

Effects of Specific Fuel Aromatic Compounds on Motor Vehicle Exhaust Emissions

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Statistical Analysis and Interpretation

Volume II
Procedures and Data Report

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Volume I Statistical Analysis and Interpretation

Health and Environmental Sciences Department

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ABSTRACT

In 1991, the American Petroleum Institute (API) sponsored an emissions testing program to determine: (a) whether changes in the composition of aromatic compounds in gasoline have a significant impact on exhaust emissions; and (b) the significance of the impact on emissions from changing fuel aromatics composition after other fuel properties (such as distillation factors) are controlled. The study measured both regulated exhaust emissions and the composition of exhaust hydrocarbons from a fleet of ten automobiles representative of 1989 and 1990 model year technology operated under 1975 Federal Test Procedure (FTP) temperatures and conditions. The test program was conducted in three phases. The first phase measured emissions on a base fuel and a set of four additional gasolines which had been systematically varied with respect to their relative compositions of C_7 , C_8 , C_9 , and C_{10+} aromatics. A second phase measured emissions from vehicles operated on the base fuel and two additional gasolines. These latter two gasolines were specified to have distillation properties which matched those of the base fuel and all other characteristics (including aromatics composition) were designed to be similar to two of the fuels from the first phase. A third test phase was conducted after an inspection revealed that the sulfur levels of the Phase II fuels were uniformly low. The fuels for the second phase were rebled to match the Phase I sulfur levels. The study found that exhaust mass emissions of hydrocarbons, carbon monoxide (CO), and nitrogen oxides (NO_x) rise when the fraction of total fuel aromatics contributed by species with higher carbon numbers (i.e., C_9 , C_{10}) is increased and fuel distillation properties are not controlled. However, when fuel distillation properties are held constant, shifts in the composition of fuel aromatic compounds by carbon number have no statistically significant effect on exhaust emissions of these pollutants.

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EXECUTIVE SUMMARY

There is a growing body of empirical data on the relationship between the aromatic content of gasoline and vehicle exhaust emissions. The ongoing Joint Auto/Oil Air Quality Improvement Research Program (AQIRP) showed that lowering the total aromatic content of gasoline reduced tailpipe emissions of Volatile Organic Compounds (VOCs). (1)¹ It also found that lowering the T_{90} distillation point of gasoline yielded lower VOC emissions. Furthermore, the Auto/Oil AQIRP found that the effect of T_{90} on emissions was significantly different at higher levels of fuel aromatic content than at lower levels. This has raised questions concerning the existence of a relationship between fuel aromatics content and distillation (specifically, T_{90}) properties with respect to impacts on exhaust emissions. The Auto/Oil AQIRP recently completed an evaluation of the effect of different refinery aromatic process streams on VOC emissions. (2) However, one issue which has not yet been resolved concerns the extent to which changes in the composition of fuel aromatic compounds may influence the mass of exhaust hydrocarbons.

In 1991, the American Petroleum Institute (API) sponsored an emissions testing program to investigate this issue. The program had two ultimate objectives:

- (a) To determine whether changes in the composition of aromatic compounds in gasoline have a significant impact on exhaust emissions.
- (b) To determine the significance of the effect of changing fuel aromatics composition after other fuel properties (such as distillation factors) are controlled.

APPROACH

The study measured both regulated exhaust emissions and the composition of exhaust hydrocarbons from a fleet of ten automobiles representative of 1989 and 1990

¹ Numbers in () are references listed at the end of the report.

model year technology operated under 1975 Federal Test Procedure (FTP) temperatures and conditions.

The test program was conducted in phases. During the first phase, exhaust emissions were measured while operating each of the ten vehicles on a set of five fuels. The base or primary fuel for this set was blended to contain a total non-benzene aromatic content of about 36 vol % and consisted of roughly equal proportions of C₇, C₈, C₉ and C₁₀₊ aromatics components. The four additional gasolines were created by systematically removing one of the four (C₇, C₈, C₉ and C₁₀₊) classes of fuel aromatic compounds from the primary fuel and proportionally increasing the concentrations of the remaining three aromatics components to maintain a constant total non-benzene aromatic content. All other fuel properties were held at industry-average levels as closely as possible.

This blending approach yielded a set of fuels for the first phase which varied systematically with respect to the concentrations of specific classes of aromatic compounds. No attempt was made to correct for the shifts in distillation properties which occurred as a consequence of varying the aromatic compositions of the fuels.

In the second phase, the primary fuel was rebled and two other additional gasolines were created. These latter two gasolines were similar in aromatics composition to two fuels from the first phase, but had distillation properties which had been matched to those of the primary fuel by substituting iso-paraffins of equivalent boiling range for the aromatic component removed. (See Table ES.1) After this second test phase was completed, an error was discovered in the composition of the three test gasolines. Although all of the aromatics content and distillation-matching specifications had been met, the sulfur levels of the three fuels were found to be uniformly lower by an order of magnitude, relative to the Phase I test gasolines. Therefore, the three fuels were rebled to match the Phase I sulfur levels and the test phase was repeated.

ES-2

TABLE ES.1 Design Test Fuel Characteristics

PHASE	FUEL	AROMATICS COMPONENTS	DISTILLATION
I	1	C ₇ , C ₈ , C ₉ , C ₁₀₊	Base
	2	C ₇ , C ₈ , (C ₉ =0), C ₁₀₊	Uncorrected
	3	C ₇ , (C ₈ =0), C ₉ , C ₁₀₊	Uncorrected
	4	(C ₇ =0), C ₈ , C ₉ , C ₁₀₊	Uncorrected
	5	C ₇ , C ₈ , C ₉ , (C ₁₀₊ =0)	Uncorrected
IIA	1A	C ₇ , C ₈ , C ₉ , C ₁₀₊	Base
	4A	(C ₇ =0), C ₈ , C ₉ , C ₁₀₊	Corrected
	5A	C ₇ , C ₈ , C ₉ , (C ₁₀₊ =0)	Corrected
IIB	1B	C ₇ , C ₈ , C ₉ , C ₁₀₊	Base
	4B	(C ₇ =0), C ₈ , C ₉ , C ₁₀₊	Corrected
	5B	C ₇ , C ₈ , C ₉ , (C ₁₀₊ =0)	Corrected

Testing was conducted by Automotive Testing Laboratories (ATL), Inc. and the emissions measurements were transmitted to API for examination using standard Analysis of Variance statistical techniques. The specific analyses that were conducted as part of this effort are described in detail in the body of this report. Key findings are summarized below.

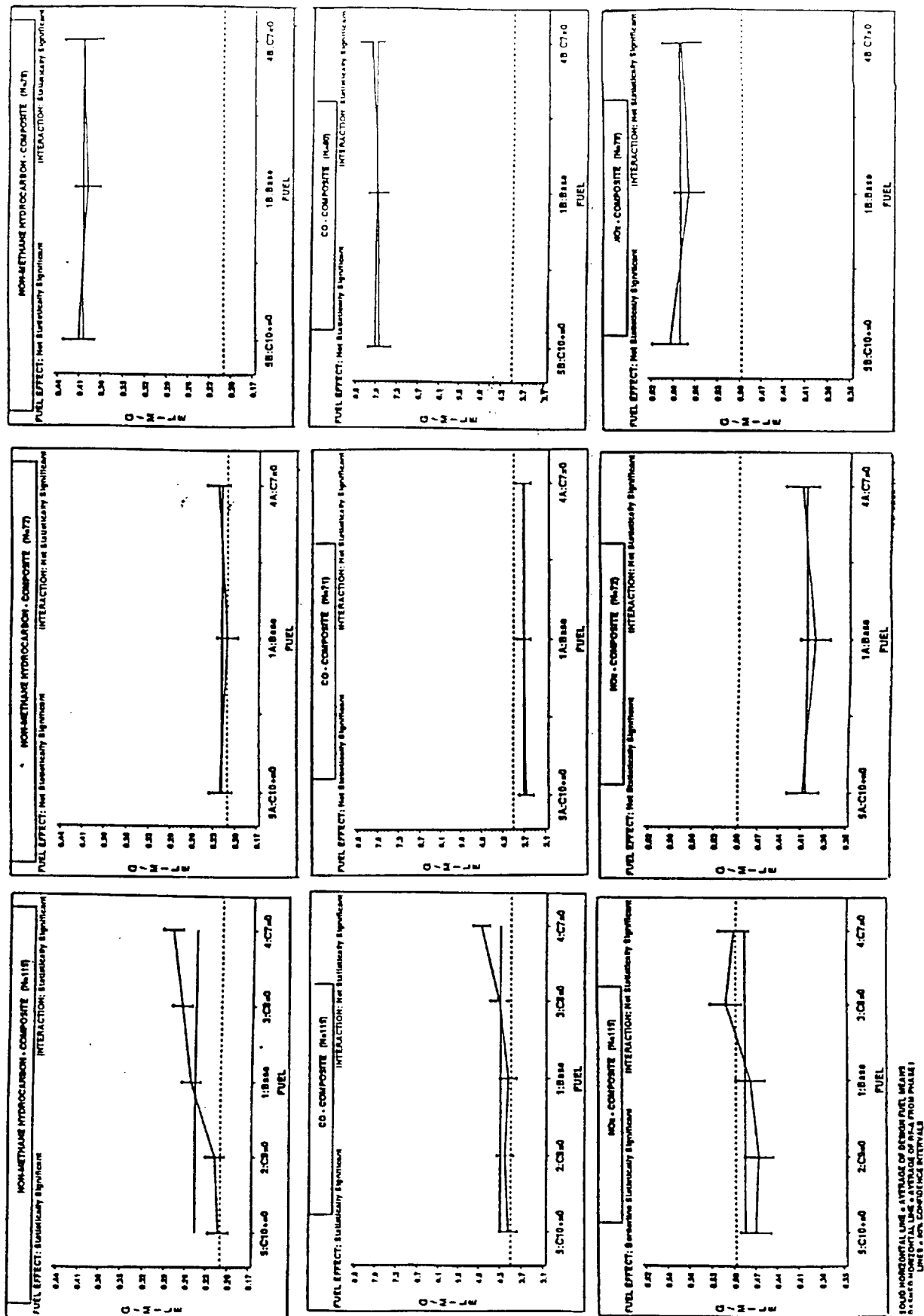
KEY FINDINGS

As shown in Figure E.1, exhaust mass emissions of hydrocarbons¹, carbon monoxide (CO), and nitrogen oxides (NO_x) rise when the fraction of total fuel aromatics contributed by species with higher carbon numbers is increased and fuel distillation properties are not controlled. However, when fuel distillation properties are held constant, shifts in the composition of fuel aromatic compounds by carbon number have no statistically significant effect on exhaust emissions of these pollutants.

¹ For clarity and simplicity, only the results for Non-Methane Hydrocarbons (NMHC) are displayed in Figure E.1. The results for exhaust hydrocarbons expressed either as Total Hydrocarbons (THC) or as Non-Methane Organic Gases (NMOG) are similar and are found in the body of the report.

Figure E.1
API AROMATICS STUDY
PHASE IIA

- PHASE IIB



ES-4

Section 1

BACKGROUND AND OBJECTIVES

Over the past years there has been substantial debate in scientific and regulatory/legislative circles over the existence of a relationship between the aromatic content of gasoline and vehicle exhaust emissions. This debate has focused on whether reductions of total aromatics, as well as specific classes of aromatics, will influence vehicle exhaust emissions. There are emissions, such as benzene, which have been shown to be affected by the weight of the aromatics present in gasoline. There are other emissions, such as total hydrocarbons and oxides of nitrogen, which have not been clearly related to the quantity of aromatics in the fuel or to the composition of the fuel aromatic component.

The ongoing Joint Auto/Oil Air Quality Improvement Research Program (AQIRP) has provided some insights with respect to the effects of changes in the total aromatic content of gasoline on Volatile Organic Compounds (VOCs). (1)¹ The Auto/Oil AQIRP also has recently completed an evaluation of the effect of different refinery aromatic process streams on VOC emissions. (2) However, one issue which has not yet been resolved concerns the extent to which changes in the composition of fuel aromatic (e.g., C₇, C₈, C₉, and C₁₀₊) compounds may influence the mass of exhaust hydrocarbons.

In 1991 the American Petroleum Institute (API) initiated an emissions testing program to investigate this issue. The study measured both regulated exhaust emissions and the composition of exhaust hydrocarbons from a fleet of ten automobiles representative of 1989 and 1990 model year technology operated under 1975 Federal Test Procedure (FTP) temperatures and conditions.

¹ Numbers in () are references listed at the end of the report.

The test program was conducted in three phases. Phase I measured emissions on a base fuel and a set of four additional gasolines which had been systematically varied with respect to the relative compositions of each of the C₇, C₈, C₉ and C₁₀₊ classes of fuel aromatic compounds. A second phase (Phase IIA) measured emissions from the ten vehicles operated on the base fuel and two additional gasolines. These latter two gasolines were similar in aromatics composition to two fuels from the first phase, but had distillation properties which had been matched to those of the base fuel. After this second test phase was completed, an inspection of the three test gasolines revealed uniformly low sulfur levels relative to the Phase I fuels. Therefore, the fuels were rebled to match the sulfur levels of the Phase I gasolines and the test phase was repeated (as Phase IIB).

Emissions from operation on the "Industry Average" gasoline tested by AQIRP were also measured as part of the API study in order to provide a point of reference to the Auto/Oil program.

Further details on the test procedures, emissions measurements and the raw data are contained in a Volume II of this study which was prepared by the contractor for the emissions measurement effort, Automotive Testing Laboratories (ATL), Inc. (3) The purpose of this document is to present the results of statistical analyses of the test data. The primary objective of these statistical analyses is to determine whether changes in the composition of fuel aromatic compounds have a statistically significant effect on exhaust hydrocarbon emissions particularly when other fuel properties--such as distillation parameters--are controlled.

Section 2

STUDY DESIGN AND PROCEDURE

2.1 TEST VEHICLES

Ten late model passenger cars equipped with three-way catalyst emission control systems with closed-loop feedback were used in the test program. Descriptions of the test vehicles are shown in Table 2.1.

TABLE 2.1 Test Vehicles Description

Fuel No.	Description	Certification	Odometer	Engine Size	Metering System ¹
701	'90 Ford Escort	Federal	22,771	1.9L	TBI
702	'89 GM Cavalier	California	29,448	2.0L	TBI
703	'90 Chrysler Voyager	Federal	20,940	2.5L	TBI
704	'90 Honda Accord	California	8,251	2.2L	MPFI
705	'90 GM Calais	Federal	11,209	2.3L	MPFI
706	'89 Toyota Camry	Federal	35,939	2.0L	MPFI
707	'90 GM LeSabre	Federal	21,230	3.8L	MPFI
708	'90 Ford Taurus	Federal	16,402	3.0L	MPFI
709	'90 GM Lumina	Federal	12,121	3.1L	MPFI
710	'90 Ford Cougar	California	18,681	3.8L	MPFI

2.2 TEST FUELS

Three sets of fuels were blended and supplied by Philtex for this test program. The primary fuel in each set or test phase was designed to the specifications shown in Table 2.2.

The primary or base fuel and four additional fuels were blended in Phase I. With each of these additional test fuels, one of four aromatic components (C_7 , C_8 , C_9 , and C_{10+}) was removed and the concentrations of the remaining aromatic components were increased by equal amounts to maintain a total non-benzene aromatic content of 37.5

¹ TBI = Throttle Body Injection
MPFI = Multi-Port Fuel Injection

volume percent. The variable fractions of C₇, C₈, C₉, and C₁₀₊ in these four fuels were always drawn from the same batches of the blend components used to create the primary fuel. This ensured that the mix of hydrocarbon compounds within each aromatics fraction (e.g., C₁₀₊ aromatics) was the same across all of the test fuels. The fuel distillations of these four fuels were allowed to float relative to the primary fuel as a result of the shift in aromatics composition. In addition to the five "specialty" blends, Phase I also included the RF-A "Industry Average" test gasoline used in the Auto/Oil Air Quality Improvement Research Program (AQIRP).

TABLE 2.2 Primary Fuel Specifications (All Phases)

Total Non-Benzene Aromatics	37.5 ± 1 vol %
C ₇ aromatics	1.0 ± 0.2 vol %
C ₈ aromatics	9 ± 1 vol %
C ₉ aromatics	9 ± 1 vol %
C ₁₀₊ aromatics	9 ± 1 vol %
Olefins	5.5 ± 0.5 vol %
Oxygenated Compounds	None
Sulfur	300 ppm
All Other Compounds	Representative of Industry Average
Distillation (T50/T90)	Auto/Oil Program Industry Average
Minimum Octane	90 (R+M)/2
Reid Vapor Pressure	9.0 ± 0.3 psi

Inspections of the Phase I fuels showed that the test blends without C₇ aromatics and without C₁₀₊ aromatics exceeded the range of variation in the ASTM D-86 distillation values specified for the primary fuel. To evaluate the effects of varying the composition of aromatics while holding distillation constant, these two fuels and the primary fuel were re-blended. The distillations of the two blends without C₇ and C₁₀₊ aromatics were matched as closely as possible across the range of the ASTM D-86 distillation curve of the primary fuel. This was done by adjusting iso-paraffin components to compensate for the aromatic components removed.

While every effort was expended to match the two test fuels to the distillation curve of the primary blend, it proved to be nearly impossible to achieve this objective and simultaneously meet the specifications for all of the other test fuel properties. The fuel without C₇ aromatics was particularly difficult to correct with respect to distillation. Ultimately, the olefin content of this fuel was allowed to drop slightly relative to the primary blend in order to achieve a sufficient distillation correction. The result was a fuel without C₇ aromatics which was very closely matched to the distillation curve of the primary blend in nearly all respects except for the 70% point.

Subsequent inspections of the three fuels blended for this Phase revealed that they were uniformly lower in sulfur than those developed for Phase I by an order of magnitude. To remove any confounding sulfur effects, the three fuels were re-blended with added sulfur and the experiment was repeated as Phase IIb.

Properties of the test fuels used in each of the three phases of the program are shown in Table 2.3. This table also includes properties of the Howell EEE certification test fuels which were used to establish emissions reference baselines for the test vehicles. The properties of the certification test fuels are included for reference purposes only. The test results with these fuels are not considered as part of the statistical analysis.

The reader should refer to Reference No. 3 if additional detail on the test fuels and vehicles is desired.

TABLE 2.3 Test Fuel Inspections

Fuel Code → HC Type (vol% by FIA):	Baseline		Phase I Fuels					Phase IIA Fuels					Phase IIB Fuels				
	Howell-EEE	AQIRP	No C ₉	No C ₈	No C ₇	No C ₁₀	Primary	No C ₇	No C ₁₀	Primary	No C ₇	No C ₁₀	Primary	No C ₇	No C ₁₀		
	I&IIA	IIB	Aromat	Aromat	Aromat	Aromat	1	2	3	4	5	1A	4A	5A	1B	4B	5B
	Ind Avg.	RF-A															
(vol% by FIA):																	
Aromatics	32.1	30.5	32.0	36.3	36.2	36.2	36.5	34.9	35.0	35.8	37.8	37.2	36.4				
Olefins	1.0	5.8	9.2	7.1	6.9	6.6	6.3	6.7	5.6	6.0	7.0	5.1	5.8				
Saturates	65.9	63.7	58.8	56.7	57.0	57.2	57.3	58.5	59.5	58.3	55.3	57.8	57.7				
Benzene (vol%)			1.53	0.79	0.79	0.79	0.81	0.78	0.46	0.57	0.54	0.65	0.69				
RVP (psi)	9.0	9.0	8.7	8.7	8.3	8.9	8.6	8.7	8.1	8.1	8.2	8.4	8.3				
Gravity (Deg. API)	59.0	58.8	57.4	55.7	54.9	55.5	55.1	56.4	57.0	53.4	54.6	54.9	53.9				
Sulfur (ppm)	80	70	339	320	317	324	313	312	45	45	305	273	298				
(R+M)/2	92.5	92.5	87.3	92.1	92.0	91.9	91.9	91.9	92.0	91.5	91.7	92.6	91.3				
Distillation, D-86 (Deg. F.)																	
10%	132	130	128	129	132	128	129	129	132	138	135	135	142				
30		184	174	188	190	187	195	188	196	198	199	197	206				
50	213	222	218	229	227	229	243	228	231	235	235	234	240				
70		268	267	267	258	270	297	256	269	292	275	300	276				
90	309	316	330	340	349	353	351	313	344	349	346	348	332				
95		348		365	376	373	369	336	368	369	369	366	365				
EP	400	400	415	401	415	413	405	391	402	399	405	403	425				
Carbon Fraction	86.28	85.97	86.74	87.02	87.07	87.00	86.90	87.28	87.12	86.87	87.16	86.98	87.23				
Hydrogen Fraction	13.18	13.37	13.22	12.98	12.93	13.00	13.10	12.72	12.80	13.13	12.84	13.02	12.77				
Average Molecular Weight:																	
Aromatics				112.8	110.5	114.1	118.6	108.1	113.7	119.5	113.7	119.4	109.3				
Paraffins				93.36	94.51	92.93	93.95	93.69	95.79	93.70	95.63	92.23	97.44				

Section 3

DATA DESCRIPTION AND VALIDATION

3.1 DATA BASE

The distribution of the entire study data base by test phase, fuel type, and availability of speciated measurements is shown in Table 3.1. As noted in the ATL Report, the FTP and HC speciation sequences in each of the three phases were conducted in duplicate, but the aldehydes were measured only once per test. (3)

TABLE 3.1 Distribution of Data Base for Entire Study

Phase	Fuels	Tests with no Speciation	Tests with Speciation (but not for aldehydes)	Tests with Complete Speciation	Total
I	EEE	22	0	0	22
	RF-A	3	8	13	24
	Design ¹	11	50	55	116
IIA	Design	8	34	30	72
IIB	EEE	50	0	0	50
	Design	15	29	38	82
Total		109	121	136	366

Table 3.2 lists the emissions variables which were analyzed as part of this study. A number of these variables were imputed or derived from the values measured by the Automotive Testing Laboratories, Inc. and reported in Reference 3. The calculations used to derive each of these variables are described in detail in Appendix C.

¹ The study design fuels were:
Phase I: 1:Base, 2:C₉=0, 3:C₈=0, 4:C₇=0 and 5:C₁₀=0;
Phase IIA: 1A:Base, 4A:C₇=0 and 5A:C₁₀=0;
Phase IIB: 1B:Base, 4B:C₇=0 and 5B:C₁₀=0.

TABLE 3.2 Emissions Variables Analyzed

Total Hydrocarbon (g/mile)
Non-Methane Hydrocarbon (g/mile)
Non-Methane Organic Gas (g/mile)
NO _x (g/mile)
CO (g/mile)
Aldehydes, Mass (mg/mile) and Weight %
Benzene, Mass (mg/mile) and Weight %
1,3-Butadiene, Mass (mg/mile) and Weight %
Formaldehyde, Mass (mg/mile) and Weight %
Acetaldehyde, Mass (mg/mile) and Weight %
Toxics, Mass (mg/mile) and Weight % ¹

3.2 IDENTIFICATION OF OUTLIERS

- Test outliers

Each of the FTP emissions test records was analyzed using a standard statistical test to identify and remove possible outliers. (4) The criterion was as follows: if at least two of the three FTP composite emissions measurements (FID total HC, CO and NO_x) of a test record were considered outliers, the entire test was to be excluded from the statistical analysis.

Using the above criterion, 7 test records from Phase I were excluded from all subsequent statistical analysis. (A list of these records is provided in Appendix D.)

- Model outliers

Individual emission values were identified as outliers with respect to a statistical model if they resulted in large residuals and consequently had too much

¹ Toxics = Benzene + 1,3-Butadiene + Formaldehyde + Acetaldehyde.

influence on the fit of that model¹. These values were excluded from that specific analysis. Table 3.3 summarizes the number of model outliers by pollutant type and by test phase which were excluded from specific statistical analyses. (A detailed list of each of the model outliers is contained in Appendix D.)

TABLE 3.3 Distribution of Model Outliers

	Phase I	Phase IIA	Phase IIB
FID Total HC, NMHC, NMOG			3
NOx			2
CO		1	1
Total Aldehydes	2	1	2
Benzene	1		2
1,3-Butadiene			2
Formaldehyde	2		1
Acetaldehyde	2		1
Total Toxics	2		

3.3 OTHER DATA ISSUES

- Exhaust Hydrocarbons (HC) Measured by Flame Ionization Detection (FID) versus Gas Chromatography (GC)

In this report, individual hydrocarbon species are expressed in terms of both total mass (mg/mile) analyzed by GC and as a percent of the total weight of hydrocarbons measured by FID. Individual aldehyde species also are expressed in terms of mass (mg/mile) analyzed by liquid chromatography and as a percent of the total weight of hydrocarbons measured by FID. To ensure that no significant bias is introduced by the use of a ratio composed of measurements using different analytical methods, it is instructive to evaluate the sum of the hydrocarbon (and aldehyde) species analyzed by GC (and by liquid

¹ See Section 4.1 for further details on the statistical models used.

chromatography) as a percent of the total HC mass measured by the FID. This is shown in Table 3.4. The table shows that without aldehydes, the sum of the individual HC species measurements in Phases I and IIB averaged about 5% and 2.5% lower, respectively, than the total HC recorded by FID. In Phase IIA the sum of the individual HC species measurements averaged about 6% higher than the total HC by FID in Phase IIA. Including the aldehyde measurements, the sum of the individual HC species was higher than the FID readings in Phases I and IIB, and still higher in Phase IIA.

Table 3.4 GC Total HC as a Percent of FID Total HC

	FID Total HC	N	Average %	Min. %	Max. %
Phase I:	without aldehydes	124	95.1	74.8	123.9
	+ aldehydes	66	98.3	89.3	113.7
Phase IIA:	without aldehydes	64	106.0	79.2	129.6
	+ aldehydes	30	107.0	93.6	119.9
Phase IIB:	without aldehydes	67	97.4	75.4	132.8
	+ aldehydes	38	98.3	76.3	110.6

- 1,3-Butadiene levels

There was some concern about the accuracy of statistical investigations of experimental effects on 1,3-Butadiene emissions if the measured values of this pollutant were found to be at very low or near detectable levels. To assess this concern, a frequency distribution for 5 level ranges of the 1,3-Butadiene emissions values was performed and is shown in Table 3.5. The table shows that for composite FTP emissions and bag 1, the vast majority of the values were above the detectable level of 0.5 mg/mile. For bags 2 and 3, most levels were

near detectable levels. Therefore, the 1,3-butadiene¹ results for bags 2 and 3 should be viewed with caution.

Table 3.5 Frequency Distribution of 1,3-Butadiene Levels

PHASE	N		RANGE OF VALUES (MG/MILE)				
			< 0.5	0.5–1.0	1.0–2.0	2.0–3.0	> 3.0
I	126	Composite	7%	47%	36%	9%	1%
		Bag 1	0%	0%	5%	14%	81%
		Bag 2	92%	4%	4%	0%	0%
		Bag 3	88%	8%	4%	0%	0%
IIA	64	Composite	16%	59%	23%	2%	0%
		Bag 1	0%	0%	6%	31%	63%
		Bag 2	100%	0%	0%	0%	0%
		Bag 3	89%	11%	0%	0%	0%
IIB	67	Composite	5%	16%	36%	33%	10%
		Bag 1	0%	0%	4%	9%	87%
		Bag 2	91%	3%	5%	0%	1%
		Bag 3	39%	12%	34%	9%	6%

- Vehicles Tested on RF-A Fuel compared to Auto/Oil Vehicle Fleet Emissions

Emissions from vehicles tested on the RF-A fuel in this study were compared to the Auto/Oil vehicle fleet average on RF-A (from Reference No. 1). As Table 3.6 indicates, the emission levels from this study were, on average, 16% higher for THC and NMHC, 43% higher for CO, and 17% lower for NO_x. Even though the RF-A fuel used in this study was drawn from the same batch used for the Auto/Oil program, the differences in emissions results are not unusual. The differences in the results can be explained by a number of factors including: test

¹ See Appendix B for analyses by bag.

laboratory variability and variation in the composition and size of the test vehicle fleet. Further assessment of these differences is beyond the scope of this study.

Table 3.6 Test Vehicle Emissions on RF-A Fuel Compared to Auto/oil Average

	N ¹	THC (g/mile)	NMHC (g/mile)	NO _x (g/mile)	CO (g/mile)
701:Escort	3	0.220	0.185	1.008	6.222
702:Cavalier	2	0.203	0.172	0.506	3.667
703:Voyager	2	0.219	0.177	0.519	6.520
704:Accord	2	0.210	0.161	0.497	3.450
705:Calais	2	0.210	0.195	0.430	1.086
706:Camry	2	0.231	0.201	0.181	1.807
707:LeSabre	3	0.271	0.226	0.429	4.113
708:Taurus	2	0.304	0.253	0.622	4.933
709:Lumina	2	0.300	0.255	0.512	4.290
710:Cougar	2	0.343	0.273	0.267	3.822
Avg	10	0.251	0.210	0.497	3.991
SE of Mean		0.016	0.012	0.070	0.538
Auto/Oil Avg		0.216	0.181	0.599	2.791
Ratio (Avg+A/O Avg)		*1.16	1.16	0.83	1.43

¹ Two outliers were excluded: 703:Voyager (10 July 1991) and 709:Lumina (17 May 1991). See Appendix D for further information.

Section 4

FUEL EFFECTS ON FTP COMPOSITE EMISSIONS BY PHASE

4.1 ANALYSIS

The test results were initially analyzed to determine whether the different classes of aromatics influenced exhaust emissions. The statistical approach involved use of an Analysis of Variance procedure to assess whether any test fuel resulted in emissions levels that were different than those resulting from any of the other fuels. This approach was applied to each of the emissions constituents measured in the study.

Each of the three phases of the program were analyzed separately. This was done to ensure that the statistical analysis would not be biased by the differences in fuel sulfur levels in Phase IIA as well as shifts in vehicle operating characteristics and the use of different test facilities in Phase IIB. (As noted in Reference 3, the emissions measurements generated for Phase I and Phase IIA of the program were collected in a different test cell than that used for Phase IIB. Statistical analysis of the results of a correlation program between the two cells showed that the differences in emissions levels were statistically significant. See Appendix E.)

- Fuel effect by phase

A linear model was fit to each of the response variables listed previously in Table 3.2. in order to determine whether fuel type had a significant effect on emissions. As noted above, each test phase was analyzed separately. The form of the model was as follows:

$$\text{Response Variable} = \text{Intercept} + \text{Vehicle} + \text{Fuel} + \text{Vehicle} \times \text{Fuel}$$

where the Vehicle and Fuel terms are class variables and the Vehicle x Fuel term denotes the vehicle-fuel interaction.

The interaction term was omitted from the above linear model and the data refitted if one of the following two cases applied: (1) the interaction was not significant at the 10% significance level; or (2) there were not enough data points to determine the statistical significance of the interaction.

Based on the final model, the least-squares mean (or population marginal mean) emission responses for each of the design fuels were estimated with 90% confidence intervals. In some cases however, there were no data for a particular vehicle-fuel combination. When this occurred and the interaction was significant, the least-squares mean emission response for that fuel could not be estimated. The vehicle with the missing vehicle-fuel combination was therefore completely excluded from that analysis, and the model refitted with the reduced data. When the interaction was not significant, no data points were excluded because the least-squares means for the fuel class variables were still estimable. Table 4.1 lists the response variables for which one or more vehicles had to be excluded.

TABLE 4.1 Vehicle/Fuel Combinations with No Valid Data

PHASE	RESPONSE VARIABLE	EMPTY CELL (VEHICLE/FUEL)	VEHICLES EXCLUDED
I	ALDEHYDES MASS	703:Voyager/3:C ₈ =0 708:Taurus/5:C ₁₀₊ =0	703 & 708
I	FORMALDEHYDE MASS	703:Voyager/3:C ₈ =0 708:Taurus/5:C ₁₀₊ =0	703 & 708
I	ACETALDEHYDE MASS	703:Voyager/3:C ₈ =0 708:Taurus/5:C ₁₀₊ =0	703 & 708

- Linear versus logarithmic scale

Analysis of variance models assume that the error terms are independent and normally distributed with constant variance, or equivalently, that the response variables Y_{ij} (in this case exhaust emissions) are independent and normally distributed $N(\mu_{ij}, \sigma^2)$, where μ_{ij} is the mean for vehicle i and fuel j obtained from

the model. The linear model assumptions, however, do not require that the overall distribution of the response variable be normal. In other words, if a histogram of all Y-values shows a positively skewed distribution, it does not automatically imply that a transformation is needed.

A general rule in statistical modeling is that the response variable (y-variable) should be transformed (e.g. by raising it to some power or taking its logarithm) only if the transformation is needed to meet model assumptions and improve the model fit. One advantage of the log transformation is that it assures that all predictions will be positive.

Based on a close examination of the distribution of residuals, verification that the model predicted values were positive, and a comparison of the root mean square errors (RMSE), it was found that no transformations were necessary. Consequently, all response variables analyzed in this report were kept in their regular scale.

4.2 RESULTS

Table 4.2 summarizes the results of fitting the model described in Section 4.1 to the data for each of the 17 response variables in the three test phases.¹ To properly interpret the effect of the design fuels on vehicle emissions, it is important to note the statistical significance of both the fuel and the fuel*vehicle interaction terms in the analysis of variance model. There are four possibilities:

1. Significant fuel effect and significant interaction:

The average emissions response of the test vehicle fleet varies by fuel type. However, the individual vehicles respond to the different fuels in different ways. Table 4.2 indicates, for example, that total

¹ This section only discusses the results for FTP composite emissions. (Appendix B shows the results for each bag of the FTP.)

hydrocarbon (THC) emissions from the overall fleet showed a significant response to fuel type in Phase I, and that the trends in the response were different for individual vehicles in the fleet. Thus, there was a significant fuel effect and a significant interaction for THC emissions.

2. Significant fuel effect and not significant interaction:

The average emissions response of the test vehicle fleet varies by fuel type, but the emissions from each of the vehicles follows roughly the same pattern. Table 4.2 shows, for instance, that fuel type had a significant effect on the average CO emissions response of the fleet in Phase I and there was no variation in the CO response to fuel type among the individual vehicles which comprised the test fleet.

3. Not significant fuel effect and significant interaction:

The average emissions response of the test vehicle fleet does not vary by fuel type but individual vehicles respond differently to the different fuels. As illustrated in Table 4.2, for example, CO emissions, on a test fleet average basis, were not influenced by fuel type in Phase IIB. However, the trend in the CO response to fuel type varied significantly for individual vehicles within the test fleet.

4. Not significant fuel effect and not significant interaction:

The emission levels of each of the test vehicles do not respond to different fuels. For example, none of the test vehicles exhibited a significant NO_x emissions response to fuel type in either Phase IIA or Phase IIB.

Note that there were insufficient data to determine the statistical significance of the fuel*vehicle interaction terms for several of the response variables in Phase IIA. In these cases, the interaction term was omitted from the model.

Figures 4.1 to 4.51 show the estimated least-squares means of the design fuels for each of the 17 response variables by test phase. Ninety percent confidence error bars also are presented. Each graph indicates whether the fuel effect and interaction were

statistically significant ($p\text{-value} \leq 0.05$), borderline significant ($0.05 < p\text{-value} \leq 0.10$), or not significant ($p\text{-value} > 0.10$).¹ The horizontal solid line represents the average of the

TABLE 4.2 Statistical Significance of Fuel and Interaction Effects²

Response Variable	PHASE I		PHASE IIA		PHASE IIB	
	Fuel	Interaction	Fuel	Interaction	Fuel	Interaction
THC, NMHC, NMOG	S	S	N	N	N	S
CO	S	N	N	N	N	S
NOx	B	N	N	N	N	N
Benzene, Mass	N	S	S	N	S	S
Benzene, Wt%	S	N	S	N	S	N
1,3-Butadiene, Mass	S	N	S	S	N	S
1,3-Butadiene, Wt%	N	B	S	B	N	N
Acetaldehyde, Mass	S	B	N	I	N	N
Acetaldehyde, Wt%	B	N	N	I	N	N
Formaldehyde, Mass	S	N	N	I	B	N
Formaldehyde, Wt%	B	N	N	I	B	N
Total Aldehydes, Mass	B	N	N	I	N	N
Total Aldehydes, Wt%	S	N	N	I	N	S
Total Toxics, Mass	S	N	N	I	N	S
Total Toxics, Wt%	S	N	S	I	N	B

least-squares means, and the horizontal dashed line represents the corresponding mean of the AQIRP Industry Average fuel (RF-A). The scale on the vertical axis is the

¹ As expected, the vehicle effect was statistically significant in all cases with the exception of acetaldehyde mass and weight percent in Phase IIB only.

² S = Statistically Significant ($p\text{-value} \leq 0.05$)
 B = Borderline Significant ($0.05 < p\text{-value} \leq 0.10$)
 N = Not Significant ($p\text{-value} > 0.10$)
 I = Insufficient data to determine significance of interaction (and therefore the interaction term was omitted from the model).

same across the three test phases for each response variable. On the horizontal axis, the fuels were spaced uniformly and positioned from lightest to heaviest (in terms of their aromatic carbon content). Thus, an upward trend shown in any of the figures suggests that emissions increase with increasing fuel aromatic carbon content.

4.3 DISCUSSION

- Total hydrocarbon, non-methane hydrocarbon and non-methane organic gas

The compositions of total hydrocarbons (THC), non-methane hydrocarbons (NMHC), and non-methane organic gas (NMOG) emissions are very similar. Each of these categories is composed of pure hydrocarbons with carbon numbers of two and higher plus alcohols and ethers (primary oxygenates). The differences between the three classifications is that total hydrocarbons has the weight of methane added, whereas non-methane organic gas adds the weights of aldehydes and ketones (carbonyls). The addition of methane and carbonyls increases mass emissions by modest and small amounts, respectively, (about 20% for methane and 3% for carbonyls). Since these three categories of emissions are very much alike in terms of composition, it is expected that they would respond similarly to changes in fuel properties -- at least within the context of this program.

Figures 4.1, 4.2, and 4.3 show the THC, NMHC, and NMOG emissions for each of the Phase I fuels. The responses of these three emissions classes to increasing weight of aromatics are nearly identical. As explained before, this similarity is not unexpected. The THC, NMHC, and NMOG responses to aromatics weight in both Phase IIA and Phase IIB also are nearly identical (Figures 4.18-4.20 and 4.35-4.37). In Phase I, exhaust emissions of THC, NMHC and NMOG increased as the aromatic carbon content of the fuel was increased and the trend was statistically significant. However, when the distillation properties of the fuels were matched in both Phase IIA and in Phase

IIB, increasing fuel aromatic carbon content had no statistically significant effect on exhaust emissions of THC, NMHC and NMOG.

- **NO_x and CO**

NO_x and CO emissions increased as a function of fuel aromatic content in Phase I. (See Figures 4.4 and 4.5 for NO_x and CO, respectively.) However, the fuel effect for NO_x was only borderline significant. When fuel distillation parameters were held constant in Phase IIA and in Phase IIB, neither NO_x nor CO emissions responded to changes in fuel aromatic content. (See Figures 4.21 and 4.38 for NO_x and Figures 4.22 and 4.39 for CO.)

- **Total Aldehydes**

Phase I total mass aldehyde emissions increased with increasing fuel aromatic carbon content, but the effect was only borderline significant. (See Figure 4.6.) Expressed on a weight percent basis, Phase I total aldehydes dropped as a function of fuel aromatic content. (See Figure 4.7.) This reversal in trends between mass and weight percent in Phase I is likely due to the fact that hydrocarbon emissions increased at a higher rate than did total aldehyde emissions. In Phases IIA and IIB, the type of fuel did not have a statistically significant effect on total aldehydes expressed either on a mass or a weight percent basis. (See Figures 4.23, 4.24, 4.40 and 4.41.)

- **Benzene**

The joint variation of fuel aromatic content and fuel distillation properties in Phase I had no statistically significant effect on benzene mass emissions. (See Figure 4.8.) However, there was a statistically significant drop in benzene mass emissions with increasing fuel aromatic carbon content when distillation properties were held constant in Phases IIA and IIB. (See Figures 4.25 and 4.42.) This was not unexpected since there was very little variation in the benzene contents of the Phase I test fuels in contrast to the variation observed in

the benzene levels of the Phase IIA and Phase IIB fuel sets. (As shown earlier in Table 2.3, the benzene content of the Phase I test fuels ranged from 0.78 vol % to 0.81 vol % while the benzene levels from the Phase IIA and Phase IIB fuels fell in the 0.46 - 0.59 vol % range and the 0.54 - 0.69 vol % range, respectively.)

When expressed in terms of the fraction of the weight of total hydrocarbons, there was a statistically significant drop in benzene with increasing fuel aromatic carbon content in all 3 phases. (See Figures 4.9, 4.26 and 4.43.)

- 1,3-Butadiene

There was a statistically significant increase in Phase I mass emissions of 1,3-Butadiene with increasing fuel aromatic carbon content. (See Figure 4.10.) However, when expressed on a weight percent basis, Phase I 1,3-butadiene was insensitive to changes in fuel type. (See Figure 4.11.) In Phase IIA, 1,3-butadiene emissions dropped with increasing fuel aromatic carbon content on both a mass and a weight percent basis and the trend was statistically significant. (See Figures 4.27 and 4.28.) In Phase IIB, 1,3-butadiene did not respond to fuel type when expressed on either a mass or a weight percent basis. (See Figures 4.44 and 4.45.) This apparent inconsistency between Phases IIA and IIB was investigated by examining the residuals and the fuel effect for each vehicle separately. However, there was no consistent pattern that could explain the divergent trends between Phase IIA and Phase IIB.

- Formaldehyde and Acetaldehyde

Mass emissions of both acetaldehyde and formaldehyde increased as a function of fuel aromatic carbon content in Phase I. (See Figures 4.12 and 4.14 for formaldehyde and acetaldehyde, respectively.) In Phase IIA both formaldehyde and acetaldehyde were unresponsive to changes in fuel type. (See Figures 4.29 and 4.31.) Both formaldehyde and acetaldehyde tended to increase with increasing aromatic carbon content in Phase IIB, but the effect was only

borderline significant for formaldehyde (as shown in Figure 4.46) and was not significant for acetaldehyde (as illustrated in Figure 4.48).

- Toxics

Total toxics mass emissions increased with higher levels of fuel aromatic carbon content in Phase I but did not respond when distillation parameters were held constant in Phases IIA and IIB. (See Figures 4.16, 4.33 and 4.50.) When expressed in terms of the fraction of the weight of total hydrocarbons, there was a statistically significant drop in total toxics with increasing fuel aromatic carbon content in Phases I and IIA, but no response in Phase IIB. (See Figures 4.17, 4.34 and 4.51.) Again, the reversal in trends between mass and weight percent in Phase I is likely due to the fact that hydrocarbon emissions increased at a higher rate than toxics emissions.

One striking result shown in Figures 4.1, 4.18 and 4.35 is that the Total HC emissions levels were quite higher in Phase IIB than in Phase I or Phase IIA. This may have been due to the fact that the tests for Phases I and IIA were conducted in cell 1 at ATL, whereas Phase IIB tests were performed in cell 3. It also is interesting to note that the fuel*vehicle interaction effect tended to be significant for the response variables analyzed more often in Phase IIB than in Phase IIA. (See Table 4.2). This is one indication that there was more variability in the vehicle responses in Phase IIB than in Phase IIA.

When test results of the base fuel in Phase I (Cell 1) and Phase IIB (Cell 3) were compared¹, unusually large differences were observed for vehicles 702:Cavalier, 703:Voyager, 708:Taurus and 709:Lumina. In order to check whether these four vehicles were forcing the overall trends, the ten vehicles were divided into two groups:

¹ The base fuels in Phases I and IIB were theoretically identical and practically very similar.

one containing the four vehicles, and the other, the remaining 6 vehicles. The two groups were then analyzed separately.

As shown in Table 4.3, the statistical significance of the fuel effect was basically unchanged when the test vehicles were analyzed as two separate groups. The fuel effect for the combined group in Phase I was borderline significant for NO_x, while not significant for each of the two groups separately. This is most likely due to the increased number of observations in the combined group.

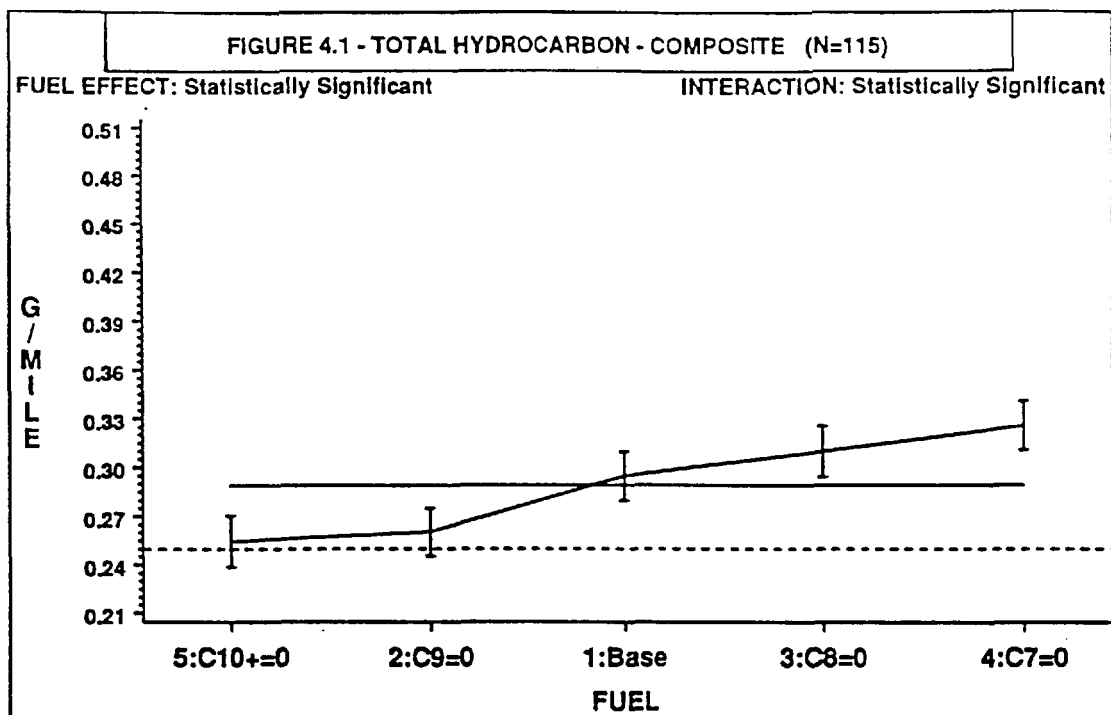
TABLE 4.3 Significance of Fuel Effect¹

RESPONSE VARIABLE	GROUP ²	PHASE		
		I	IIA	IIB
TOTAL HC	1	S	N	N
	2	S	N	N
	COMBINED	S	N	N
NMHC	1	S	N	N
	2	S	N	N
	COMBINED	S	N	N
NO _x	1	N	N	N
	2	N	N	N
	COMBINED	B	N	N
CO	1	S	N	N
	2	B	N	N
	COMBINED	S	N	N

¹ S = Statistically Significant (p-value ≤ 0.05)
 B = Borderline Significant (0.05 < p-value ≤ 0.10)
 N = Not Significant (p-value > 0.10)

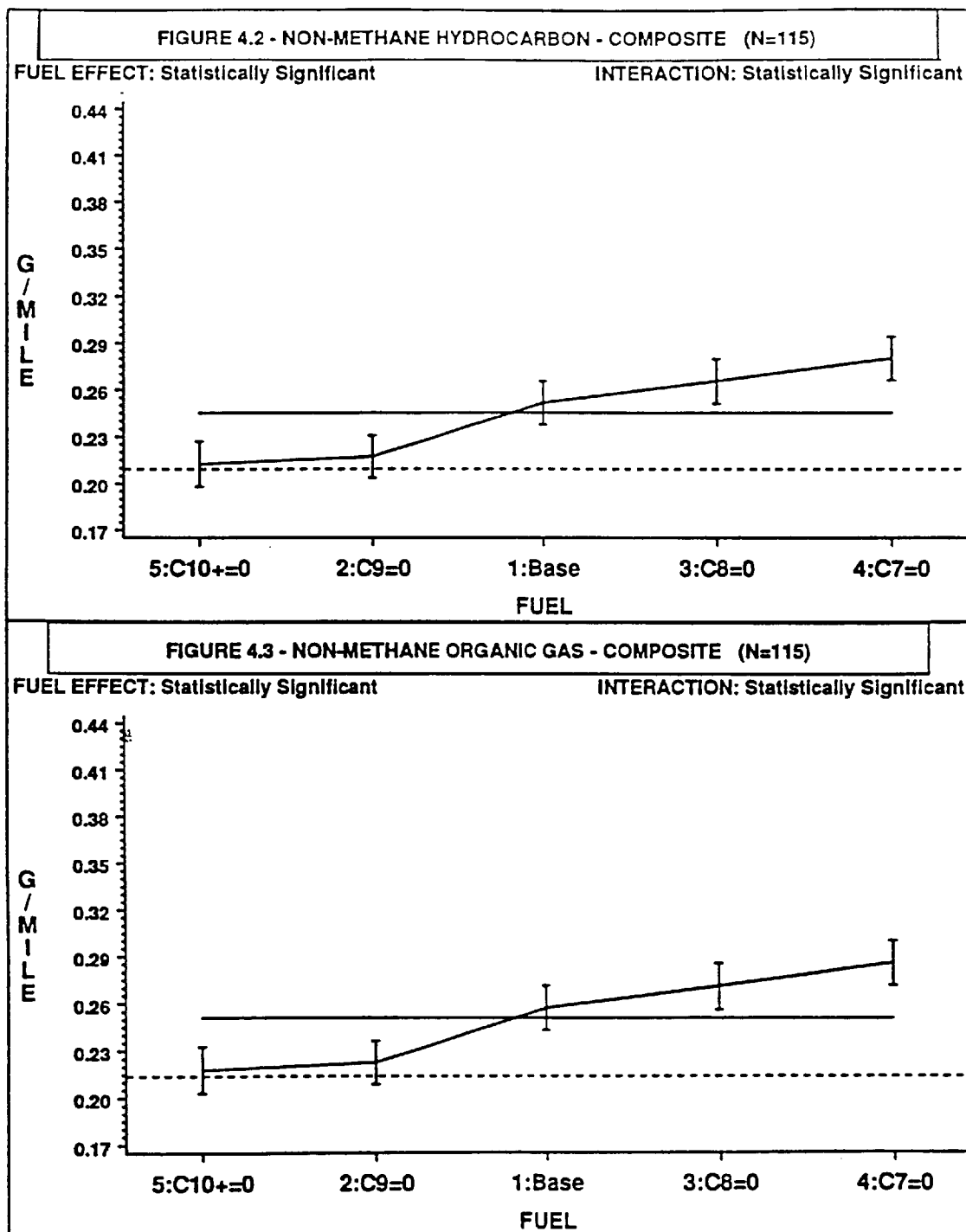
² GROUP 1 includes vehicles 701, 704, 705, 706, 707 and 710.
 GROUP 2 includes vehicles 702, 703, 708 and 709.

API AROMATICS STUDY - PHASE I



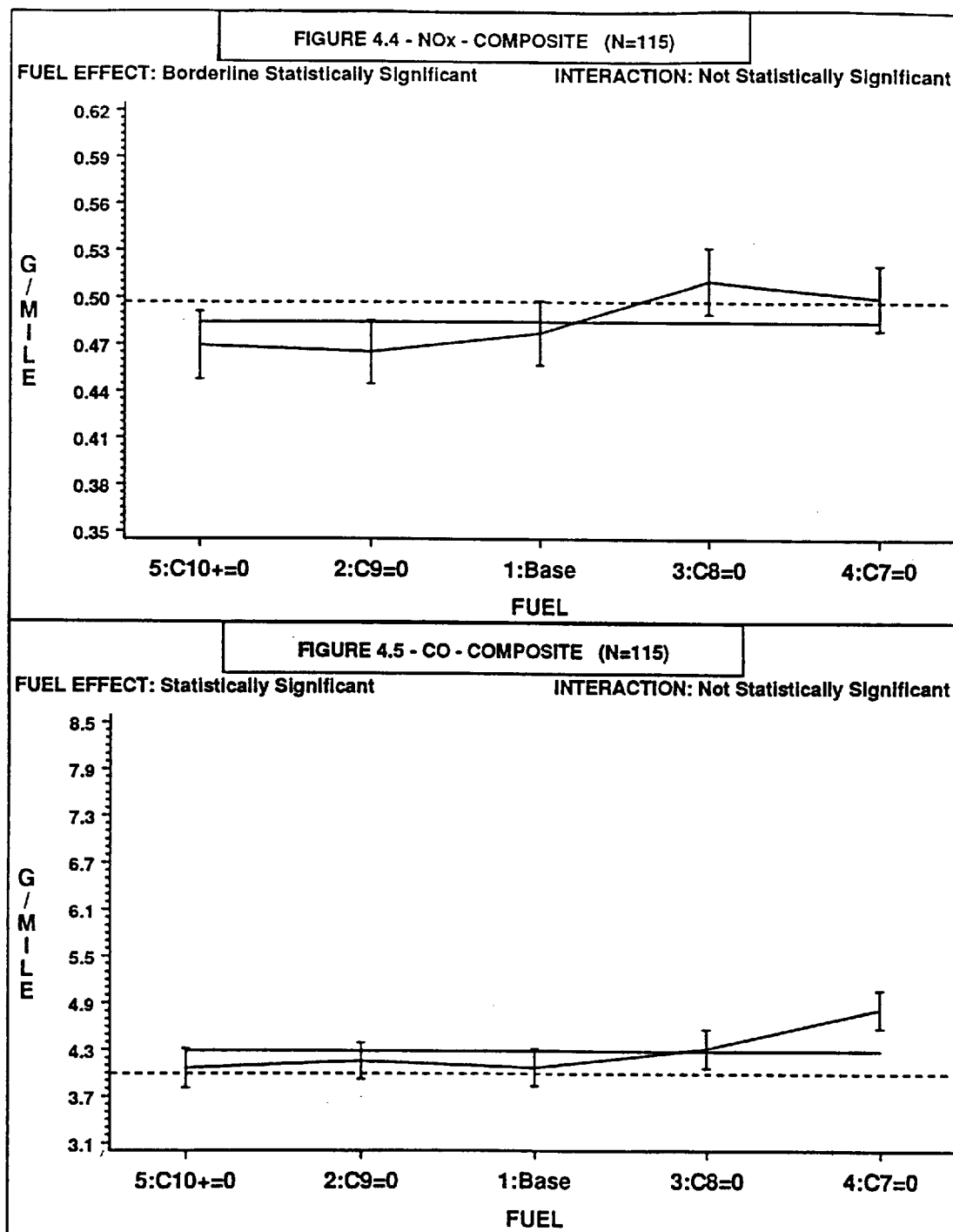
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



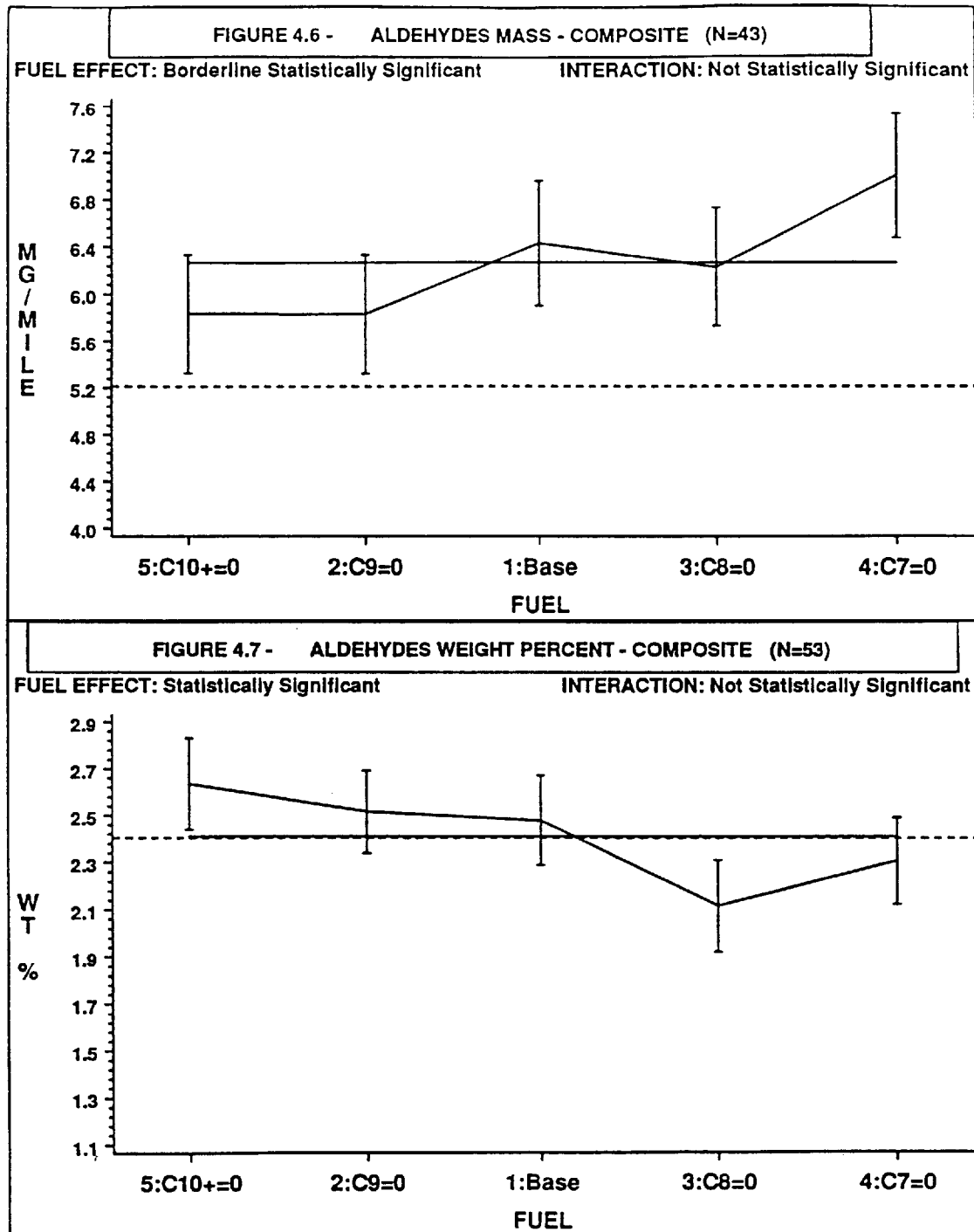
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 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



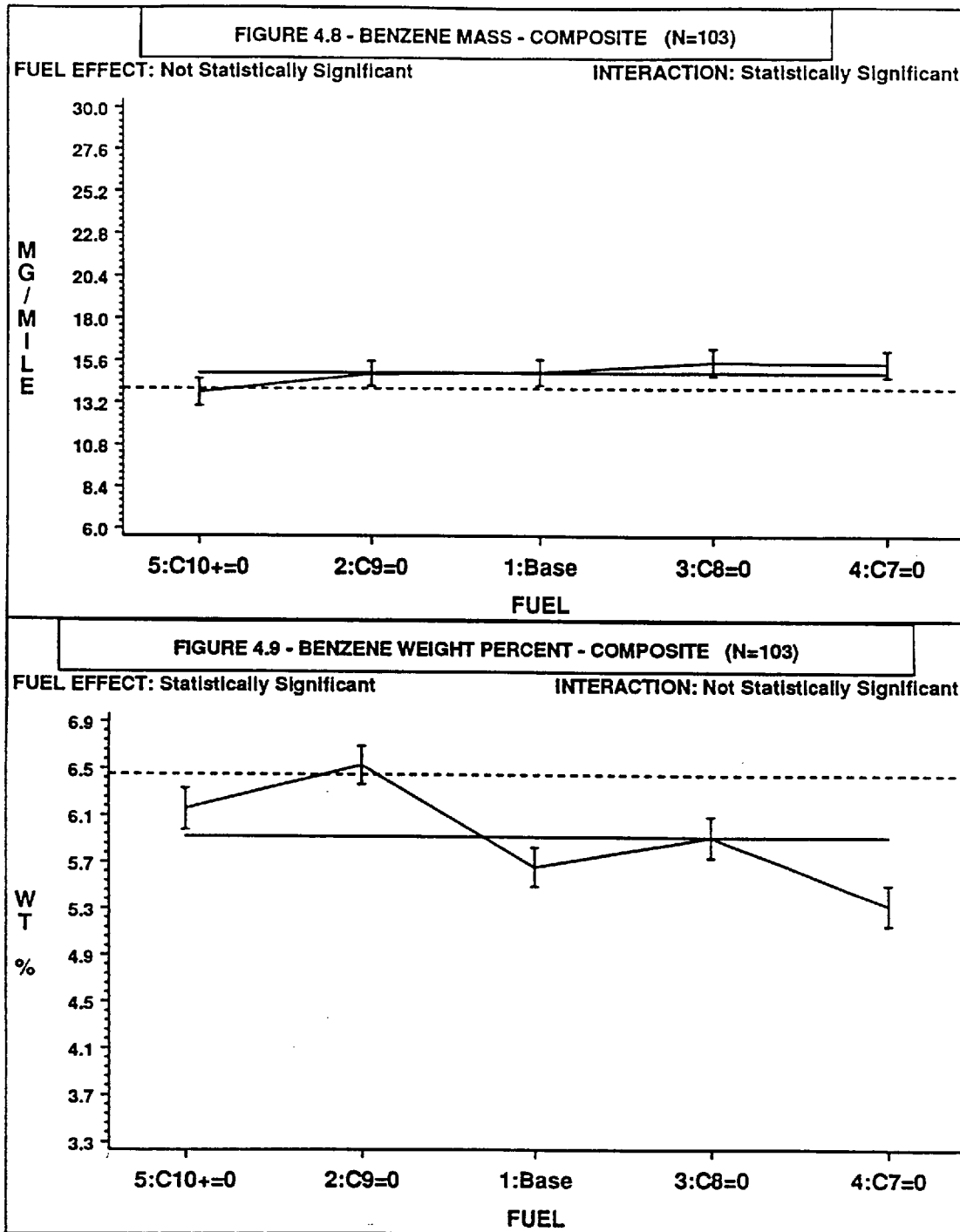
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 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



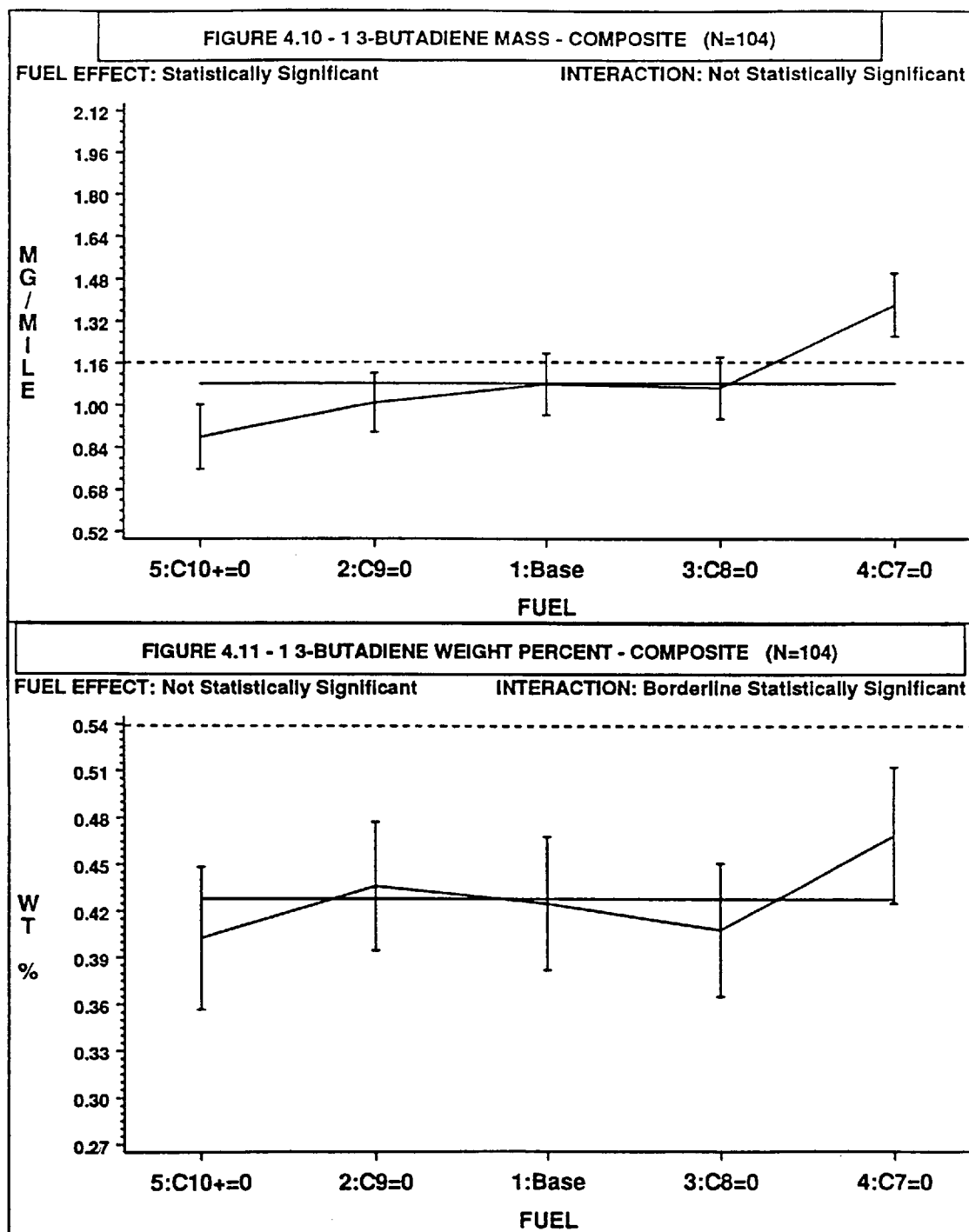
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 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



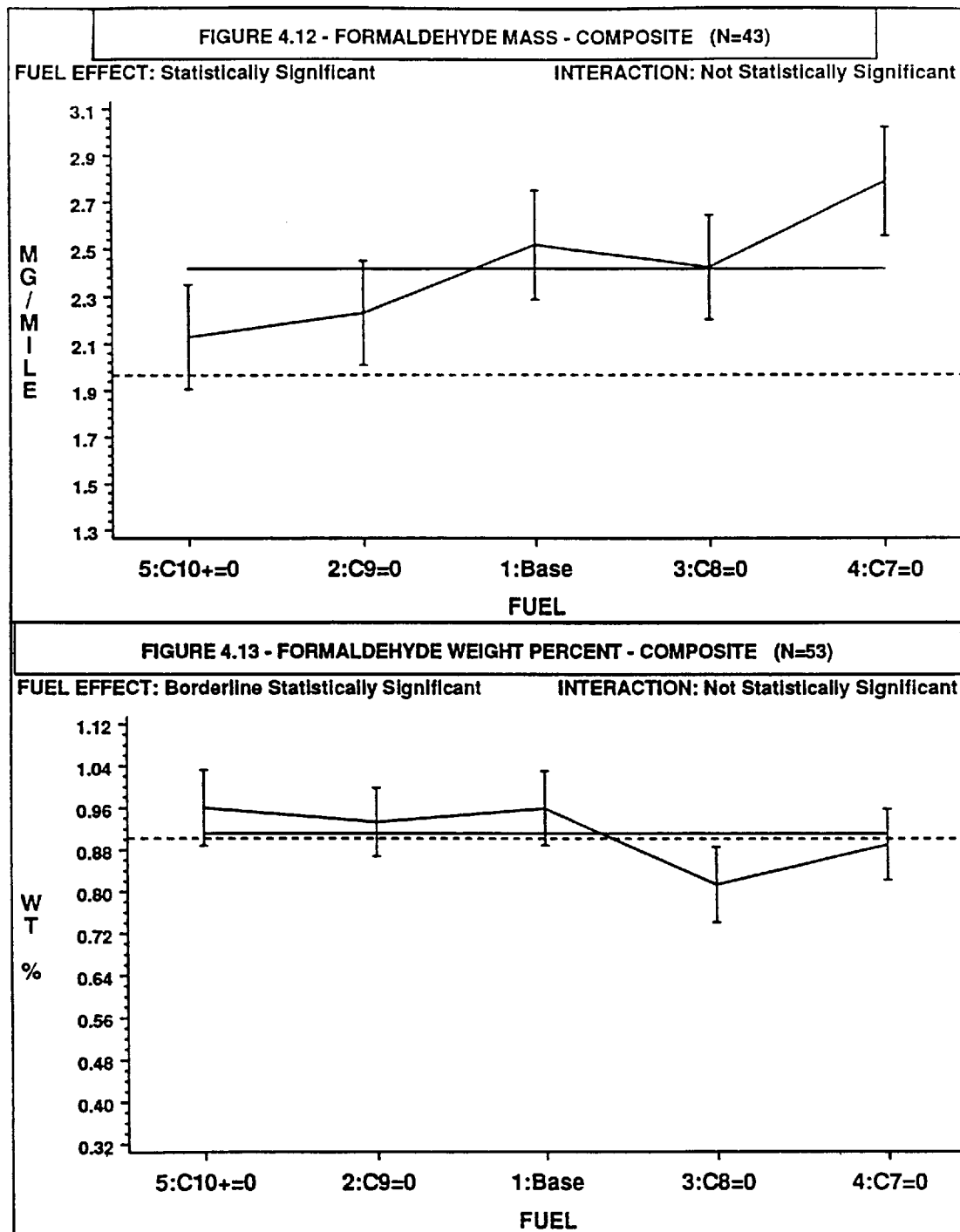
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 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



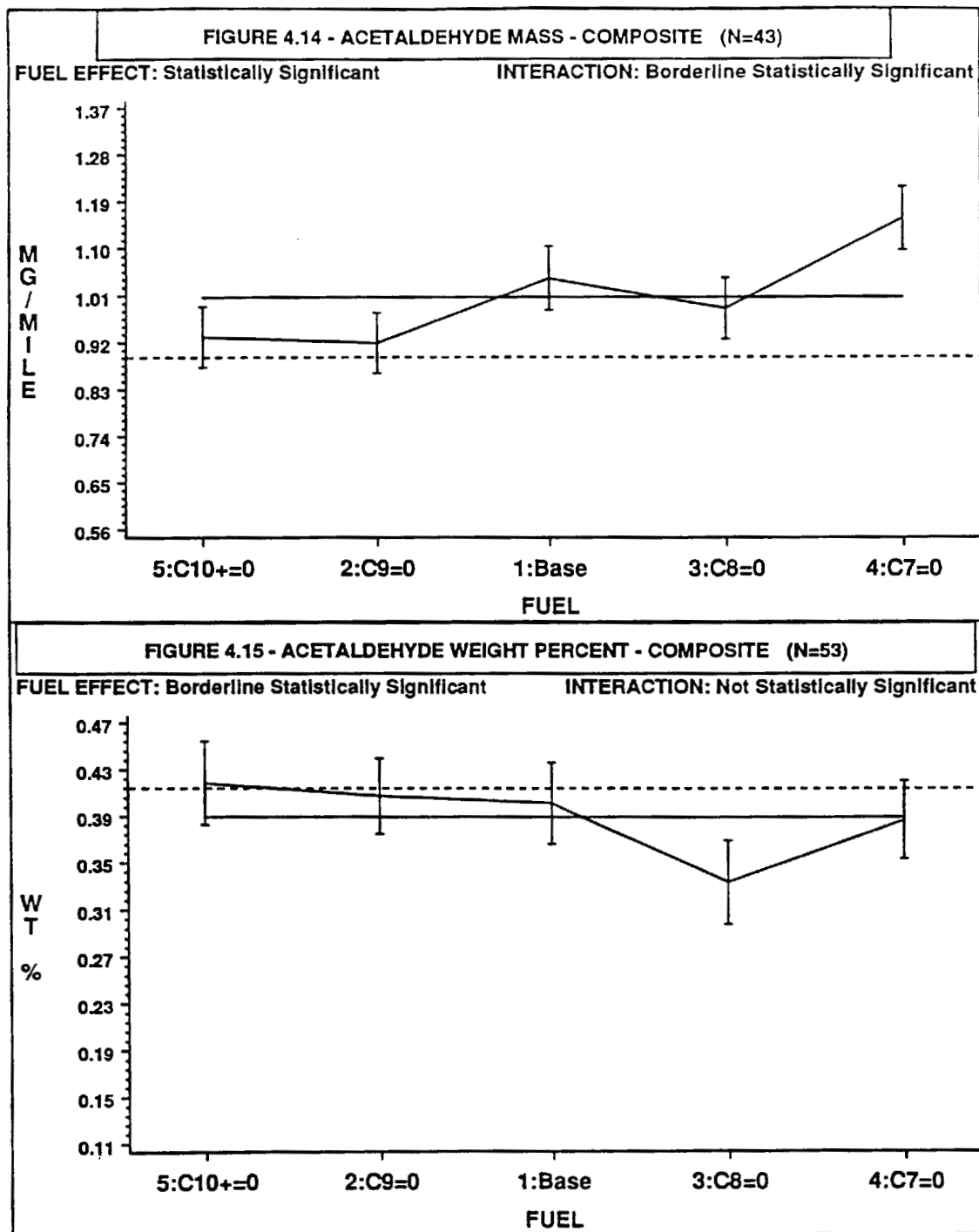
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 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



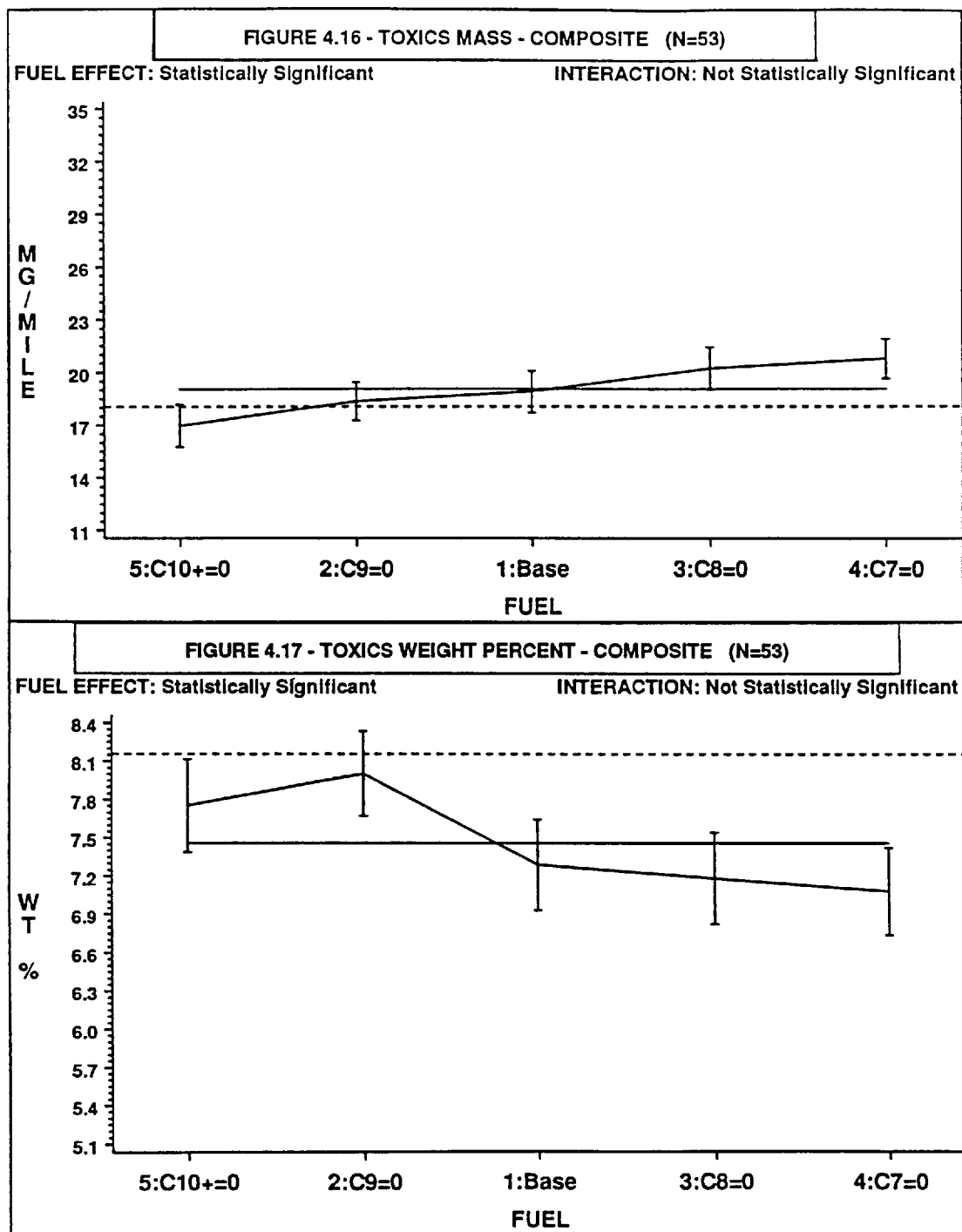
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



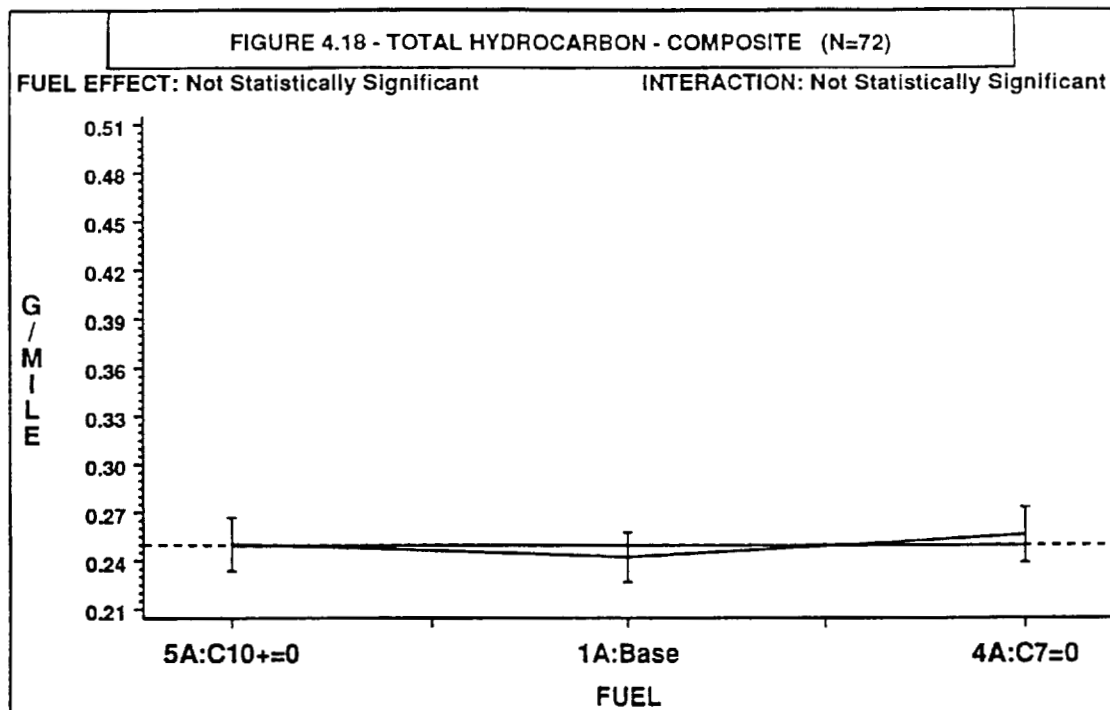
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE I



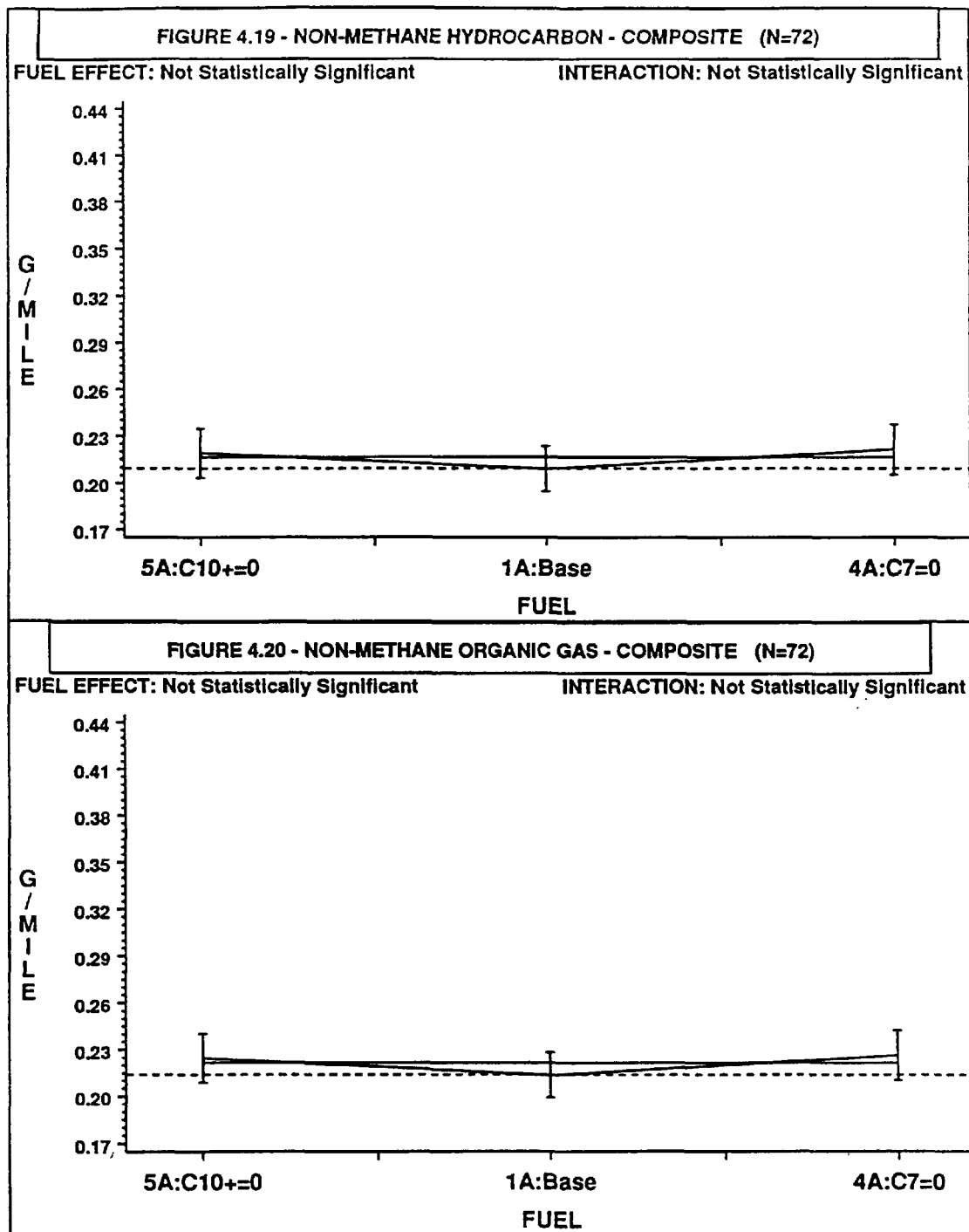
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE IIA



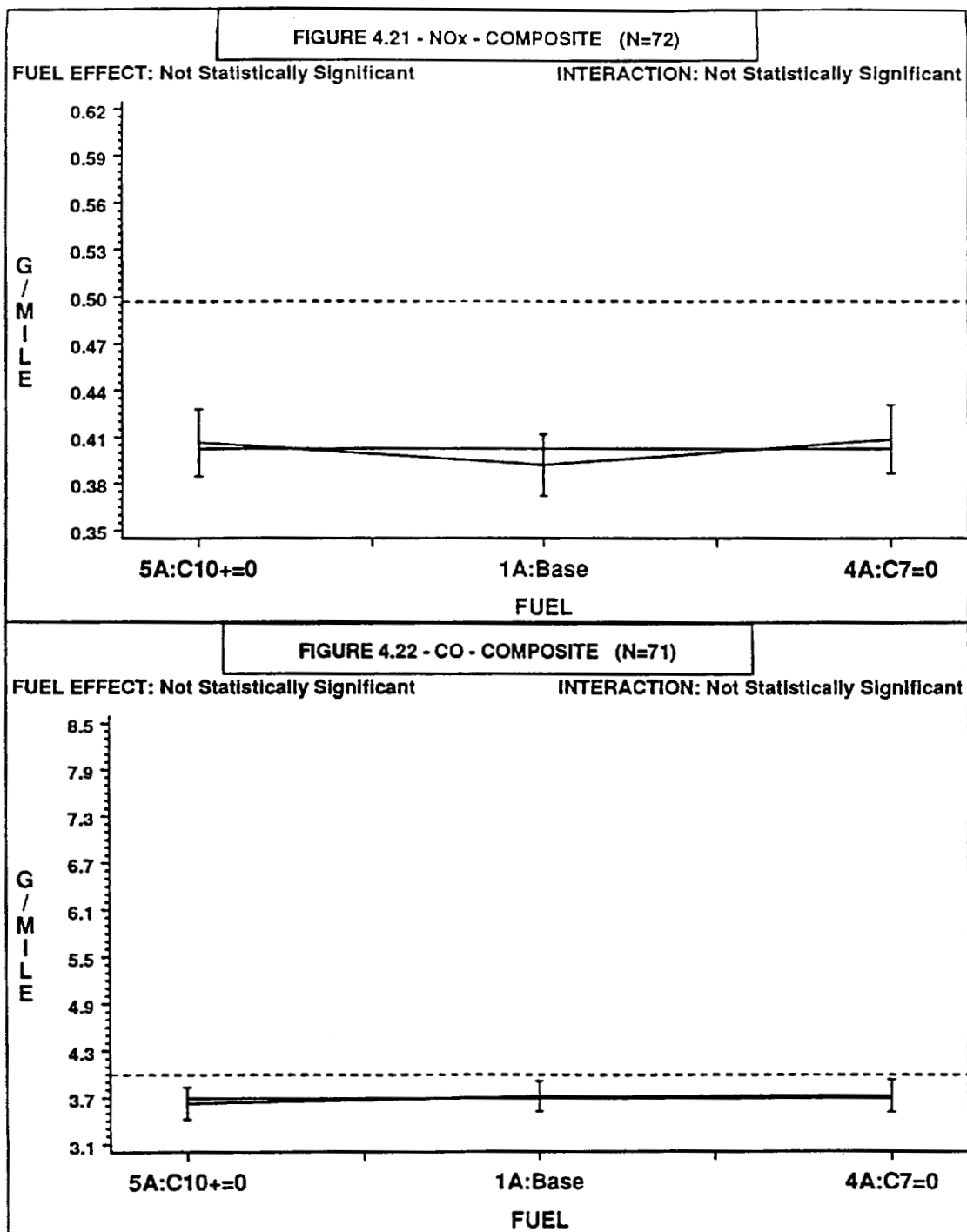
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE IIA



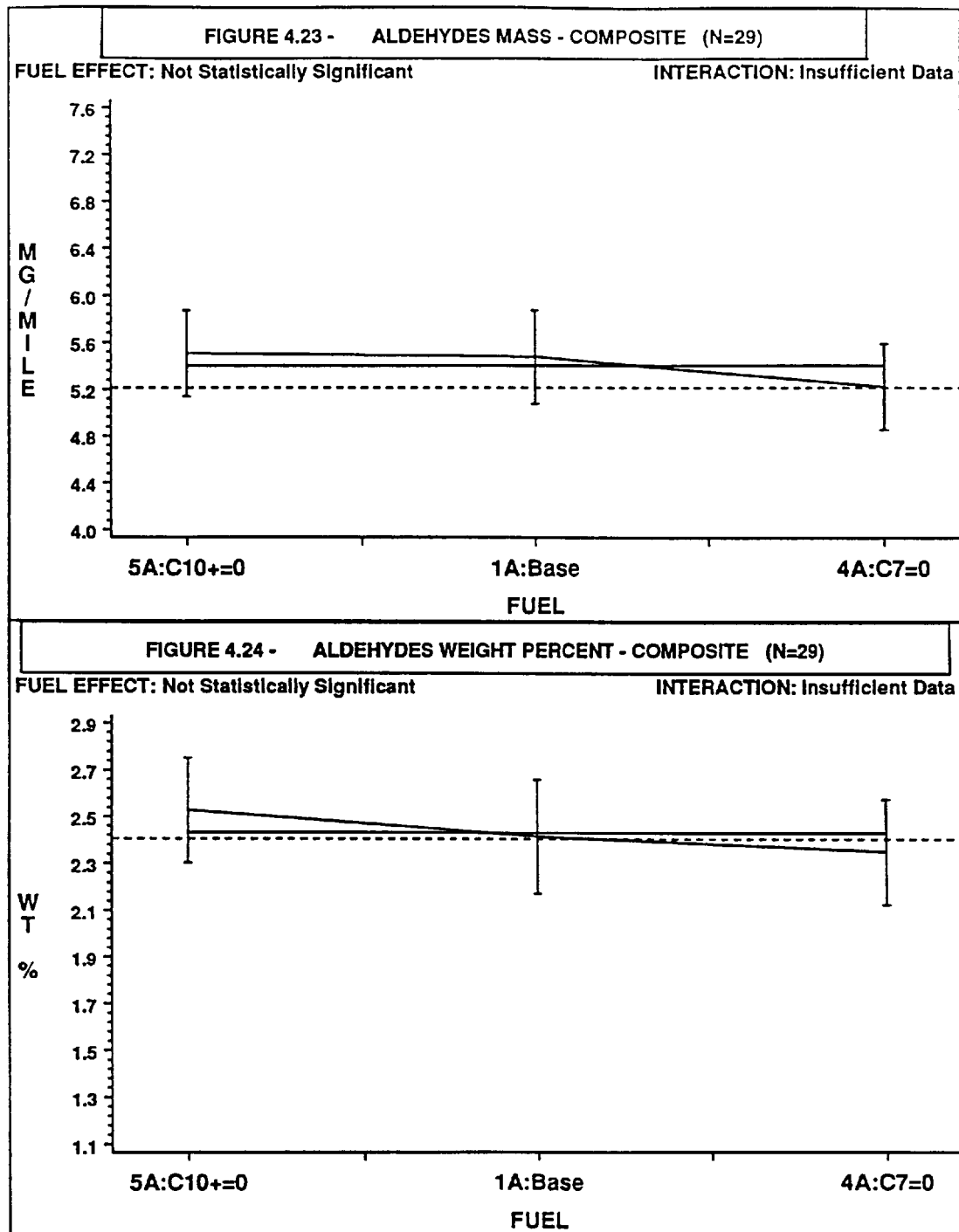
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE IIA



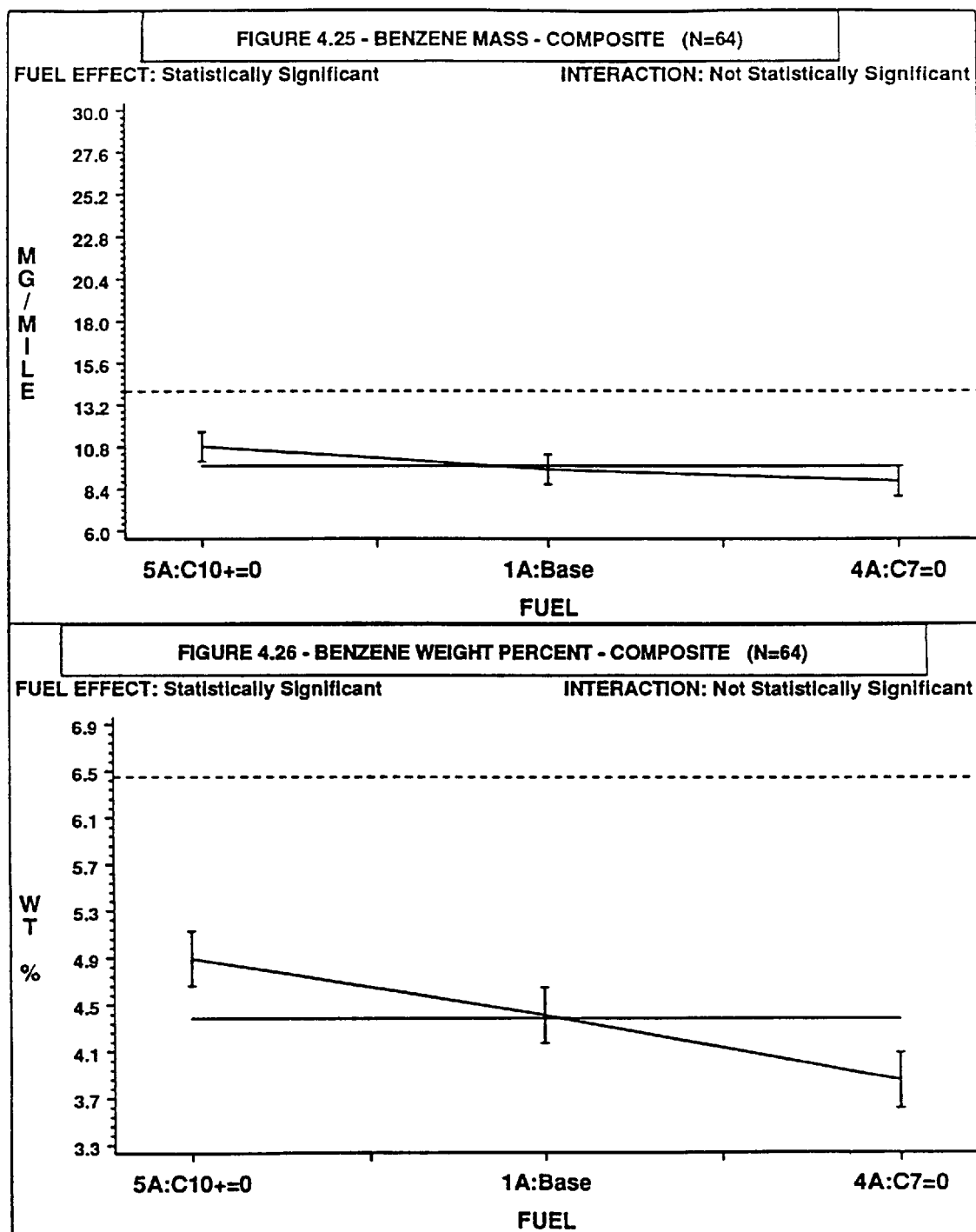
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
 DASHED HORIZONTAL LINE = AVERAGE OF RF-A FROM PHASE I
 VERTICAL LINES = 90% CONFIDENCE INTERVALS

API AROMATICS STUDY - PHASE IIA



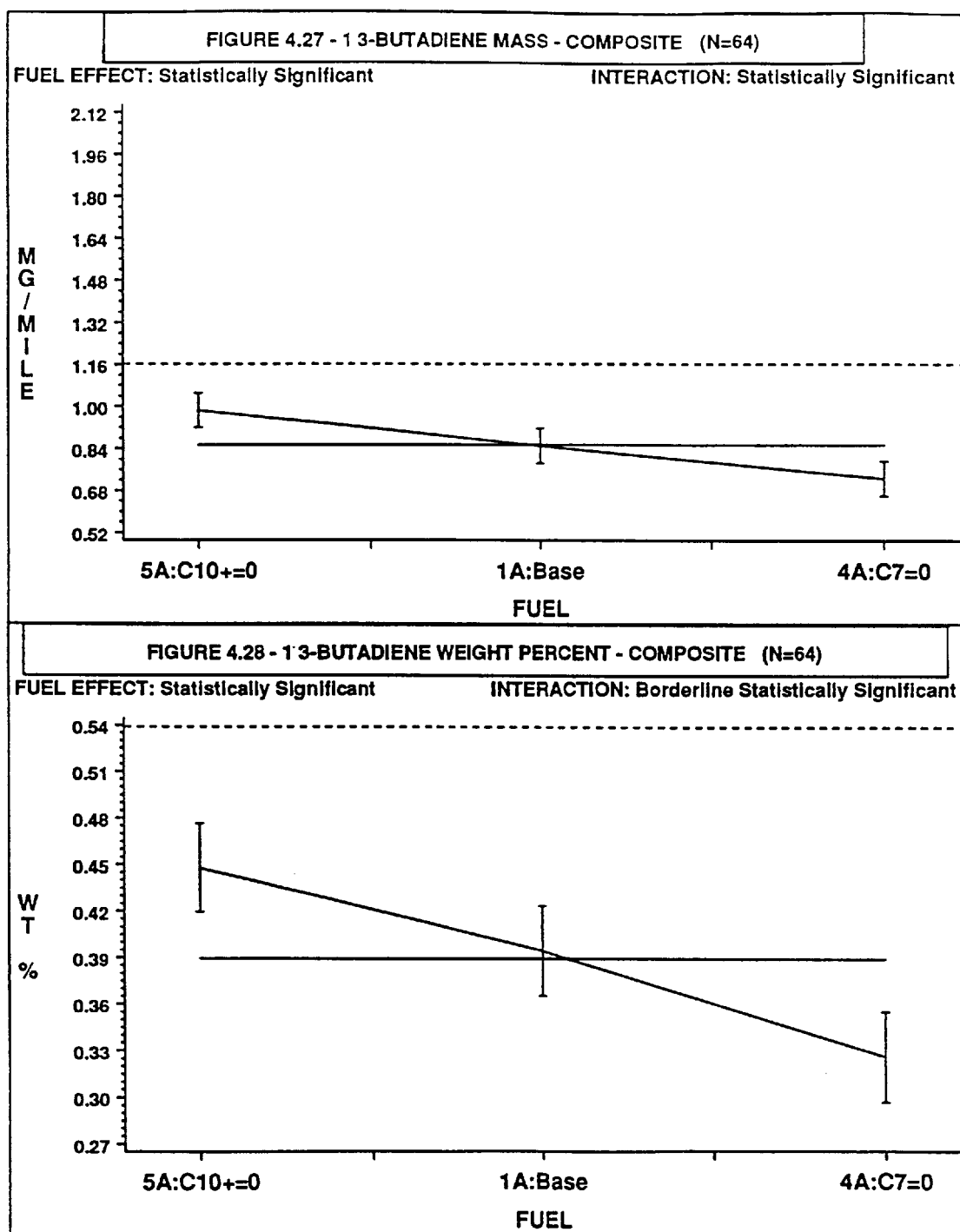
SOLID HORIZONTAL LINE = AVERAGE OF DESIGN FUEL MEANS
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API AROMATICS STUDY - PHASE IIA



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