi and had different base blending stocks. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the BLENDTYP*OXY term of the regression.

The regressions also indicated that 75°F produced 66 percent lower DIEOP levels than 95°F for carburetted vehicles and 48 percent lower DIEOP levels than 95°F for fuel-injected vehicles, and these differences were significant at the 95% confidence level.

4. Diurnal Toxic Emissions. Benzene is currently the only evaporative emission that is considered to be toxic. The quantity of benzene emitted during diurnal tests was measured as part of the speciation of diurnal emissions. The benzene emissions are shown in Appendix J. They are given in grams as a function of vehicle, blend season, temperature, and blend type. Test date is used in the table to make the distinction between results from replicate tests.

Examination of the data in the table indicates that all measured benzene values for diurnal emissions were greater than 0.0000 grams. Figure 5-55 shows a plot of the diurnal benzene emissions against the total diurnal emissions for those conditions where both values are available. The plot indicates that the benzene emissions in general decreased with decreasing diurnal emissions and that benzene emissions made up between 0.5% and 4.0% of the total diurnal emissions.

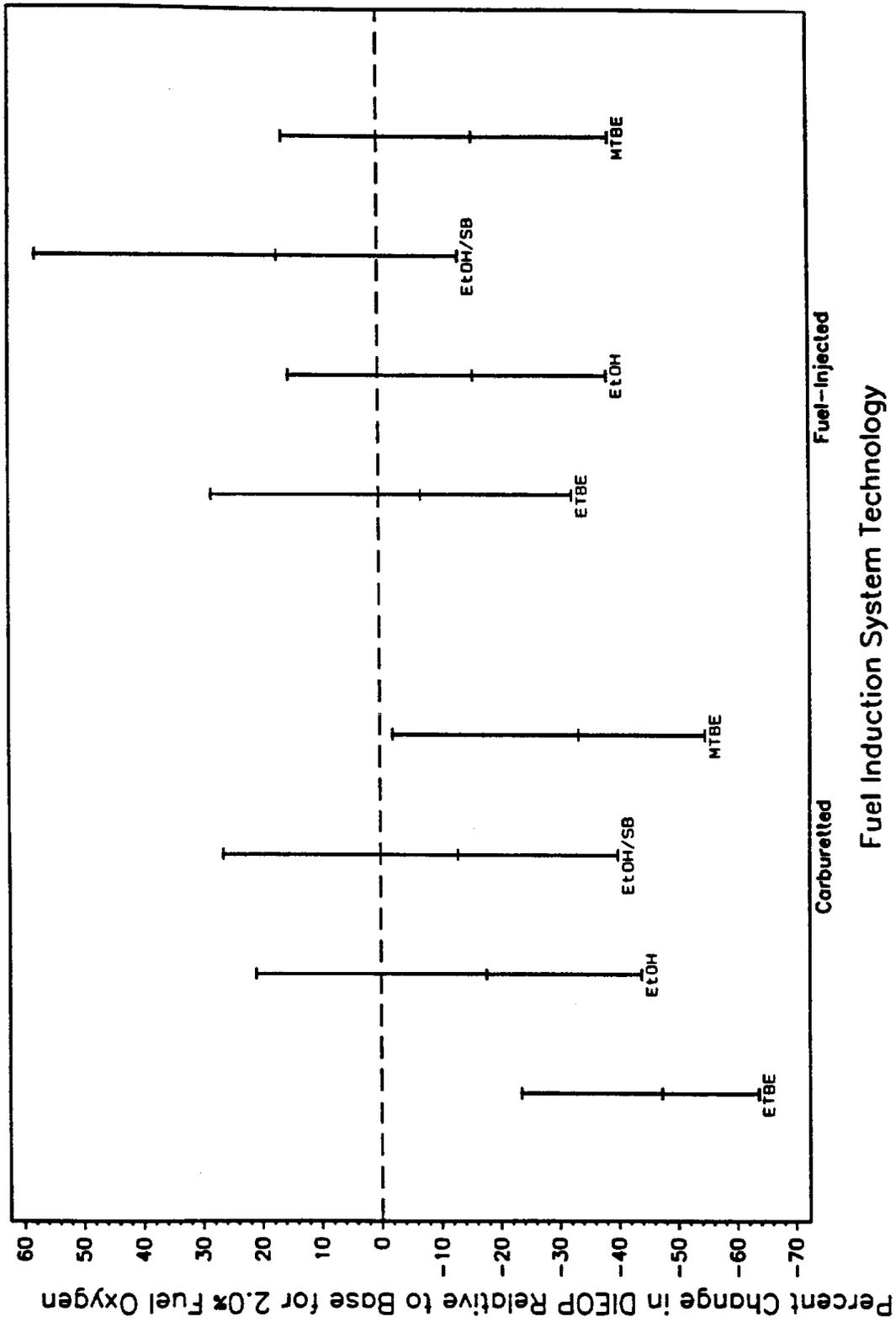
Examination of the diurnal benzene emissions (DIBZ) began with separate regression models for the total diurnal benzene emissions of individual vehicles. Thus, the following regression was used:

$$\ln\text{DIBZ} = \text{TEMP SEASON BLENDTYP}$$

Other transformations were tried, but the log transformation provided the most homogeneous residuals. As a result of this regression, one data point was found to be an outlier: Vehicle 3/-75°/Fuel N on 12OCT92 = 0.1409 grams. These regressions found that while there were sig-

Effect of Blend Type on Diurnal Estimated Ozone Production

Model: InDI = vehid temp season blendtyp*oxy (by carbfi)



nificant blend type effects for individual vehicles, there was not a dominant pattern of effects observed for all the vehicles.

Because the regressions indicated that there was no consistent and significant VEHI*BLENDTYP interaction, assignment of general vehicle technology behavior factors to the regression was not attempted. Instead, it was assumed that the separate models for carburetted and fuel-injected vehicles as separate groups were adequate to describe the behavior. Thus, the technology-based model for DIBZ had the form:

$$\ln \text{DIBZ} = \text{VEHID TEMP SEASON BLENDTYP*OXY}$$

and separate regressions were used for carburetted and fuel-injected technologies. The SAS output and parity plot of the two regressions are given in Appendix K. The 42 observations on 3 vehicles used for the carburetted model gave an r^2 of 0.945, a standard deviation of about 23%, and a model F of 1235. The 56 observations on 4 vehicles used for the fuel-injected model gave an r^2 of 0.880, a standard deviation of about 32%, and a model F of 1250.

From these regressions, the effects of blend types for the two fuel induction technologies on diurnal benzene emissions, relative to the base fuel, are shown in Figure 5-56. Only ETBE showed a significant reduction in the diurnal benzene levels for carburetted vehicles. In addition, ETBE produced significantly lower levels than the other three blend types for the carburetted vehicles. For fuel-injected vehicles, all blend types were not significantly different from the base fuel or from each other.

The regressions also indicated that the summer blends produced 15 percent lower (not significant) diurnal benzene levels than the winter blends for carburetted vehicles and 15 percent higher (not significant) diurnal benzene levels than the winter blends for fuel-injected vehicles. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the BLENDTYP*OXY term of the regression. The regressions also indicated that 75°F produced 41 percent lower (significant) diurnal benzene levels than 95°F for carburetted vehicles and 13 percent lower (not significant) diurnal benzene levels than 95°F for fuel-injected vehicles.

The diurnal emissions of benzene would not be expected to be influenced by changes in the blend season or in the blend type to any great degree. The reason for this is that the concentration of benzene in the vapor space of a solution containing benzene depends primarily on the concentration of benzene in the liquid phase and the temperature. Thus, changes in the relative concentration of other components in the gasoline, such as butane, which controls the blend season, and oxygenate compound, which controls the blend type, would have only a small effect on the gasoline benzene concentration.

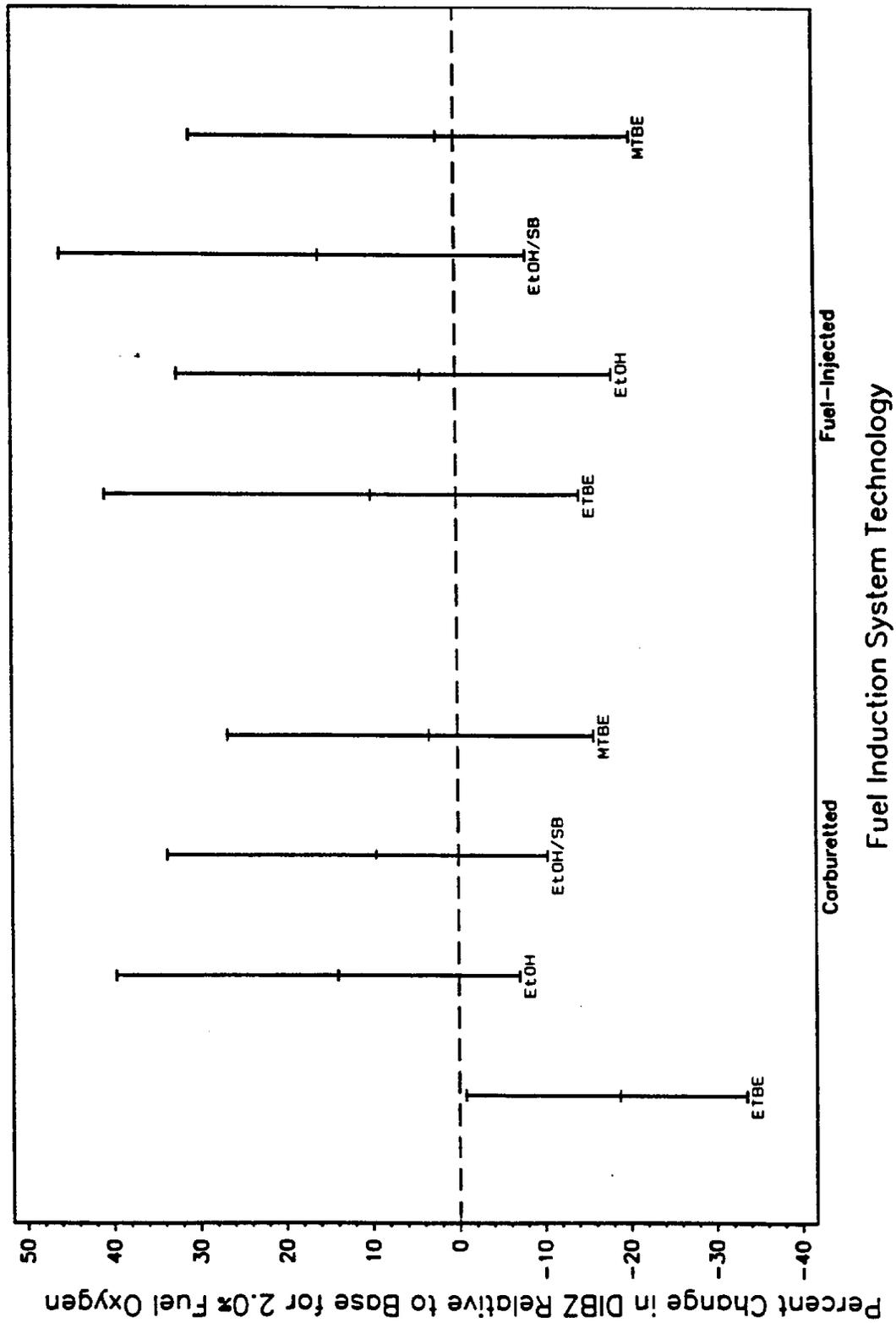
5. *Total Hot Soak Emissions (HS)*. The results of the hot soak measurements are given in the table in Appendix G. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The HS emissions in grams are listed as a function of vehicle, blend season, temperature, and blend type. Driving cycle was not a test parameter. Test date is used in the table to make the distinction between results from replicate tests.

The following preliminary class regression statement was used to evaluate the main effects of the four parameters in the absence of any interactions:

$$\ln \text{HS} = \text{VEHID BLENDTYP TEMP SEASON}$$

Figure 5-56
Effect of Blend Type on Diurnal Benzene Emissions

Model: InDIBZ = vehid temp season blendtyp*oxy (by carbfi)



The analysis of variance indicated that the four parameters had the following order of magnitude effect on the lnHS:

VEHID > TEMP > SEASON > BLENDTYP

Graphical and tabular examination and preliminary regressions of the data indicated that VEHID had large effects on the HS emission levels. Temperature, blend type, and blend season had much smaller effects. Evaluation of the transformation to be used for the HS emissions was made by individual regressions for each vehicle using the following model statement:

$\ln HS = \text{VEHID BLENDTYP TEMP SEASON}$

These regressions indicated that the natural log of hot soak emissions was a reasonable transformation to be used. In addition, four data points seem to be outliers in the regression: Vehicle 1/75°/Fuel N on 25FEB92 = 7.757 grams, Vehicle 6/95°/Fuel U on 29JUN92 = 1.284 grams, Vehicle 8/75°/Fuel V on 21JAN92 = 3.845 grams, and Vehicle 11/75°/Fuel V on 25MAR92 = 12.364 grams. These hot soak test results appear to be outliers, both in terms of the regression and in terms of examination of the data in Appendix G. These values were left out of further examination of the data. This left 124 observations remaining to be analyzed.

A series of regressions was used to try to discover the best model statement which would describe the HS emissions. In the process of performing these regressions, several observations were made:

- The individual vehicle had a strong effect on the HS emissions.
- Vehicles 1, 7, and 9 were much more sensitive to TEMP, SEASON, and BLENDTYP than the other vehicles. All of the other vehicles were relatively insensitive to TEMP, SEASON, and BLENDTYP, and behaved similarly to each other in this regard. The split between sensitive and insensitive vehicles did not seem to follow any technological grouping parameter.

Based on the individual vehicle results, it was decided to proceed with the hot soak analysis in three vehicle groups. The first group of vehicles was the group that was more sensitive to TEMP, SEASON, and BLENDTYP and included Vehicles 1, 7, and 9. This group contains carburetted and fuel-injected vehicles. The second group was a group of carburetted vehicles which had low sensitivity to TEMP, SEASON, and BLENDTYP. This includes Vehicles 2, 3, 10, 11, and 12. The third group contains fuel-injected vehicles which had low sensitivity to TEMP, SEASON, and BLENDTYP. These included Vehicles 4, 5, 6, 8, and 13. It should be noted that these three groups were formed by their sensitivities to these three parameters, and not to the level of the overall emissions of each vehicle. Final regressions were performed on the three groups of vehicles using the following model statement:

$\ln HS = \text{VEHID TEMP SEASON BLENDTYP*OXY}$

The insensitive carburetted group and the insensitive fuel-injected group were fit well by this regression. The sensitive group was not fit as well; the data evidently contained more noise. The SAS output and parity plots of the three regressions are given in Appendix K. The regressions fit the measured hot soak values with a standard deviation of about 25%, 24%, and 130% for the insensitive carburetted, insensitive fuel-injected, and sensitive vehicles, respectively.

The blend type effects for the three groups of vehicles based on the regressions are shown in Figure 5-57 for the 2.0% oxygen fuel set. The plots also give an estimate of the error on each effect. For the insensitive carburetted vehicles, the effect of ETBE and MTBE was not significantly different than the Base. However, EtOH and EtOH/SB produced about 22% higher hot soak emissions, and these were statistically significant changes. For the insensitive fuel-injected vehicles, no significant difference in hot soak emission production was noted between the oxygenated blends and the Base. For the sensitive vehicle group, the only blend which produced a significant increase (166%) in hot-soak emissions was the EtOH/SB.

The regressions also indicated that the summer blends produced 25 percent lower (significant) hot soak emissions than the winter blends for the insensitive carburetted vehicles, 11 percent higher (not significant) hot soak emissions than the winter blends for the insensitive fuel-injected vehicles, and 58 percent lower (not significant) hot soak emissions than the winter blends for the sensitive vehicles. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the BLENDTYP*OXY term of the regressions.

The regressions also indicated that 75°F produced 18 percent lower (significant) hot soak emissions than 95°F for the insensitive carburetted vehicles, 30 percent lower (significant) hot soak emissions than 95°F for the insensitive fuel-injected vehicles, and 65 percent lower (significant) hot soak emissions than 95°F for the sensitive vehicles.

6. Estimated Photochemical Reactivity of Hot Soak Emissions. The results of the hot soak estimated ozone production (EOP) measurements are given in the table in Appendix H. Hot soak EOP levels are available only for Vehicles 1, 2, 3, 4, 5, 9, and 12 since hot soak speciations were performed only on these vehicles. The hot soak EOP levels in grams are listed as a function of vehicle, blend season, temperature and blend type. Driving cycle was not a test parameter. Test dates are used in the table to make the distinction between results from replicate tests.

A comparison of the hot soak EOP with the total hot soak emissions as measured by the sum of the hot soak speciations is shown in Figure 5-58. The plot shows a linear trend over two orders of magnitude. The effective reactivity (MIR) for each vehicle/test condition, which is determined by the ratio of the hot soak EOP to the total hot soak emissions, ranges from 1 to 5.

The following preliminary class regression statement was used to evaluate the main effects of the four parameters on the hot soak estimated ozone production (HSEOP) in the absence of any interactions:

$$\ln HSEOP = VEHID \text{ BLENDTYP } TEMP \text{ SEASON}$$

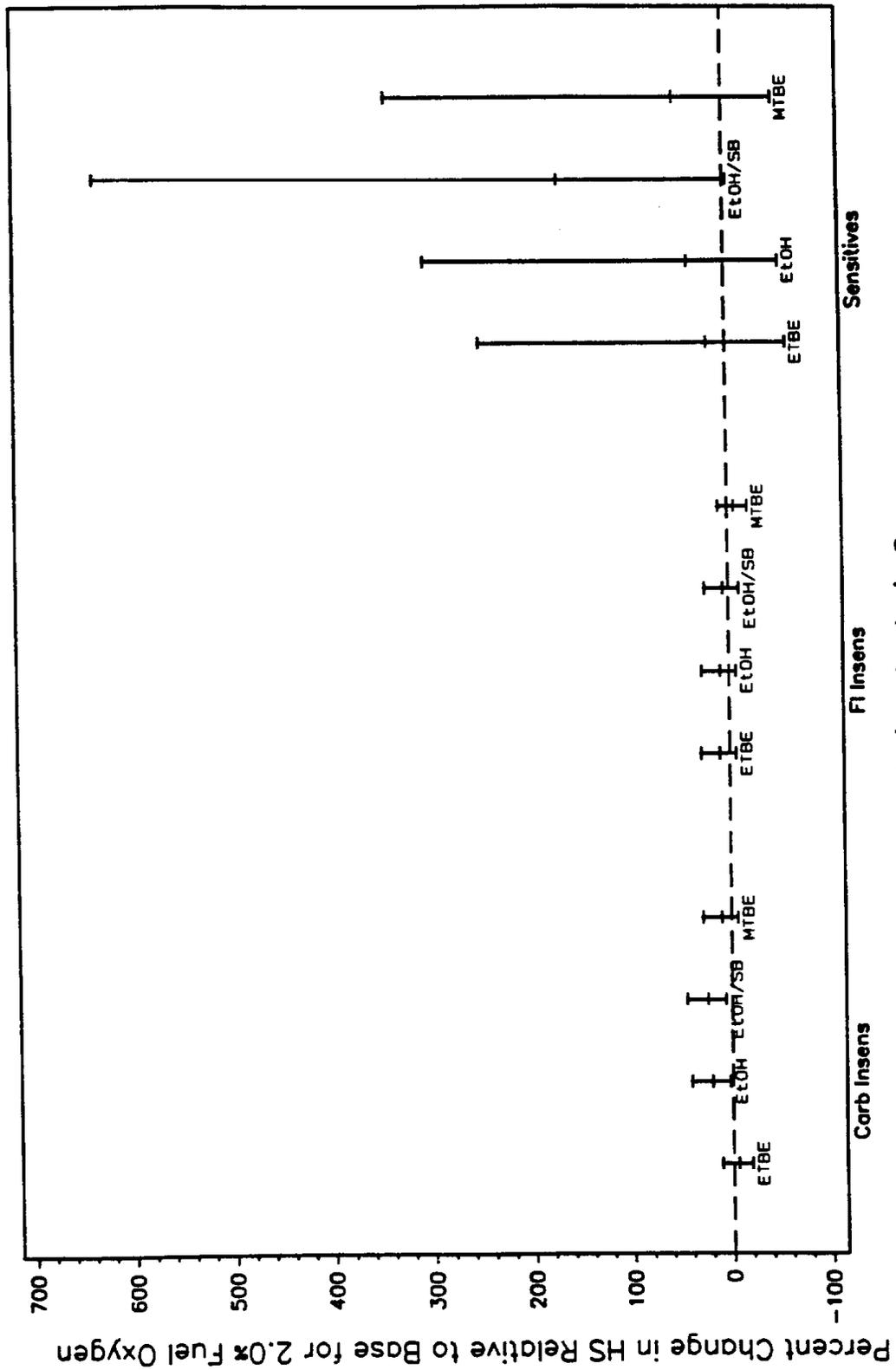
This analysis of variance indicated that the four parameters have the following order of magnitude effect on the $\ln HSEOP$:

$$VEHID > TEMP > SEASON = BLENDTYP$$

Graphical and tabular examination and preliminary regressions of the data indicated that VEHID had large effects on the hot soak EOP levels. Temperature, blend season, and blend type had small effects. Evaluation of the transformation to be used for the hot soak EOP levels was made by individual regressions for each vehicle against the following combination of effects: TEMP, SEASON, BLENDTYP. These regressions indicated that the natural log of the hot soak EOP was a reasonable transformation to be used.

Effect of Blend Type on Hot-Soak Emissions

Model: InHS = vehid temp season blendtyp*oxy (by group)



A series of regressions was used to try to discover the best model statement which would describe the hot soak EOP levels. In the process of performing these regressions, several observations were made:

- The individual vehicle had a strong effect on the hot soak EOP levels.
- Just as in total hot soak emissions, the hot soak EOPs of Vehicles 1 and 9 were more sensitive to TEMP, SEASON, and BLENDTYP than the other vehicles. All the other vehicles were relatively insensitive to TEMP, SEASON, and BLENDTYP and behaved similarly to each other in this regard.

Final regressions were performed on three groups of vehicles using the following model statement:

$$\ln\text{HSEOP} = \text{VEHID TEMP SEASON BLENDTYP*OXY}$$

The first group of vehicles was the group that was more sensitive to TEMP, SEASON, and BLENDTYP and included Vehicles 1 and 9. The remaining vehicles were placed in two groups that had low sensitivity to TEMP, SEASON, and BLENDTYP. The insensitive carburetted vehicles (2, 3, and 12) were placed in the second group; the insensitive fuel-injected vehicles (4 and 5) were placed in the third group. It should be noted that these three groups were formed by the sensitivities to the three parameters and not to the level of the overall emissions of each vehicle.

The insensitive groups were fit well by the regression. The sensitive group was not fit as well; this data evidently contained more noise. The SAS outputs and parity plots of the three regressions are given in Appendix K. The regressions fit the measured hot soak EOP values with standard deviations of about 25%, 31%, and 78% for the insensitive carburetted vehicles, insensitive fuel-injected vehicles, and the sensitive vehicles, respectively.

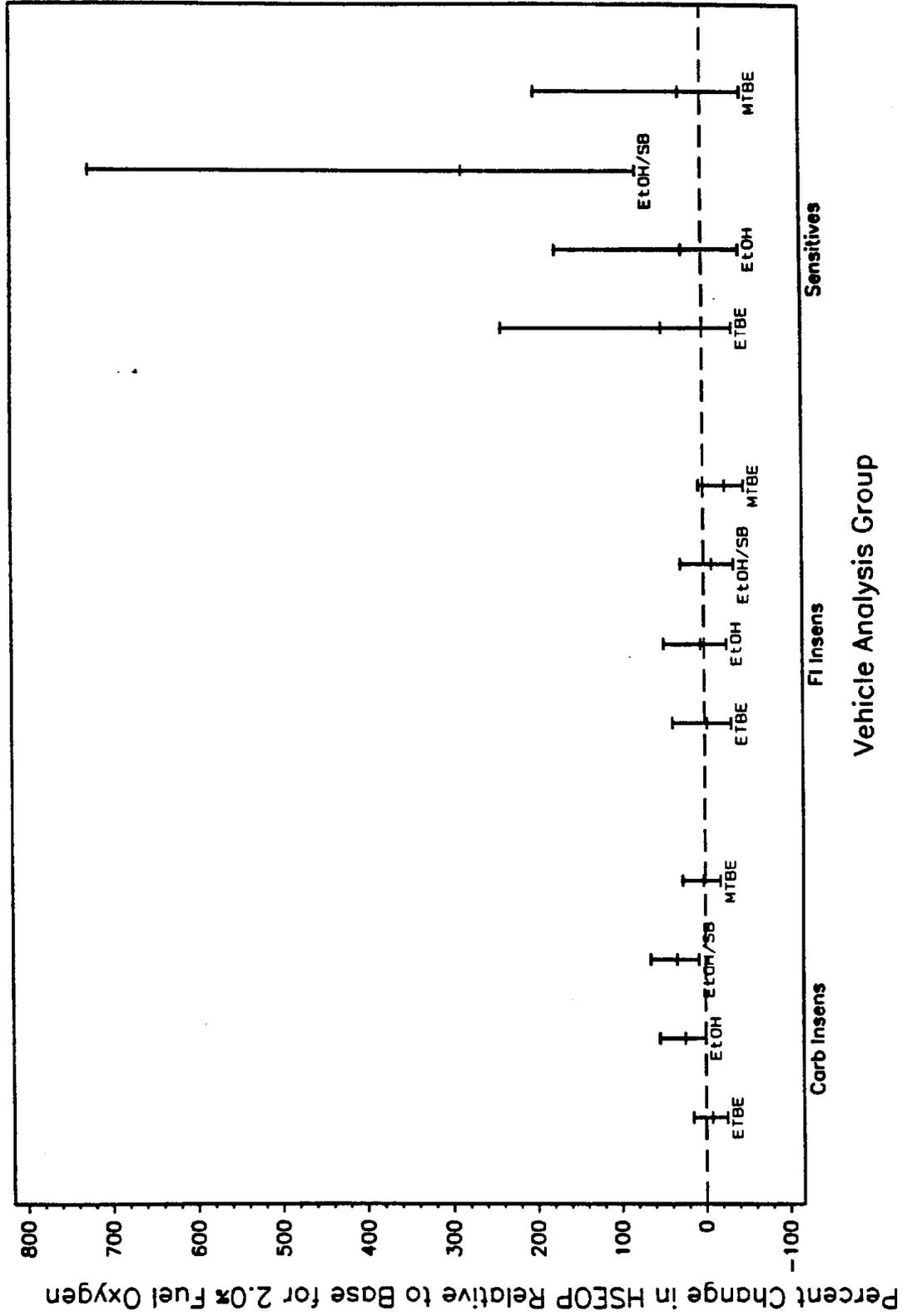
The responses of the $\ln\text{HSEOP}$ values to different blend types with 2.0% oxygen content for the three groups of vehicles are shown in Figure 5-59. The insensitive carburetted group responded with significant hot soak EOP increases of 24% for the EtOH and 33% for EtOH/SB. The ETBE and MTBE blends did not cause significant changes to hot soak EOP with respect to the base for this vehicle group. However, ETBE produced significantly lower HSEOP levels than EtOH and EtOH/SB. None of the blends produced significant changes for the insensitive fuel-injected vehicle group with respect to the base fuels or with respect to each other. The only significant change to the sensitive vehicle group was an increase associated with EtOH/SB.

The regressions also indicated that the summer blends produced 25 percent lower (significant) hot soak EOP levels than the winter blends for the insensitive carburetted vehicles, 13 percent higher (not significant) hot soak EOP levels than the winter blends for the insensitive fuel-injected vehicles, and 32 percent lower (not significant) hot soak EOP levels than the winter blends for the sensitive vehicles. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the BLENDTYP*OXY term of the regressions.

The regressions also indicated that 75°F produced 18 percent lower (significant) hot soak EOP levels than 95°F for the insensitive carburetted vehicles, 28 percent lower (significant) hot soak EOP levels than 95°F for the insensitive fuel-injected vehicles, and 81 percent lower (significant) hot soak EOP levels than 95°F for the sensitive vehicles.

Figure 5-59
Effect of Blend Type on Hot-Soak Estimated Ozone Production

Model: InHSEOP = vehid temp season blendtyp*oxy (by group)



7. *Hot Soak Toxic Emissions.* The only hot soak toxic compound of concern is benzene. The benzene values for the tests where speciations were performed are shown in Appendix J. Hot soak speciations were performed only on Vehicles 1, 2, 3, 4, 5, 9, and 12. The measured values are given as a function of vehicle, blend season, temperature, blend type, and test date.

Examination of the data values shows that all measured values were greater than 0.0000 grams. A comparison of the hot soak benzene emissions with the total hot soak emissions is shown in Figure 5-60 where both data values are available. This figure shows that under most conditions, the hot soak benzene emission was approximately 4% of the total hot soak emission.

The best individual vehicle hot soak total emission regression model was used as the hot soak benzene (HSBZ) emission model. This was:

$$\ln\text{HSBZ} = \text{TEMP SEASON BLENDTYP}$$

This regression was run separately for each vehicle. Different transformations were tried, and a log transformation was found to be the one that produced the most homogeneous residuals. The regressions identified one outlier in the data: Vehicle 1/95°F/ Fuel U on 20OCT92 = 0.1085 grams. This left 98 observations remaining in the data set. Only a few parameter levels were found to have significant effects on the hot soak benzene emissions of individual vehicles: Vehicle 4: 75°, MTBE; Vehicle 12: EtOH/SB; and Vehicle 1: EtOH, EtOH/SB.

The regressions were run again on the carburetted (Vehicles 2, 3, and 12) and fuel-injected vehicles (Vehicles 1, 4, 5, and 9) in separate groups to determine how these different technologies affected hot soak benzene emissions. The SAS outputs and parity plots of the two regressions are given in Appendix K. The r^2 of these regressions were 0.95 and 0.87, respectively.

The effects of the blends with respect to the base fuels are given in Figure 5-61. The figure shows that for carburetted vehicles EtOH and EtOH/SB increased the benzene significantly above the level for the base fuels. In addition, it can be seen that ETBE and MTBE produced HSBZ levels significantly lower than EtOH and EtOH/SB for the carburetted vehicles. For the fuel-injected vehicles, no blend type was significantly different than the base fuels; however, MTBE produced significantly lower hot soak benzene emissions than EtOH.

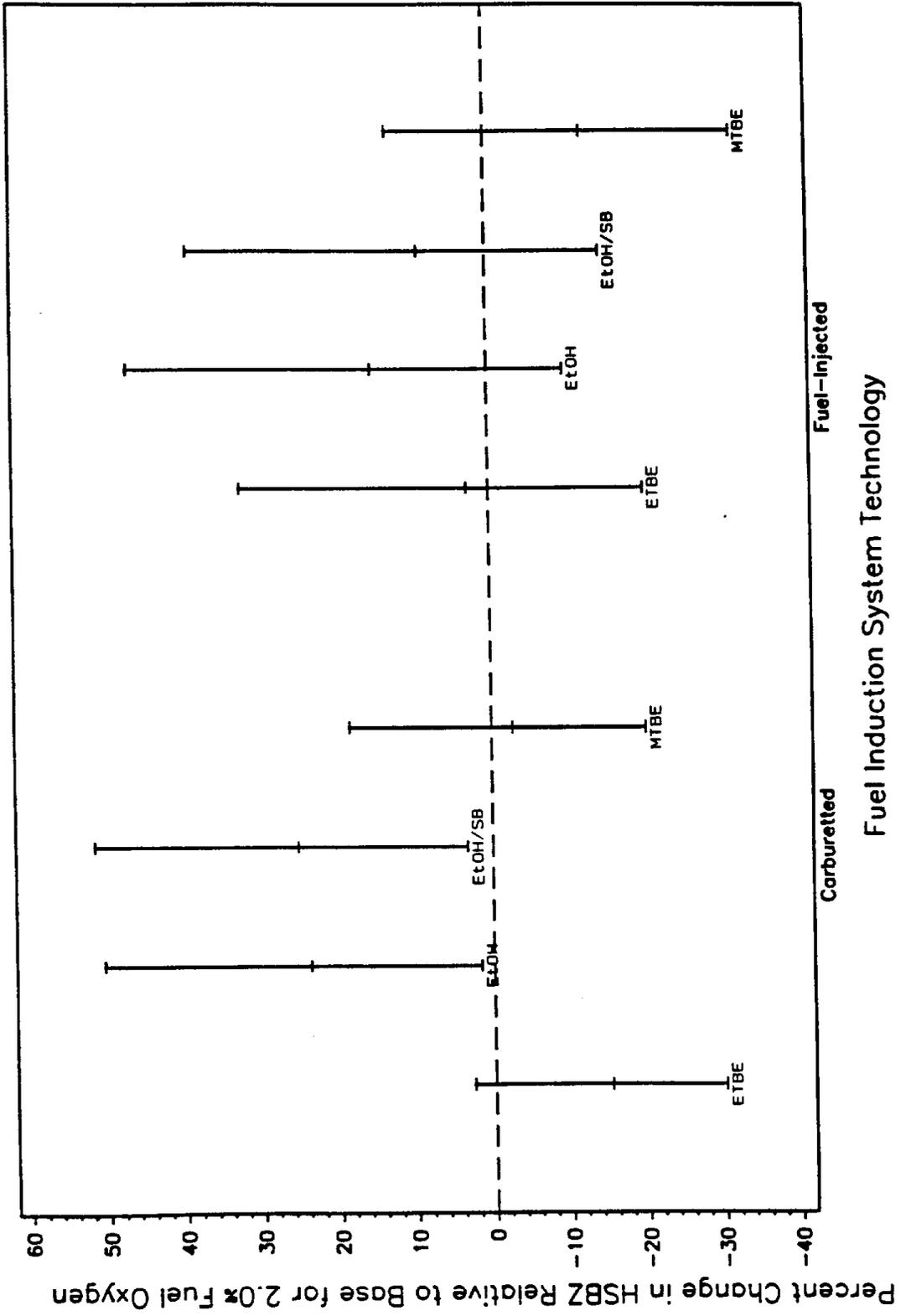
SEASON and TEMP had weak effects in these regressions. The regressions indicated that the summer blends produced 17 percent lower (significant) hot soak EOP levels than the winter blends for the carburetted vehicles and 21 percent higher (not significant) hot soak EOP levels than the winter blends for the fuel-injected vehicles. Note that the summer and winter blends had volatility differences of 2 psi and had different base blending stocks. While the oxygen content of the blends was different, the effect of oxygen content is accounted for in the BLENDTYP*OXY term of the regressions.

The regressions also indicated that 75°F produced 10 percent lower (not significant) hot soak EOP levels than 95°F for the carburetted vehicles and 16 percent lower (not significant) hot soak EOP levels than 95°F for the fuel-injected vehicles.

8. *Total Running Loss Emissions (RL).* The results of the evaporative running loss measurements are given in the table in Appendix G, along with the other types of evaporative emissions. This table is provided for documentation purposes and for the reader to examine trends in the raw data. The RL emissions in grams are listed as a function of vehicle and blend type. Blend season,

Effect of Blend Type on Hot-Soak Benzene Emissions

Model: InHSBZ = vehid temp season blendtyp*oxy (by carbfi)



temperature, and driving cycle were held constant for these tests. The value for total RL given in the table is the sum of the six running loss bags from the database.

Running loss tests were performed on six vehicles. Vehicles 1, 6, and 9 were fuel-injected, and Vehicles 2, 3, and 12 were carburetted. The total running loss, as well as the speciation of the total running loss, were determined for all tests.

The following preliminary class regression statement was used to evaluate the main effects of the two parameters in the absence of any interactions:

$$\ln RL = \text{VEHID BLENDTYP}$$

This analysis of variance indicated that the two parameters had the following order of magnitude effect on the $\ln RL$:

$$\text{VEHID} > \text{BLENDTYP}$$

In this regression, VEHID had a significant effect on $\ln RL$ and BLENDTYP did not have a significant effect. In none of the regressions did BLENDTYP have a significant effect on running losses. Since SEASON and TEMP were not varied in this study of running losses, those effects cannot be measured. None of the 30 running loss observations were designated as outliers as a result of these regressions.

Graphical examination of the data is shown in Figure 5-62. The plot shows that the three carburetted vehicles had larger running losses than the three fuel-injected vehicles. Vehicle 3 showed a large increase (not significant) in running loss emissions for the EtOH and EtOH/SB fuels. Other than this effect, no other trends for the different blend types seem apparent.

Vehicles were grouped into a carburetted group and a fuel-injected group, and the regressions were repeated. Again, VEHID was significant, and BLENDTYP was not. Figure 5-63 shows the estimated effect of blend type on running loss emissions for the two groups. The error bars indicate that, with the exception of MTBE for fuel-injected vehicles, none of the blend types showed a significant difference in running loss emissions with respect to the base fuels or with respect to other oxygenated blend types.

9. Estimated Photochemical Reactivity of Running Loss Emissions. The results of the evaporative running loss estimated ozone production (EOP) measurements are given in Appendix H, along with the other types of evaporative emissions. This table is provided for documentation purposes and for the reader to examine trends in the data. The running loss EOP levels in grams of ozone are listed as a function of a vehicle and blend type. Blend season, temperature, and driving cycle were held constant for these tests. The value for total running loss EOP given in the table is a cumulative estimated ozone production for the entire running loss test; that is, for the combination of all six running loss bags.

A comparison of the running loss EOP with the total running loss emissions as measured by the sum of the speciations is shown in Figure 5-64. This plot shows a linear trend over one order of magnitude. The effective reactivity (MIR) of the running loss emissions, which is determined by the ratio of the running loss EOP to the total running loss emissions, ranges from 2 to 3.

Running loss tests were performed on six vehicles. The total running loss as well as the speciation of the running losses were determined for all tests. Vehicles 1, 6, and 9 were fuel-injected

Figure 2-65
 Effect of Blend Type for Running Loss Data

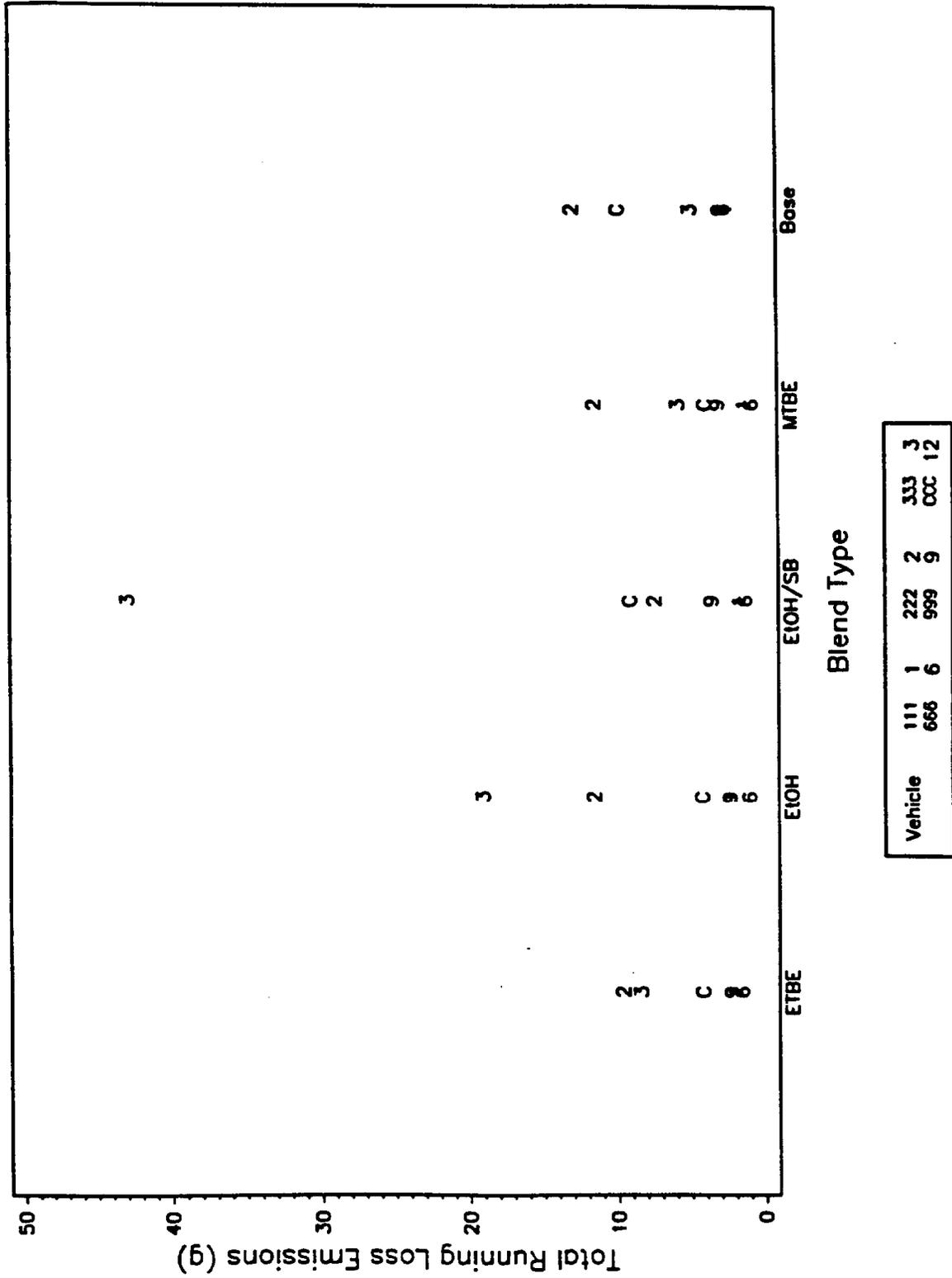
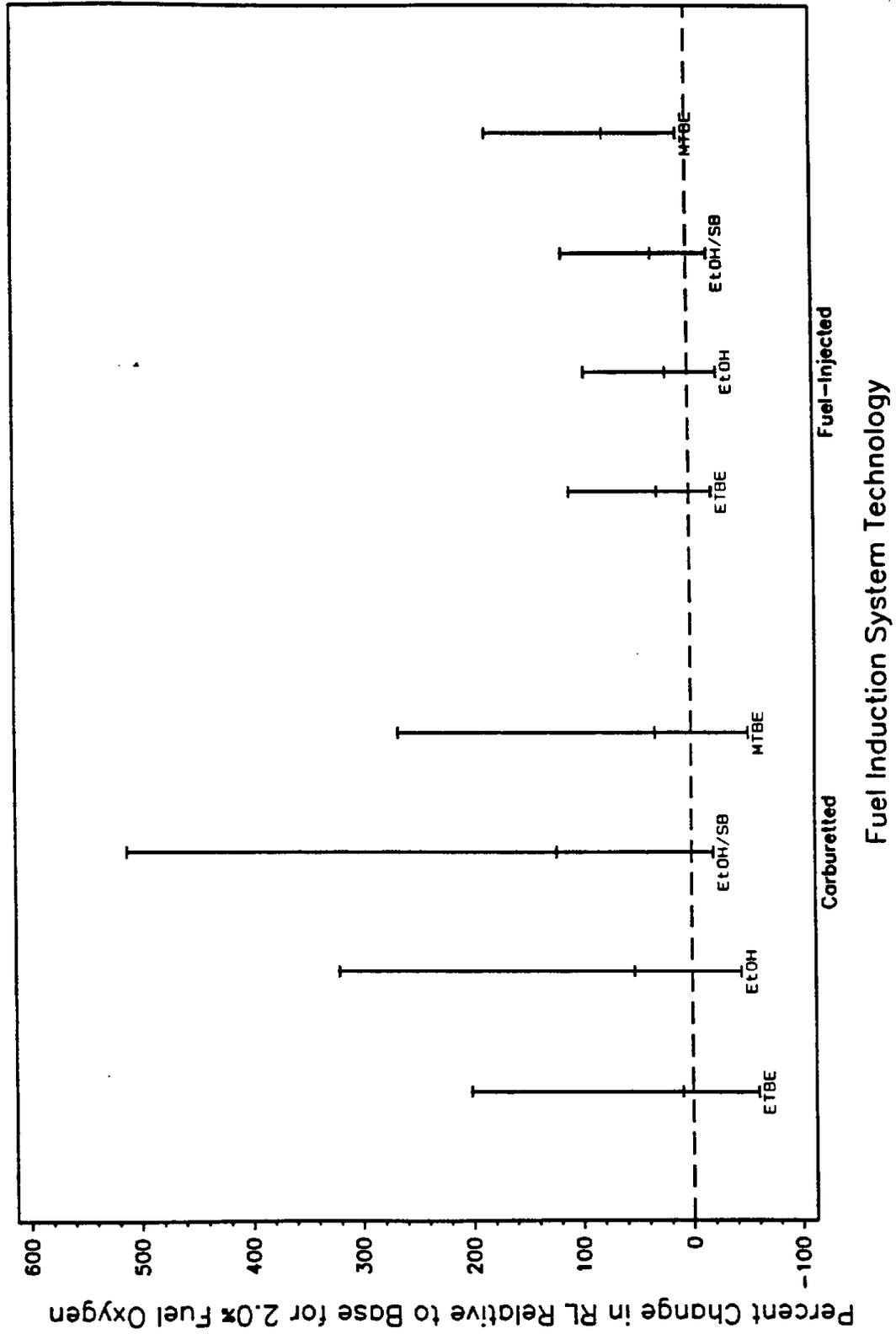
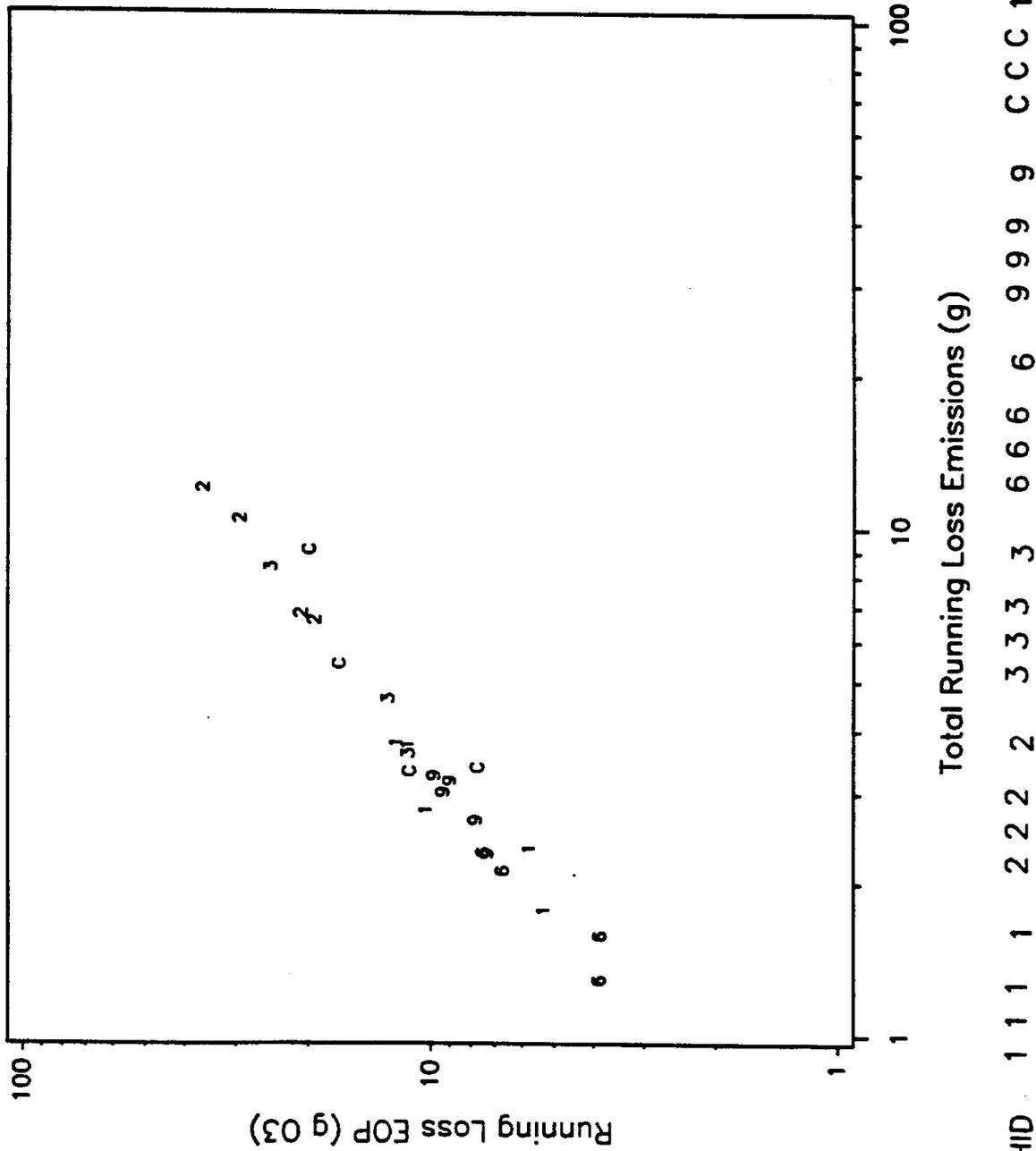


Figure 5-63
Effect of Blend Type on Running Loss Evaporative Emissions

Model: InRL = vehid blendtyp*oxy (by carbfi)



Comparison of Running Loss EOP and Total Running Loss



VEHID 1 1 1 1 2 2 2 2 3 3 3 3 6 6 6 6 9 9 9 9 C C C 12

and Vehicles 2, 3, and 12 were carburetted. The following preliminary class regression statement was used to evaluate the main effects of the two parameters on the running loss estimated ozone production (RLEOP) in the absence of any interaction:

$$\ln RLEOP = \text{VEHID BLENDTYP}$$

This analysis of variance indicated that the two parameters had the following order of magnitude effect on the lnRLEOP:

$$\text{VEHID} > \text{BLENDTYP}$$

Graphical examination of the data is shown in Figure 5-65. The plot shows that speciation data are not available for the following vehicles and test conditions: Vehicle 2/95°/Fuel M = ETBE; Vehicle 3/95°/Fuel Q = ETBE; Vehicle 3/95°/Fuel S = EtOH; Vehicle 3/95°/Fuel U = EtOH/SB; Vehicle 6/95°/Fuel U = EtOH/SB; Vehicle 12/95°/Fuel Q = ETBE; and Vehicle 12/95°/Fuel U = EtOH/SB. In addition, the following two data points were found to be outliers: Vehicle 1/95°/Fuel U on 30JUN92 = 0.076 g O₃ and Vehicle 2/95°/Fuel U on 29JUN92 = 0.565 g O₃. These data points were removed from subsequent examination of the data. This left 21 data points to be analyzed. The plot shows that the three carburetted vehicles had larger running loss EOPs than the three fuel-injected vehicles.

Analysis of the running loss EOP was completed by the regression of the six vehicle data in a carburetted group and a fuel-injected group using the same model statement. The estimated responses of the blends are shown in Figure 5-66. For the carburetted group, the EtOH and MTBE blends produced significant increases in RLEOP with respect to the base blends and the ETBE blends. No data was available to analyze for EtOH/SB on carburetted vehicles. No significant effects on running loss EOP of fuel-injected vehicles were found for the oxygenated blends relative to the base blends. However, the plot indicates that MTBE blends produced lower RLEOP levels than ETBE and EtOH blends.

10. Running Loss Toxic Emissions. The only toxic emission for running losses is benzene. The benzene values which were measured during the speciation of running losses are shown in Appendix J as a function of vehicle, blend type, and test date. The values are a cumulative value for the entire running loss test. Running loss tests were performed on six vehicles. The total running loss as well as the speciation of the running losses were determined for all tests. Vehicles 1, 6, and 9 were fuel-injected and Vehicles 2, 3, and 12 were carburetted.

Examination of the values for running loss benzene indicate that all 21 values except one were greater than 0.0000 gram. A comparison of the running loss benzene emissions versus the total running loss emissions is made in Figure 5-67. The plot indicates that the running loss benzene is approximately 3% of the total running loss emissions.

Because running loss emissions were measured for only one driving cycle, one temperature, and one blend season, the effect of running loss benzene emissions (RLBZ) can only be examined as a function of vehicle and blend type. Therefore, the following model statement was used to examine the data:

$$\ln RLBZ = \text{VEHID BLENDTYP}$$

The results of the regression indicated that the effect of vehicle was significant, but that blend type was not significant. Analysis of the running loss benzene was completed by regression of the six

Effect of Blend Type for Running Loss EOP Data

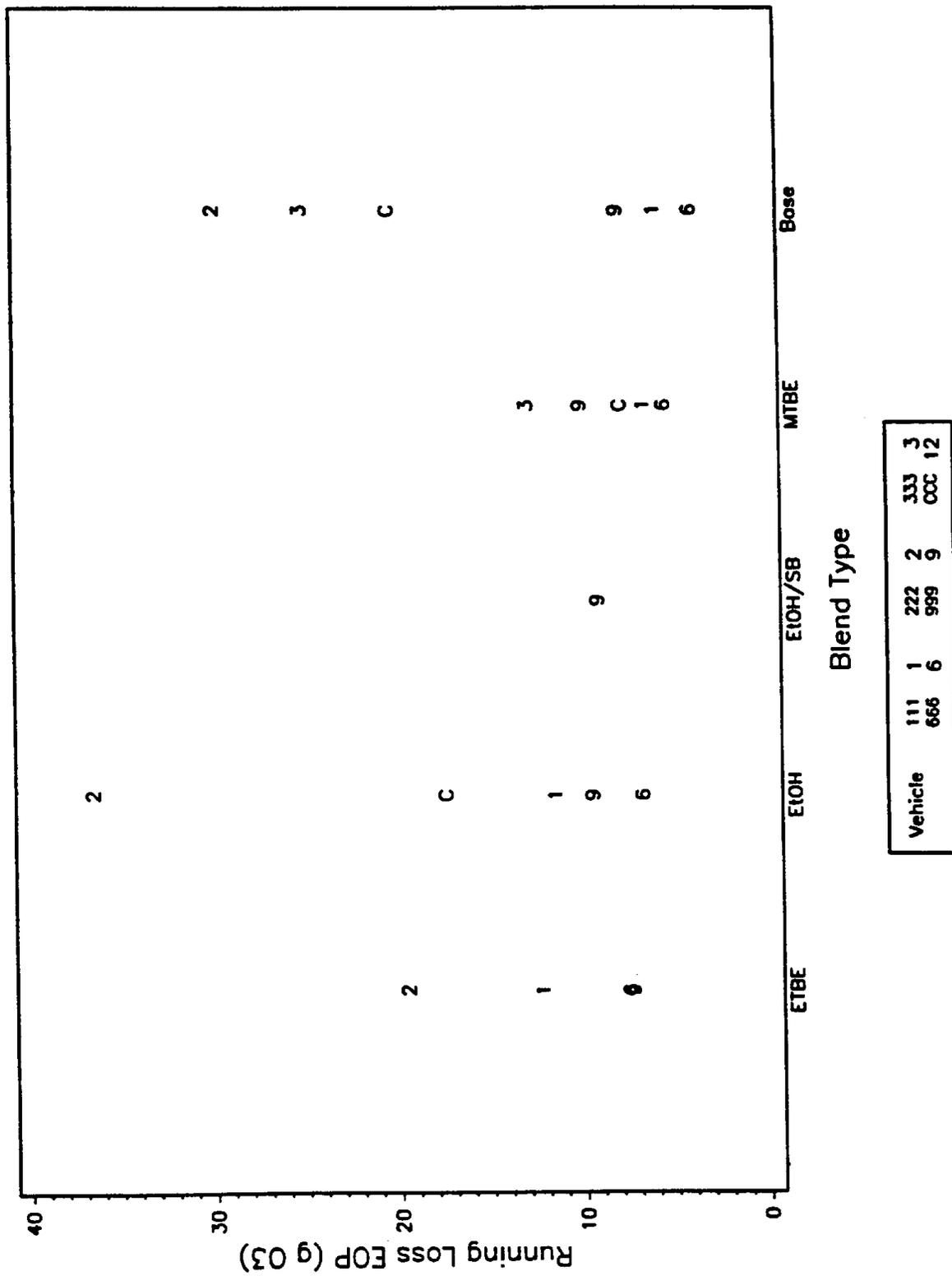
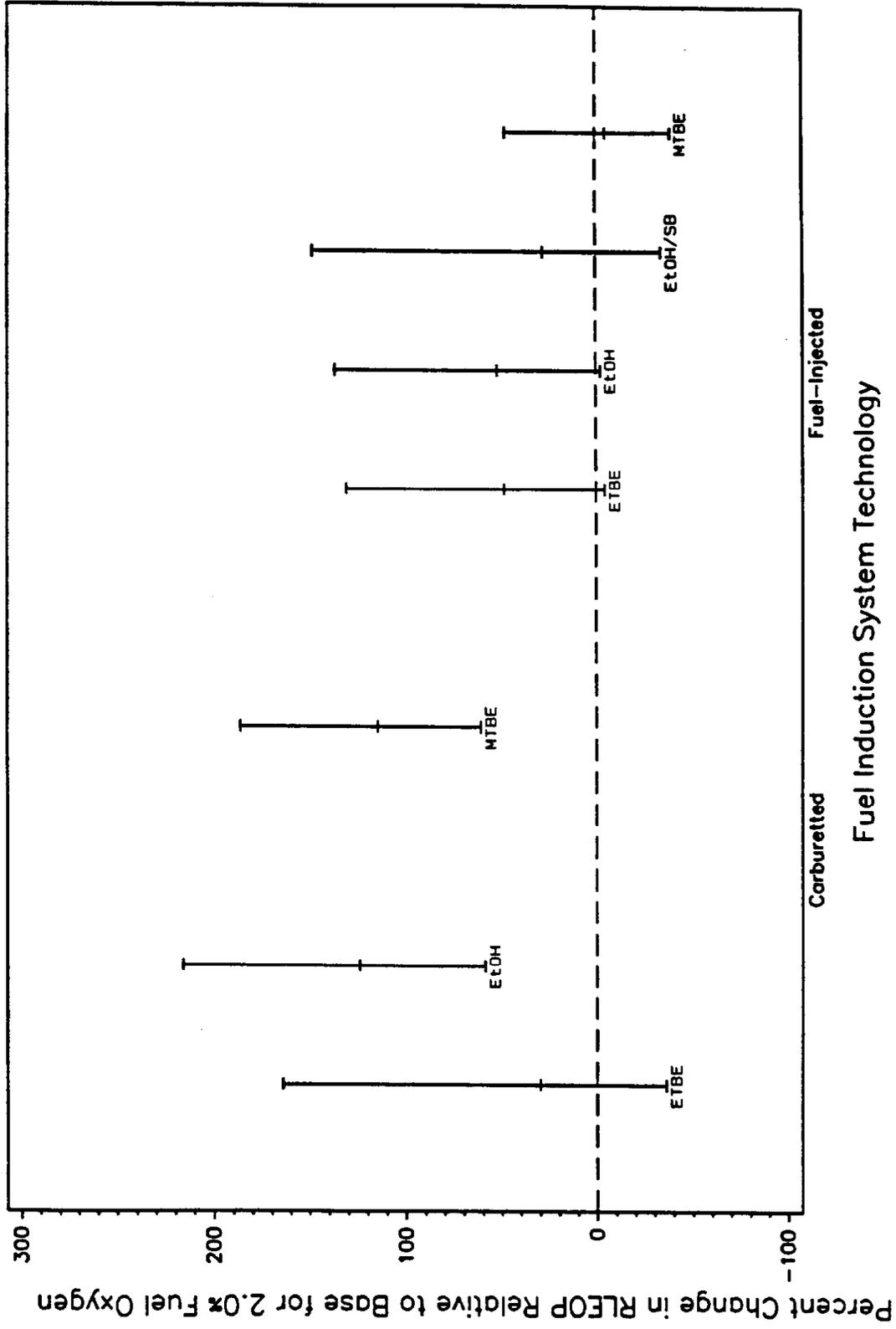


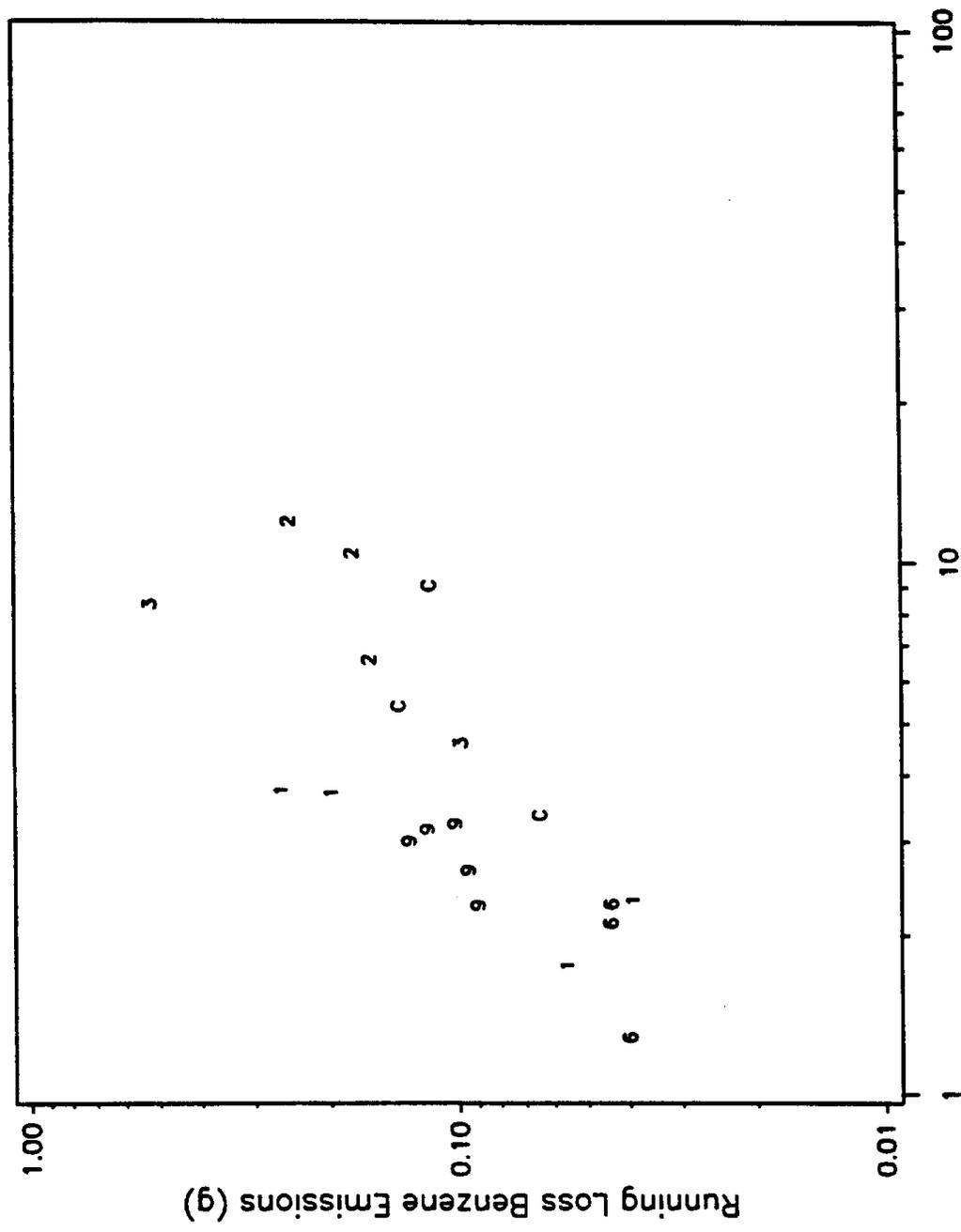
Figure 5-66

Effect of Blend Type on Running Loss Estimated Ozone Production

Model: InRLEOP = vehid blendtyp*oxy (by carbfi)



Comparison of Running Loss Benzene with Total Running Losses



VEHID	1	1	1	2	2	2	2	3	3	3	3	6	6	6	6	9	9	9	9	C	C	C	12
	1	1	1	2	2	2	2	3	3	3	3	6	6	6	6	9	9	9	9	C	C	C	12

vehicle data in a carburetted group and a fuel-injected group using the same model statement. No significant effects were found for any of the oxygenated blends for either technology group.

The estimated responses of the blends are shown in Figure 5-68. The regressions in Appendix J indicate that none of the blend types produced running loss benzene emissions significantly different from that produced by the base blends. Since only 8 carburetted and 12 fuel-injected observations were available for this analysis, the uncertainty in blend type effects is large. Future measurements with a larger number of observations would provide a more powerful test for blend type effects on running loss benzene emissions.

Effect of Blend Type on Running Loss Benzene Emissions

Model: InRLBZ = vehid blendtyp*oxy (by carbfi)

