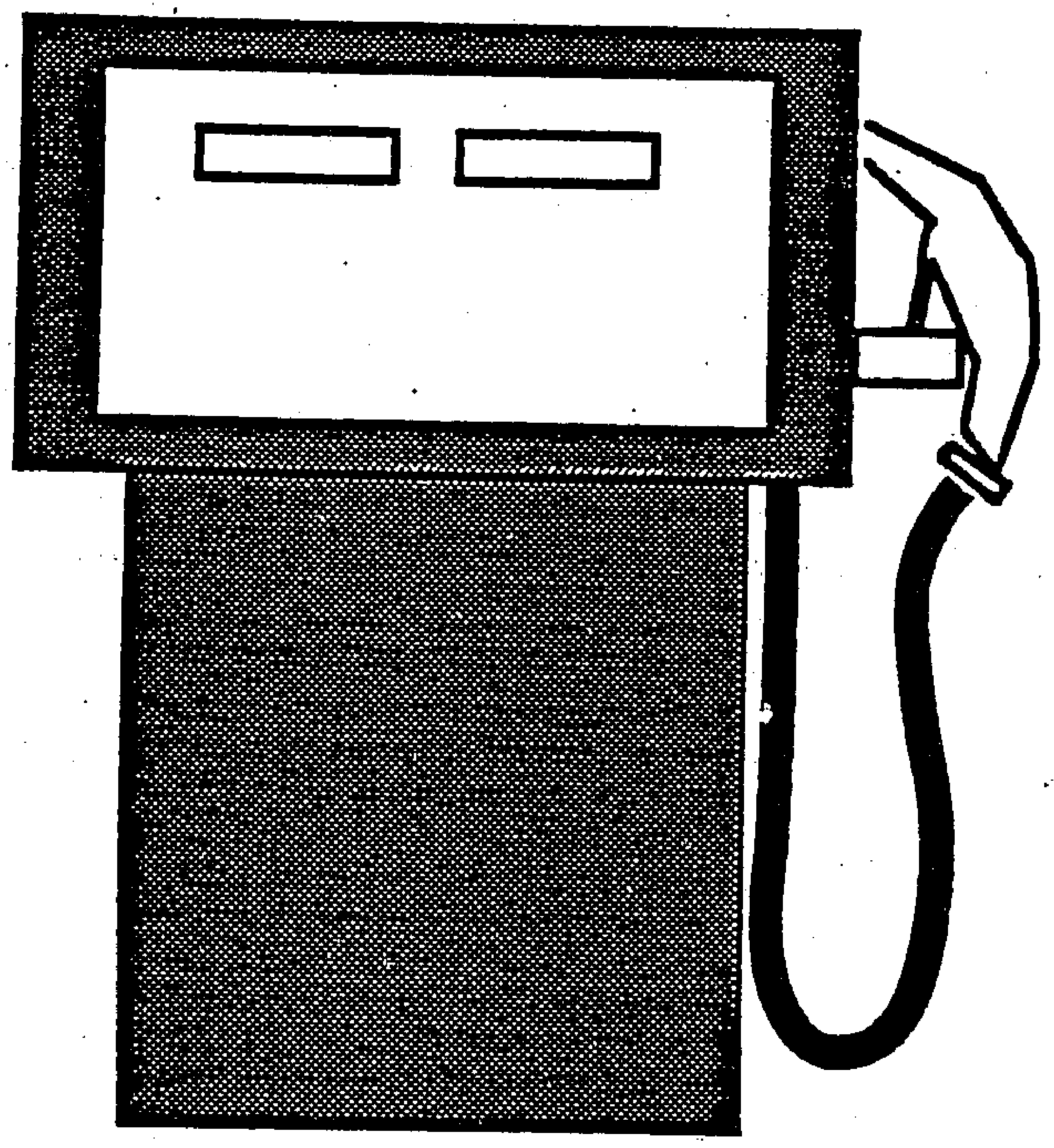
California Air Resources Board

California Phase 2 Reformulated Gasoline Specifications

Proposed Regulations for California Phase 2 Reformulated Gasoline



Technical Support Document

Release Date: October 4, 1991

State of California
Air Resources Board

CX5

State of California
AIR RESOURCES BOARD
Stationary Source Division

PUBLIC HEARING TO CONSIDER THE ADOPTION OF AND AMENDMENTS TO REGULATIONS REGARDING REFORMULATED GASOLINE (PHASE 2 GASOLINE SPECIFICATIONS), AND THE WINTERTIME OXYGEN CONTENT OF GASOLINE

Technical Support Document

Proposed Regulations for California Phase 2 Reformulated Gasoline

Date of Release: 10/4/91
Schedule for Consideration: 11/21/91

Location:

Auditorium
State Building
107 South Broadway, Room 1138
Los Angeles, CA

TABLE OF CONTENTS

Contents

Page

Acknowledgments

I. Introduction....1

II. Basis for Adopting Gasoline Specifications Affecting Criteria Pollutants....2

- A. Emissions Inventory....2
- B. Typical California Gasoline Properties....5
- C. Impact of Gasoline Properties on Emissions....14

III. Emission Benefits From Reducing Criteria Pollutants....41

- A. Emission Reductions From On-Road Gasoline-Powered Motor Vehicles....42
- B. Emission Reductions From Other Mobile Sources....63
- C. Emission Reductions From Stationary Sources....65
- D. Summary of Emission Reductions....68
- E. Reactivity Benefits....71

IV. Basis for Adopting Gasoline Specifications Affecting Toxic Pollutants....74

- A. Overview of Toxic Pollutants from Gasoline-Powered Vehicles....74
- B. Benzene Emissions....77
- C. Ambient Benzene Concentrations; Risk of Cancer....81
- D. Potential Cancer Incidence Due to Benzene Emission....82
- E. Reducing Benzene Emissions....84
- F. Butadiene From Gasoline Vehicles....87
- G. Formaldehyde and Acetaldehyde From Gasoline Vehicles....87
- H. Effects of Phase 2 Specifications on Toxic Pollutant Emissions....88

V. Discussion of the Proposed Regulation....97

- A. Organization of the Regulations....97
- B. Standards for California Phase 2 Reformulated Gasoline and Overall Structure of the Regulations....99
- C. Application of the Standards for Producers and Importers..101
- D. Provisions Unique to the RVP and Oxygenate Standards....102
- E. Designated Alternative Limits....103
- F. Alternative Gasoline Specifications-Predictive Model....105
- G. Alternative Gasoline Specifications-Emission Testing....109
- G. Test Methods and Sampling....117

H. Variances....122
I. Other Elements of the Regulations....122
J. Proposed Modifications to Existing Regulations....123

VI. Economic Impacts of the Proposed Regulations....124

A. Background....124
B. Discussion of Process Options to Meet Phase 2 Gasoline Specifications....126
C. Costs of Compliance....132
D. Cost-Effectiveness....139
E. Comparison to Other Measures....145
F. Analysis of Costs Using Linear Programming Models....145
G. Cost Estimates for Benzene Limit Implemented Alone....150
H. Economic Effects on Small Refiners and Importers....157
I. Economic Effects on Small Businesses....158

VII. Analysis of Alternatives....160

VII. References....163

Appendices

1. ESTIMATION OF EMISSIONS, RISK, AND CANCER INCIDENCE FOR BENZENE
2. EMISSION ESTIMATES RESULTING FROM TRANSPORTATION OF OXYGENATES
3. ARB SURVEY OF REFINERS ON GASOLINE COMPOSITION AND COSTS OF REDUCING BENZENE IN GASOLINE
4. ESTIMATION OF AVERAGE AMBIENT CONCENTRATIONS OF BENZENE 1986
5. TEST METHOD SOP 116
6. ESTIMATION OF COST, PRICE AND FINANCIAL EFFECTS FOR THE BENZENE LIMIT
7. UPDATED EMISSION INVENTORIES, CONCENTRATION AND RISK ESTIMATES
8. CALCULATIONS CONCERNING TOXIC POLLUTANTS
9. PROCESSES FOR REDUCING BENZENE IN GASOLINE
10. DERIVATION OF STATISTICAL PARAMETERS
11. UNOCAL REGRESSION EQUATION
12. AUTO/OIL REGRESSION EQUATIONS
13. BASIS FOR CALCULATING EVAPORATIVE EMISSION REDUCTIONS FROM ON-ROAD GASOLINE-POWERED MOTOR VEHICLES

ACKNOWLEDGMENTS

This report was prepared with the assistance and support from the other divisions and offices of the Air Resources Board. In addition, we would like to acknowledge the assistance and cooperation that we have received from many individuals and organizations. In particular, we would like to thank members of the Auto/Oil Air Quality Improvement Research Program, the American Petroleum Institute, the Western States Petroleum Association, the Motor Vehicle Manufacturers Association, the California Renewable Fuels Council, the American Independent Refiners Association, and the U.S. Environmental Protection Agency.

Principal Authors:

Fuels Section:

Jim Aguila
Nelson Chan
John Courtis

Technical Analysis Section:

Richard Vincent

Office of Legal Affairs:

Tom Jennings

Contributing Authors:

Steve Francis
Jim Guthrie
Linda Lee
Peggy Miller
Ritchie Nipper

Raul Cisneros
Lisa Jennings
Harlan Quan
Alex Santos
Eileen Wenger

With Special Thanks for Clerical Support To:

Theresa Dade
Marline Hicks

Debbie Jaramillo
Lynna Negri
Sonia Villalobos

Reviewed and Approved By:

Peter D. Venturini, Chief, Stationary Source Division
Ronald A. Friesen, Assistant Chief, Stationary Source Division
Donald J. Ames, Assistant Chief, Stationary Source Division
Dean C. Simeroth, Chief, Criteria Pollutants Branch
Susan V. Huscroft, Chief, Toxic Air Contaminant Control Branch
Robert D. Fletcher, Manager, Fuels Section
Daniel E. Donohoue, Manager, Technical Analysis Section

I.

INTRODUCTION

This report presents the technical information in support of the Air Resources Board (ARB) staff's proposed regulations for California Phase 2 reformulated gasoline. Phase 2 reformulated gasoline is a proposal for a comprehensive set of specifications designed to achieve maximum reductions in criteria and toxic pollutants and in the mass and reactivity (ozone-forming potential) of emissions from gasoline-fueled vehicles.

This report is intended to support and provide more detailed information than contained in the "Staff Report" <u>California Phase 2 Reformulated Gasoline Specification, Volume 1 Proposed Regulations for California Phase 2 Reformulated Gasoline</u> (October 4, 1991).

This report and associated appendices:

- provide relevant background information,
- identify information and data used in developing the regulation,
- discuss how the information was analyzed,
- present the results of the analyses,
- discuss the specific regulatory provisions,
- examine the potential environmental impacts of the proposal, and
- discuss various alternative approaches.

II.

BASIS FOR ADOPTING GASOLINE SPECIFICATIONS AFFECTING CRITERIA POLLUTANTS

A. EMISSIONS INVENTORY

1. Statewide Emissions Inventory from Gasoline-Powered Vehicles

Motor vehicle fuel related emissions are a significant source of carbon monoxide, volatile organic compounds, and oxides of nitrogen. These latter two pollutants are also precursors to ozone formation. PM10, visibility reducing particles, and sulfur dioxide are among the other criteria pollutants produced by motor vehicle fuel use.

It is clear that many heavily populated areas of the state experience exceedances of both the state and federal standards for several criteria pollutants. The importance of reducing the emissions from gasoline-powered vehicles in order to eliminate exceedances of the state and federal standards can be shown by examining the statewide emissions inventory. Table II-1 shows the statewide emissions inventory breakdown for 1987 for volatile organic compounds, carbon monoxide, oxides of nitrogen, PM10, and oxides of sulfur.

According to the data presented Table II-1, in 1987 gasoline-powered vehicles contributed 35 percent of the volatile organic compound emissions, 38 percent of the oxides of nitrogen emissions, 57 percent of oxides of nitrogen emissions, and 11 percent of the oxides of sulfur emissions. While gasoline-powered motor vehicles only contributed 0.2 percent of the directly emitted PM10, they were significant contributors of oxides of nitrogen and oxides of sulfur, which are precursors to the sulfate and nitrate fraction of PM10 pollutants. Throughout California, the percentage of combined nitrate and sulfate in the ambient concentrations of PM10 averaged over the years 1987 through 1989 varied from a high of 42 percent in the South Coast Air Basin to a low of seven percent in the Great Basin Valleys Air Basin.

Therefore, the gasoline-powered motor vehicle is a major contributor to all of the above pollutants.

Table II-1

Statewide Emissions of Gasoline-Powered Motor Vehicles, Other Mobile Sources, and Stationary Sources for 1987

Source	Average Daily Emissions, Tons/Day				
	VOC	NOx	CO	PM10	SO2
On-road Gasoline-Powered Motor Vehicles	1,400	1,300	11,000	65	65
Other Mobile Sources	420	1,130	2,000	135	245
Stationary Sources	2,200	970	6,000	5,900	210
Total Emissions	4,020	3,400	19,000	6,100	520

Source: Air Resources Board, Emissions Inventory, 1987, March 1990.

Planning inventories are designed for those areas of the state that are not in attainment of the state ambient air quality standards and only for those pollutants for which the areas are in nonattainment. For example, ozone planning inventories are prepared only for air basins designated as nonattainment areas for ozone. A planning inventory represents "typical episodic day" emissions in the nonattainment area. A "typical episodic day" is based on the ten worst air quality days of a particular pollutant. For this report, the staff have used the ozone planning inventory, which includes emissions of volatile organic compounds and oxides of nitrogen, and the carbon monoxide inventory to project future trends in emissions.

The majority of areas in California are not in attainment of the ozone ambient air quality standards. Therefore, the ozone planning inventory is a good representation of statewide emissions. Table II-2 shows the future trend in emissions of volatile organic compounds and oxides of nitrogen, respectively. From this table, it is apparent that future gasoline-powered vehicles will continue to comprise a significant portion of the total inventory. In the year 2000, gasoline-powered vehicles will account for about 17 percent of the total emissions of volatile organic compounds, and 25 percent of the total emissions of oxides of nitrogen.

Table II-2

Future Trends in Emissions of Volatile Organic Compounds and Oxides of Nitrogen from Gasoline-Powered Motor Vehicles, Other Mobile Sources, and Stationary Sources (Basis: All Nonattainment Areas)

Source	Emissions, Tons/Day 1996	2000	2005	2010
Volatile Organic Compounds				
On-road Gasoline-Powered Motor Vehicles	710	550	400	260
Other Mobile Sources	450	480	510	540
Stationary Sources	2,160	2,220	2,310	2,400
Total VOC Emissions	3,320	3,250	3,220	3,200
Oxides of Nitrogen				
On-road Gasoline-Powered Motor Vehicles	870	750	640	540
Other Mobile Sources	1,270	1,320	1,400	1,490
Stationary Sources	900	890	920	950
Total NOx Emissions	3,040	2,960	2,960	2,980

Source: Air Resources Board, Draft Ozone Planning Inventory, December 1990.

The carbon monoxide planning inventory can be used to determine the future trends of the contribution of gasoline-powered vehicles to the total emissions inventory. The carbon monoxide planning inventory only projects emissions for areas that are designated as nonattainment. Since there are areas of the state which are in attainment of the carbon monoxide ambient air quality standard, the carbon monoxide planning inventory is not as good of a representation of total statewide emissions as is the ozone planning inventory. To assess the trends in emissions, staff evaluated the future emissions for the South Coast Air Basin. Table II-3 presents the results of this evaluation. As shown in this table, gasoline-powered vehicles will continue to account for about 80 percent of the carbon monoxide emissions in the year 2000.

Table II-3

Future Trends in Emissions of Carbon Monoxide from Gasoline-Powered Motor Vehicles, Other Mobile Sources, and Stationary Sources For the South Coast Air Basin

Source	Emissions, Tons/Day 1996	2000	2005	2010
On-road Gasoline-Powered Motor Vehicles	3,780	3,210	2,820	2,420
Other Mobile Sources	740	780	840	910
Stationary Sources	140	150	160	160
Total CO Emissions	4,660	4,140	3,820	3,490

Source: Air Resources Board, Draft Carbon Monoxide Planning Inventory, December 1990.

During the past few years, a number of independent investigators have conducted studies that assert that the inventory of VOCs in urban areas may be underestimated by substantial amounts. Investigations by ARB staff have shown that these underestimates are in the order of 50 to 100 percent. Staff believes that the on-road motor vehicle portion of the inventory is underestimated by at least as much as the overall inventory; however, studies to date have not been able to establish error bands for specific categories of the inventory. Efforts toward improving both the mobile and stationary source portions of the inventory continue and a major effort is underway to obtain improved emission rates and vehicular activity data for the on-road motor vehicle emission estimates.

C. TYPICAL CALIFORNIA GASOLINE PROPERTIES

1. Required Properties of Gasoline

Gasolines used in spark ignition engines are complex mixtures of hydrocarbons which range in boiling points from 85° to 440°F and are blended from refinery streams so that the final product has desirable properties for vehicle performance under a variety of conditions. The critical properties of gasoline for automotive performance are octane rating, volatility, and other parameters as listed by the ASTM-D 439 gasoline specifications in Table II-4.

Table II-4

Detailed Requirements for Gasoline by ASTM D 439

Volatility Class	Distillation Temperature (°F) 10 Vol % max	50 Vol % min	50 Vol % max	90 Vol %, max	End Point, max	Dist. Residue Vol %, max	Vapor/Liquid Ratio a/ Test Temp. (°F)	Vapor/Liquid Ratio a/ V/L, max
A	158	170	250	374	437	2	140	20
B	149	170	245	374	437	2	133	20
C	140	170	240	365	437	2	124	20
D	131	170	235	365	437	2	116	20
E	122	170	230	365	437	2	105	20

Volatility Class	RVP max (psi)	Lead Content max, (g/gal) Unleaded b/	Lead Content max, (g/gal) Leaded c/	Copper Strip Corrosion max	Existent Gum max, mg/100 mL	Oxidation Stability, Minimum Minutes
A	9.0	0.05	4.2	No. 1	5	240
B	10.0	0.05	4.2	No. 1	5	240
C	11.5	0.05	4.2	No. 1	5	240
D	13.5	0.05	4.2	No. 1	5	240
E	15.0	0.05	4.2	No. 1	5	240

a/ At 101.3 kPa pressure (760 mm Hg).

b/ The intentional addition of lead or phosphorus compounds is not permitted. EPA regulations limit their maximum concentrations to 0.05 g of lead per gallon and 0.005 g of phosphorus per gallon (by Test Method D 3231), respectively.

c/ Effective January 1, 1986, the EPA required that the lead concentration of leaded gasoline be limited to 0.1 g/gal (0.026 g/L) averaged for quarterly production of leaded gasoline.

Source: ASTM D 439

2. Schedule of Seasonal and Geographical Volatility Classes

Table II-5 specifies the ASTM schedule, subject to agreement between purchaser and seller, that denotes the volatility properties of the gasoline at the time and place of shipment. Shipments intended for future use may anticipate this schedule. Where alternative classes are permitted, either class is acceptable: the option shall be exercised by the seller.

Table II-5

ASTM Volatility Classes

Region of California	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
North Coast a/	E/D	D	D	D/C	C	C/B	B	B	B	B/C	C/D	D/E
South Coast b/	D	D	D/C	C	C/B	B	B	B	B	B/C	C/D	D
Southeast c/	D	D/C	C/B	B	B/A	A	A	A	A	A/B	B/C	C/D
Interior d/	E/D	D	D	D/C	C/B	B	B	B	B	B/C	C/D	D/E

a/ California, North Coast - Alameda, Contra Costa, Del Norte, Humboldt, Lake, Marin, Mendocino, Monterey, Napa, San Benito, San Francisco, San Mateo, Santa Clara, Santa Cruz, Solano, Sonoma, Trinity.

b/ California South Coast - Orange, San Diego, San Luis Obispo, Santa Barbara, Ventura, Los Angeles (except that portion north of the San Gabriel Mountain range and east of the Los Angeles County Aqueduct).

c/ California Southeast - Imperial, Riverside, San Bernardino, Los Angeles (that portion north of the San Gabriel Mountain range and east of the Los Angeles County Aqueduct), Mono, Inyo, Kern (that portion lying east of the Los Angeles County Aqueduct).

d/ California Interior - Lassen, Modoc, Plumas, Sierra, Siskiyou, Alpine, Amador, Butte, Calaveras, Colusa, El Dorado, Fresno, Glenn, Kern (expect that portion lying east of the Los Angeles County Aqueduct), Kings, Madera, Mariposa, Merced, Placer, Sacramento, San Joaquin, Shasta, Stanislaus, Sutter, Tehama, Tulare, Tuolumne, Yolo, Yuba, Nevada.

Source ASTM D 439

3. Grades of Gasoline

There are three main grades of gasolines marketed today: leaded regular which has octane number of 88-89, unleaded regular with an octane of 87, and premium with an octane of about 91-93. In addition, small amounts of unleaded midgrade are marketed with an octane rating between 87 and 93. Table II-6 shows the 1990 California refinery production for each grade. In September 1990, the ARB adopted section 2253.4, which precludes the addition of lead additives to any gasoline for on-road use by January 1, 1992, because of the adverse health effects of lead and because lead poisons the catalytic converters. On January 1, 1994, all gasoline must be unleaded except for gasoline used in implements of husbandry.

Table II-6

Projected 1990 California Refinery Production

Gasoline		Barrels per Day
Leaded Regular		180,000
Unleaded Regular		495,000
Unleaded Midgrade		18,000
Unleaded Premium		216,000
	Total	899,000

Source: Chevron Research and Technology Company. "Informal Discussion for CEC on Manufacturing of Gasoline", January 4, 1990.

4. Refining of Gasoline

Gasoline is blended in the refinery from a number of hydrocarbon streams produced at the refinery or purchased which have different octane values, composition, and ASTM properties. The blendstocks available to a refiner depend upon the crude source and the refinery's complexity. Table II-7 lists the estimated generic blendstocks that go into the California gasoline pool and Table II-8 list properties of blendstocks that are available to the refiner.

From Table II-7 it is apparent that reformate and gasoline produced from the fluid catalytic cracking unit (FCC gasoline) are significant components of the California gasoline pool. As can be seen from Table II-8, reformates have high octane values and high aromatic hydrocarbon/benzene content. While reformates' high octane value make them desirable blendstocks for conventional gasoline, their high aromatic hydrocarbon/benzene content limits their use as blendstocks for reformulated gasoline. FCC and coker gasolines are undesirable as blendstocks for reformulated gasoline because of their high olefins and sulfur contents. Butanes are also undesirable for the blending of reformulated gasoline because of their high RVP values. It is expected that refiners, when blending reformulated gasolines, will use lower volumes of reformates, FCC gasoline, and coker gasoline, and eliminate the use of butanes. These blendstocks are expected to be replaced by oxygenates, alkylates, or other blendstocks that have more desirable properties.

Table II-7

Estimated California Gasoline Pool, 1990

Component	Volume (MBPCD)
Reformate	320
FCC Gasoline	300
Alkylate	80
Light Straight Run	60
Coker Gasoline	20
Hydrocraker Light	80
Butane and Others	40
Pool Total	900

Source: Chevron Research and Technology Company, "Presentation to CEC", January 1990.

Table II-8

Example Properties of Process Streams Blended into Gasoline

Process Stream	Par. Vol. %	Olef. Vol. %	Nap. Vol. %	Aro. Vol. %	Ben. Vol. %	Octane Number Rec. Oct	Octane Number Motor Oct	R+M 2	RVP (psi)	S ppm	Distillation ASTM D 86 10%	Distillation ASTM D 86 50%	Distillation ASTM D 86 90%
Reformate	28	0	1	71	3	98	88	93	6	10	166	279	339
FCC Light Naptha	41	42	11	7	1	91	79	85	12	60	93	141	224
FCC Heavy Naptha	31	13	17	40	0	89	79	84	1	300	226	274	339
Alkylate	98	0	0	0	0	91	89	90	7	26	136	227	244
Light Straight Run	77	0	19	3	2	75	73	74	12	10	123	161	270
Hdrocrackate(light)	82	0	17	1	1	81	78	79	13	47	11	140	181
Isomerate	94	0	6	0	0	86	86	86	15	0	132	176	176
Polymer Gasoline	0	99	0	0	0	97	81	89	9	125	152	170	334
Coker Light	51	43	6	1	1	78	71	74	12	1800	94	109	164
Butane	100	0	0	0	0	94	90	92	60	0	31	31	31
MTBE	--	--	--	--	-	114*	90*	102*	8	0	135	135	135
EtOH	--	--	--	--	-	115*	84*	77*	2		172	172	172

* Octane values for neat oxygenates are presented here for general comparison purposes. These values do not represent octane performance when blended with hydrocarbons.

Source: (a) Chevron Research and Technology Company, "Presentation to CEC" Richmond, CA. January, 1990, and (b) information provided by Bechtel Corporation.

5. Typical Properties of California Gasoline

In cooperation with California refiners, the ARB has been collecting detailed data on the chemical composition and physical properties of California gasoline. The program, referred to as the Voluntary Gasoline Properties Reporting Program, was initiated late last year. Data have been reported by most of the refiners in California during the period from January 1991 through June 1991.

To estimate the average properties and composition of California gasoline, the ARB provided monthly summaries of the data to the California Energy Commission (CEC) on a confidential basis. The CEC then calculated weighted monthly averages using data reported to them pursuant to the Petroleum Industry Information Reporting Act (PIIRA). The production data were not provided to ARB because of confidentiality requirements of the PIIRA. Since only the total unleaded gasoline is reported to the CEC, the ARB provided the CEC with splits of premium gasoline versus unleaded regular gasoline based on surveys conducted by the ARB in 1986. In addition to the weighted monthly averages, the CEC calculated average winter (January, February), average summer (March, April, May, and June), and overall averages for premium gasoline, unleaded gasoline, and total unleaded gasoline. These data are summarized in Table II-9. Figures II-1 through II-4 present the monthly data for RVP, sulfur, olefins, and total aromatic hydrocarbons.

Table II-9

Voluntary Gasoline Data Reporting Results

(weighted average by gasoline component)

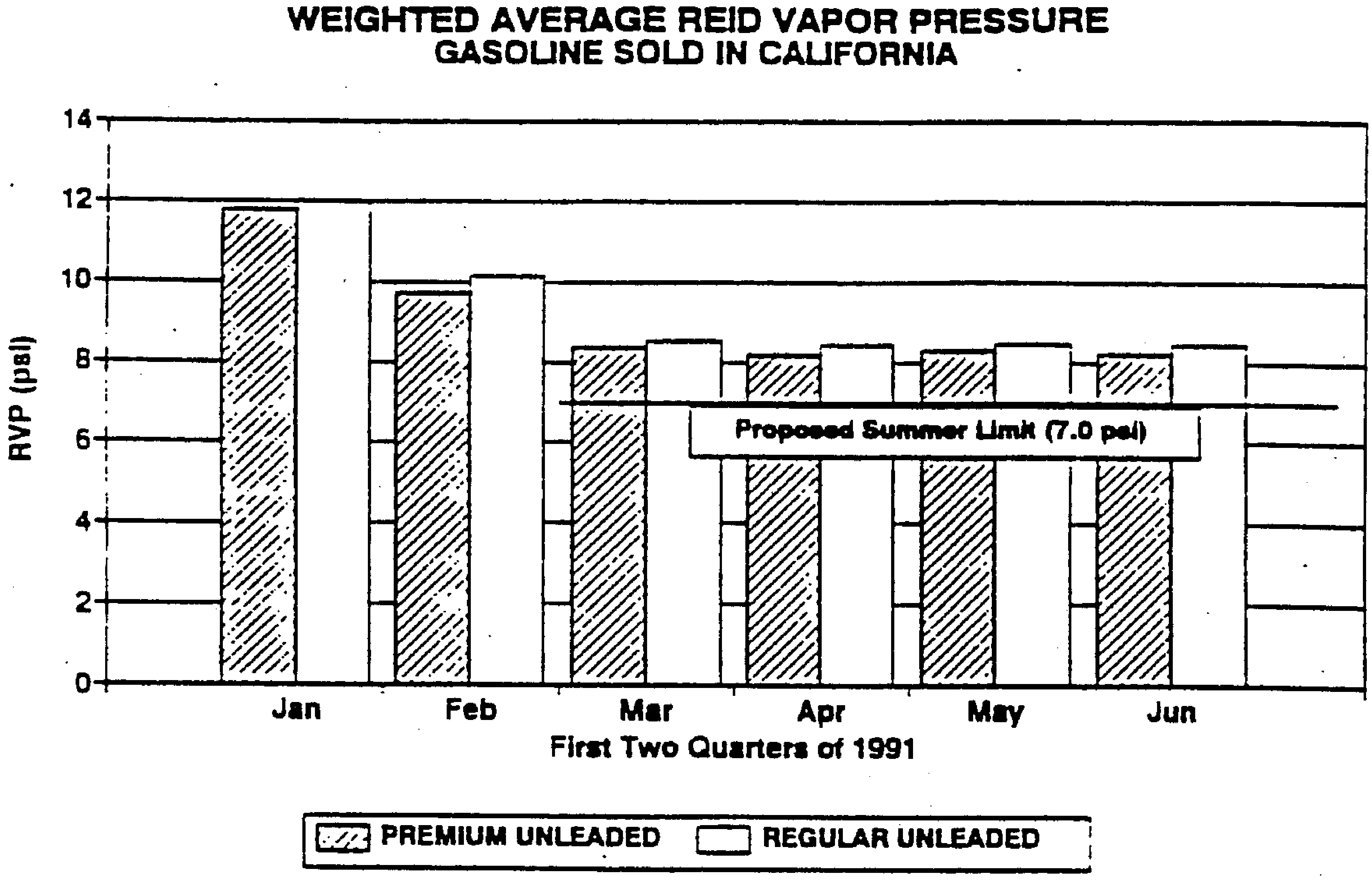
	Jan-Jun,1991 Average Sulfur ppmw	Average RVP psi	Average T10 Deg. F	Average T50 Deg. F	Average T90 Deg. F	Average Bromine No.	Average Olefin vol %	Average AC9 vol %	Average AC10 vol %	Average AC11+ vol %	Average Tot. Arom. vol %	Average Benzene vol %
Premium	100.	9.0	128	221	319	14.4	7.96	8.47	3.90	1.29	36.04	[illegible]
Unleaded	168	9.3	123	209	332	21.0	10.33	7.11	4.62	2.59	30.72	[illegible]
Total	151	9.2	125	212	329	19.4	9.60	7.45	4.44	2.27	32.26	[illegible]
Reported Mbbl	161739	166527	166527	166527	166527	131789	138319	154577	154577	144252	158645	[illegible]
CEC Total Rep.	179052	179052	179052	179052	179052	179052	179052	179052	179052	179052	179052	[illegible]
% Reported of Total as Volume	90.3	93.0	93.0	93.0	93.0	73.6	77.3	86.3	86.3	80.6	88.6	[illegible]

	Jan-Feb,1991 Winter Average Sulfur ppmw	Winter Average RVP psi	Winter Average T10 Deg. F	Winter Average T50 Deg. F	Winter Average T90 Deg. F	Winter Average Bromine No.	Winter Average Olefin vol %	Winter Average AC9 vol %	Winter Average AC10 vol %	Winter Average AC11+ vol %	Winter Average Tot. Arom. vol %	Winter Average Benzene vol %
Premium	101	10.8	118	216	315	14.6	7.62	7.41	3.60	1.25	34.01	[illegible]
Unleaded	161	11.2	114	203	326	19.2	10.49	6.60	4.30	2.24	28.85	1.76
Total	146	11.1	115	206	324	18.0	9.84	6.80	4.12	1.99	30.17	1.28
Reported Mbbl	48322	49499	49499	49499	49499	37155	37998	42926	42926	42562	44183	[illegible]
CEC Total Rep.	54927	54927	54927	54927	54927	54927	54927	54927	54927	54927	54927	[illegible]
% Reported of Total as Volume	88.0	90.1	90.1	90.1	90.1	67.6	69.2	78.2	78.2	77.5	80.3	[illegible]

	Mar-Jun,1991 Summer Average Sulfur ppmw	Summer Average RVP psi	Summer Average T10 Deg. F	Summer Average T50 Deg. F	Summer Average T90 Deg. F	Summer Average Bromine No.	Summer Average Olefin vol %	Summer Average AC9 vol %	Summer Average AC10 vol %	Summer Average AC11+ vol %	Summer Average Tot. Arom. vol %	Summer Average Benzene vol %
Premium	100	8.3	133	223	321	14.4	6.84	8.88	4.01	1.31	37.95	[illegible]
Unleaded	170	8.5	127	212	335	21.7	10.27	7.30	4.74	2.74	31.44	[illegible]
Total	153	8.4	129	215	331	19.9	9.51	7.70	4.56	2.39	33.07	[illegible]
Reported Mbbl	113417	117028	117028	117028	117028	94634	100321	111652	111652	101691	114508	[illegible]
CEC Total Rep.	124125	124125	124125	124125	124125	124125	124125	124125	124125	124125	130125	[illegible]
% Reported of Total as Volume	91.4	94.3	94.3	94.3	94.3	76.2	80.8	90.0	90.0	81.9	92.2	[illegible]

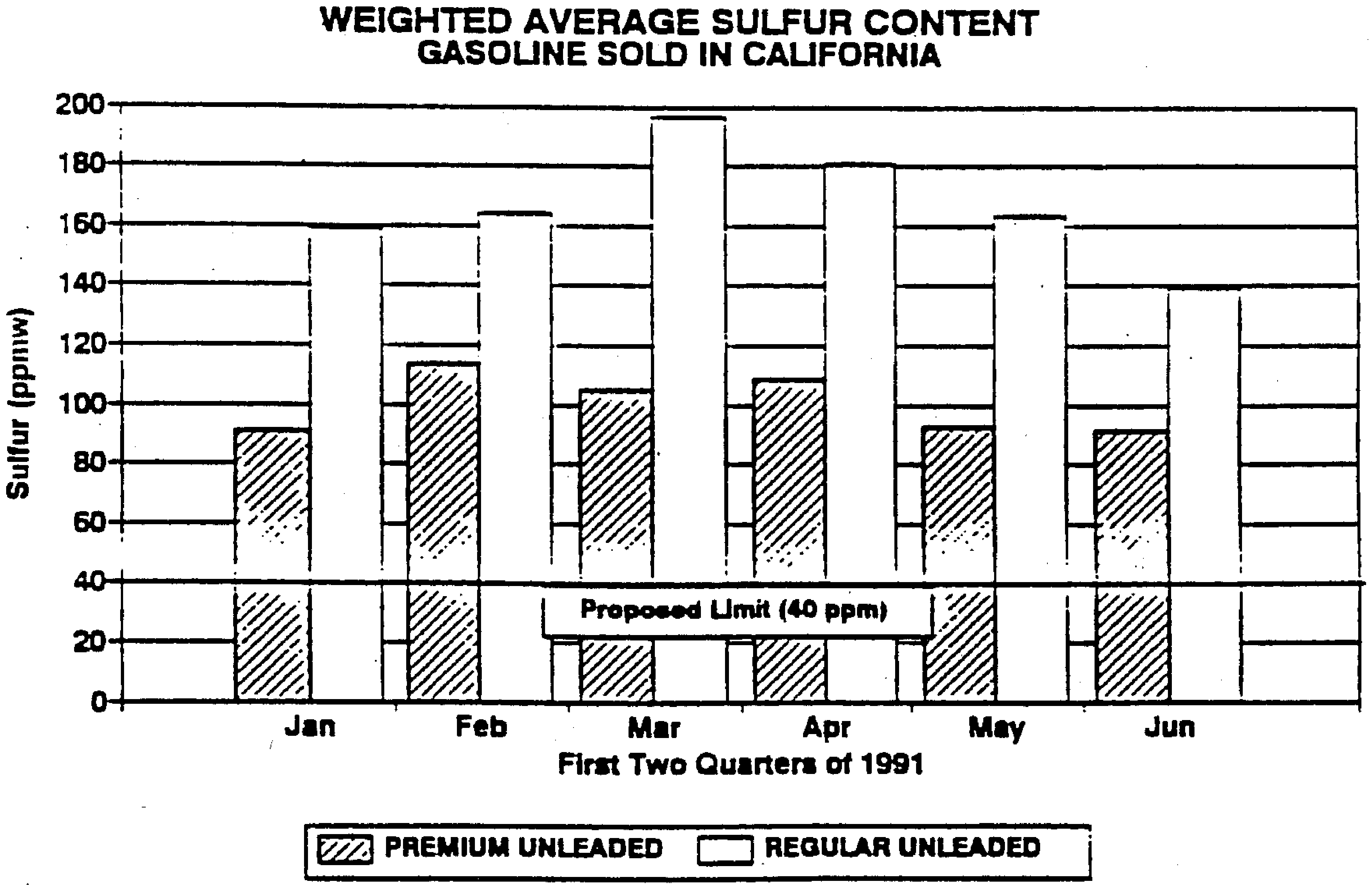
Source: ARB/CEC

Figure II-1



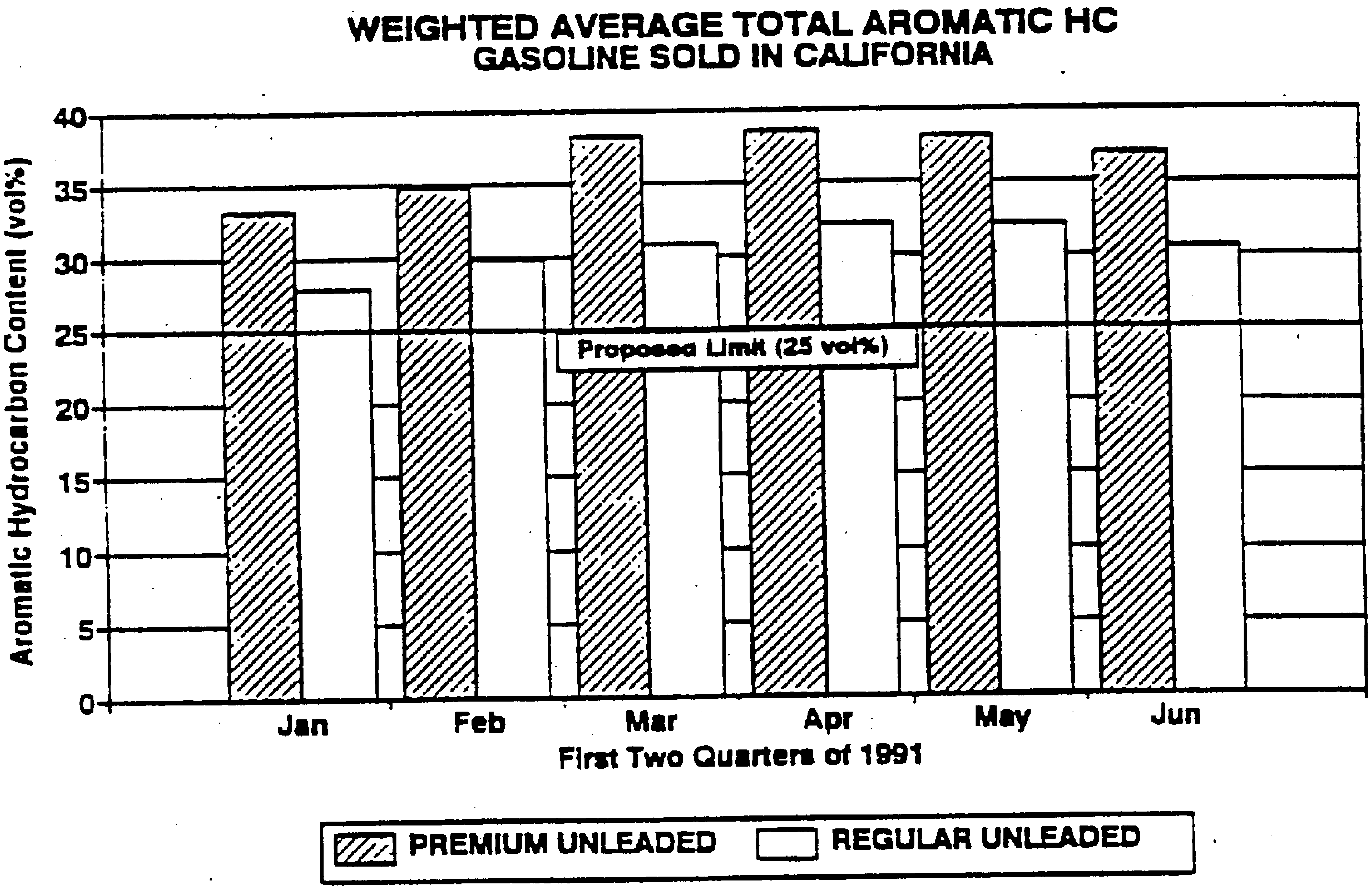
Source: ARB's Voluntary Gasoline Properties Reporting Program

Figure II-2



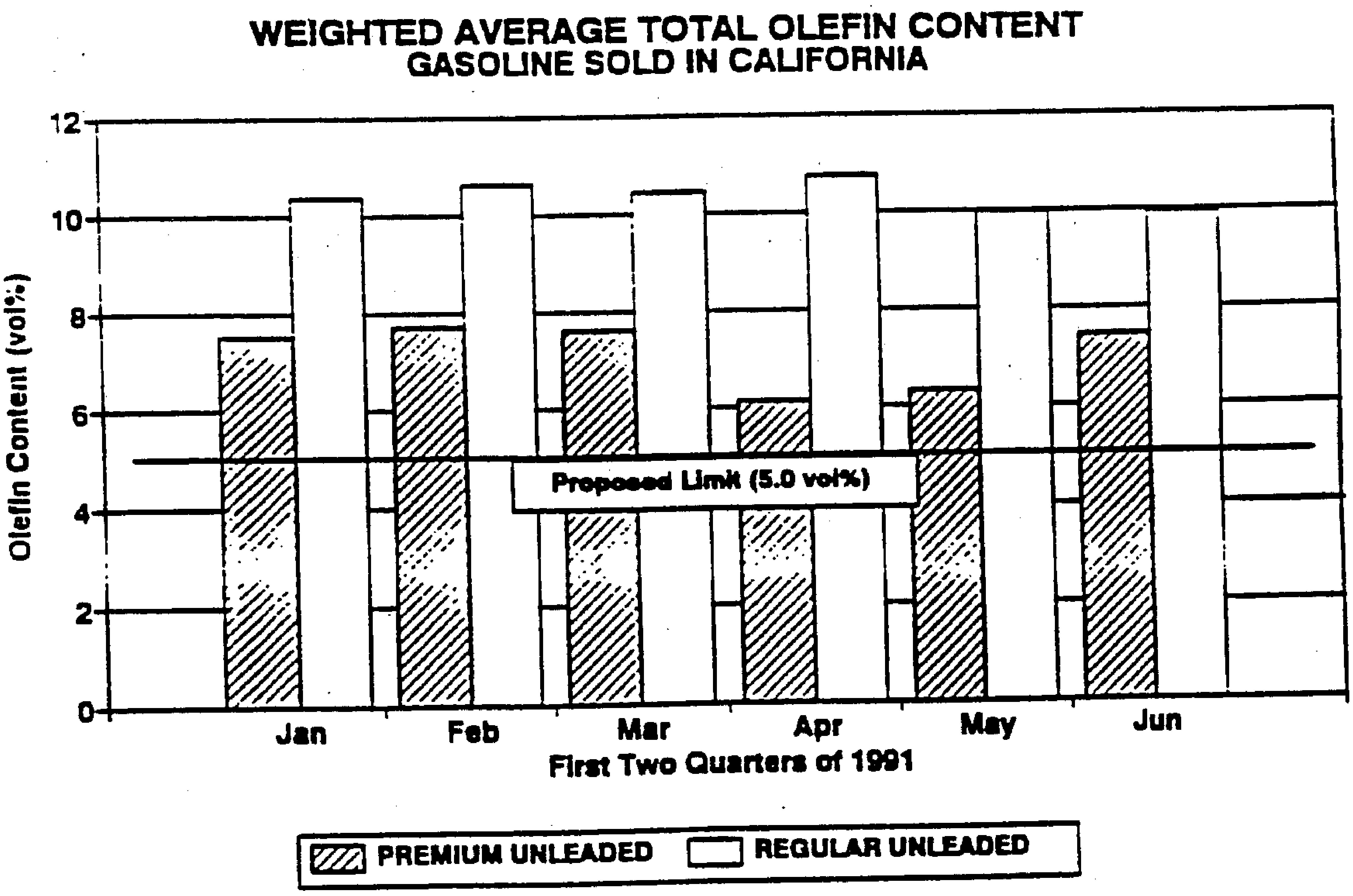
Source: ARB's Voluntary Gasoline Properties Reporting Program

Figure II-3



Source: ARB's Voluntary Gasoline Properties Reporting Program

Figure II-4



Source: ARB's Voluntary Gasoline Properties Reporting Program

D. IMPACT OF GASOLINE PROPERTIES ON EMISSIONS

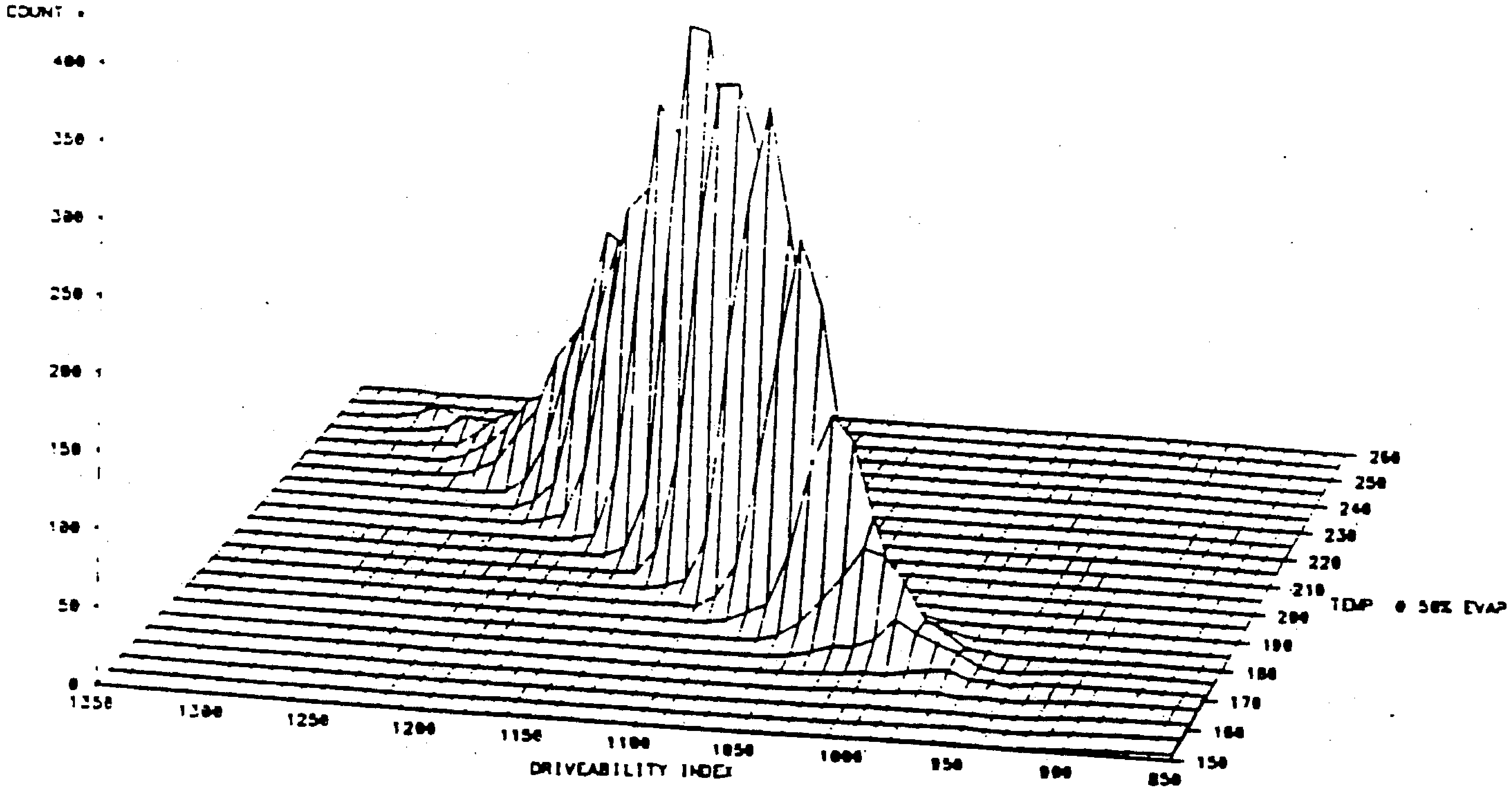
1. Reid Vapor Pressure and Driveability Index

The Reid vapor pressure (RVP) is a measurement of gasoline volatility and is defined as the absolute vapor pressure of gasoline at 100°F by the RVP. Gasoline RVP must be above a certain value to ensure that gasoline vaporization is sufficient to ensure acceptable performance during cold weather operation. The reduction in gasoline volatility, achieved by reductions in RVP, will result in reductions of motor vehicle evaporative VOC emissions. Since 1971, evaporative VOC emissions have been reduced significantly in California by limiting the maximum RVP of motor vehicle gasoline to 9.0 pounds per square inch (psi) during the summer smog season. In September 1990 the Board adopted section 2251.5, Title 13, California Code of Regulations, which reduced the summertime RVP limit from 9.0 to 7.8 psi. The 7.8 psi RVP limit will become effective during the RVP season (March through October) in 1992.

At the September 1990 public hearing, General Motors recommended that the gasoline RVP be reduced further based on the potential for additional reductions in evaporative emissions. At that time, the staff did not concur with General Motors' recommendation because of concerns that fuel RVP reductions may have an adverse impact on exhaust emissions, or on the driveability of vehicles during cold weather conditions or in the warm-up mode. Insufficient volatility during cold starts may result in difficulties in the starting of vehicles and excessive misfiring. Misfires, mixture enrichment needed during the start-up phase, and low catalytic converter efficiency during the cold-start mode could result in excessive carbon monoxide and volatile organic compound exhaust emissions. Therefore, the staff proposed the 7.8 psi RVP limit as part of the Phase 1 reformulated gasoline specifications because analysis of the existing data available to the staff at the time indicated that a 7.8 psi limit would result in the optimum combination of maximum emission reductions and minimal impact on vehicle performance. However, because additional evaporative emission benefits can be achieved by further reductions in RVP, staff agreed at the September hearing to conduct, in cooperation with affected industries, additional studies on the effects of further lowering gasoline RVP.

Staff believes that although RVP is a good indicator of fuel volatility, it can be a poor predictor of vehicle driveability. If low RVP gasoline is produced in an integrated refinery configuration by changes across the whole gasoline distillation range, the low RVP values would not affect vehicle driveability. In that case, to accurately predict vehicle driveability, the distillation characteristics of the fuel are needed as given by the temperatures at which 10 percent (T10), 50 percent (T50), and 90 percent (T90) of the fuel is distilled. A CRC study also evaluated vehicle driveability and has found that vehicle driveability is more related to T50 (see Figure II-5) than to RVP. In the process, they developed a driveability index which they believe sufficiently describes the behavior of

Figure II-5



* COUNT EQUALS THE NUMBER OF GASOLINE SAMPLES AT INTERSECTIONS – ABOUT 12,000 TOTAL SAMPLES

DISTRIBUTION OF DRIVEABILITY INDEX VERSUS T50
HYDROCARBON GASOLINES IN THE U.S. MARKET

Source: SAE paper 881668

the distillation properties of the fuel as related to vehicle driveability. The Driveability Index (DI) is expressed as:

Driveability Index = 1.5*(T10) + 3*(T50) + T90

Generally, the performance of automobile engines will improve when operated on gasolines with low driveability indexes. That is, the lower the gasoline DI, the better the engine will perform. A refiner can decrease the gasoline's DI by making the gasoline more volatile through its entire distillation range. Such an approach would improve the ability of the fuel to vaporize and create a more homogeneous air-fuel mixture during the cold-start mode. This in turn will improve combustion and reduce exhaust VOC emissions. It is possible that even at low RVPs, reductions in the driveability index could be sufficient to allow motor vehicles to operate without excessive cold-start/warm-up emissions.

This hypothesis was tested during a cooperative research venture conducted by General Motors, Western States Petroleum Association, and the Air Resources Board (The GM/WSPA/ARB Volatility Study). In this study, a matrix of fuels was selected and tested on different vehicle technology classes to determine the independent impacts of DI and RVP changes on exhaust emissions. Four fuels were tested which were created in a balanced refinery configuration and had RVP values of about 7.8 and 7.0 psi and DI values of about 1020 and 1090. These fuels were tested against a baseline fuel which had properties approximating the properties of the Phase 1 gasoline that will be marketed in California after 1992. This baseline fuel has a DI of about 1200 and an RVP of 7.8 psi.

Based on preliminary results from GM/ARB/WSPA Volatility Study, the staff has calculated the percent differences in VOC, CO, and NOx emissions by vehicle groups. The percent differences in emissions were obtained by comparing the vehicle exhaust emissions from vehicles operating on fuels with various RVP and DI to the emissions from the same vehicles operating on the baseline fuel. The resulting percent differences in emissions are presented in Table II-10. The results presented in these table indicate that there are significant reductions in VOC, CO, and NOx exhaust emissions when gasoline DI is lowered together with RVP. These results are similar to results from the Auto/Oil, Unocal and ARCO studies if one considers that DI reductions in this study are achieved solely through reductions in T50 and T90. The results shown in Table II-10 could also be looked at as representing the combined effects of T50 and T90 on exhaust emissions.

To further analyze the effects of lowered RVP, the staff plotted the average percent differences in emissions and the 95 percent confidence limits when RVP and DI are lowered together and when RVP is lowered at a constant low DI. The percent differences in exhaust emissions when RVP is reduced from 7.8 to 6.8 while DI is lowered from 1199 to 1099 at two test temperatures (50 °F and 75°F) are shown in Figure II-6 and Figure II-7. The percent differences in exhaust emissions when RVP is lowered from 7.8 to 6.8 at DIs of about 1095 and at test temperatures of 50°F and 75°F are shown in Figure II-8 and Figure II-9. Figures II-6 and II-7 show that for most of

Table II-10

AVERAGE PERCENT DIFFERENCES IN EXHAUST VOC EMISSIONS

			50 DEGREE TESTS					75 DEGREE TESTS				
FUEL NO.	RVP	DI	A	B	C	D	ALL	A	B	C	D	ALL
0	7.8	1199.0	***	***	***	***	***	***	***	***	***	***
1	7.8	1090.0	-10.0	-11.9	-0.9	-21.4	-11.1	-6.1	-3.0	-7.6	-10.6	-6.8
2	6.8	1096.0	-10.9	-8.7	0.1	-12.1	-7.8	-9.8	-2.7	-4.8	-10.9	-7.8
3	7.7	1015.0	-7.2	-1.4	-2.6	-15.4	-6.6	-10.4	5.0	-5.6	-13.6	-6.1
4	7.0	1023.0	-10.6	-11.0	1.5	-8.9	-7.1	-8.1	5.6	-3.2	-19.8	-6.2
5	7.7	1266.0	1.0	2.1	8.4	38.8	13.2	-3.1	23.5	0.1	16.8	9.3

Source: ARB/GM/WSPA Volatility Study

AVERAGE PERCENT DIFFERENCES IN EXHAUST CO EMISSIONS

			50 DEGREE TESTS					75 DEGREE TESTS				
FUEL NO.	RVP	DI	A	B	C	D	ALL	A	B	C	D	ALL
0	7.8	1199.0	***	***	***	***	***	***	***	***	***	***
1	7.8	1090.0	-13.7	-9.3	-6.3	-3.6	-7.9	-14.2	-10.3	-17.8	4.0	-9.6
2	6.8	1096.0	-13.8	-8.7	-6.5	9.8	-4.3	-17.8	-18.2	-17.0	24.7	-7.1
3	7.7	1015.0	-10.6	-0.8	10.4	21.2	5.8	-19.1	-14.2	-10.2	7.6	-9.8
4	7.0	1023.0	-8.0	-3.5	9.2	35.8	9.2	1.9	-17.5	10.5	-3.8	-2.2
5	7.7	1266.0	-7.0	-7.8	-4.5	17.5	-0.1	-14.9	-3.3	-0.2	11.4	-1.7

Source: ARB/GM/WSPA Volatility Study

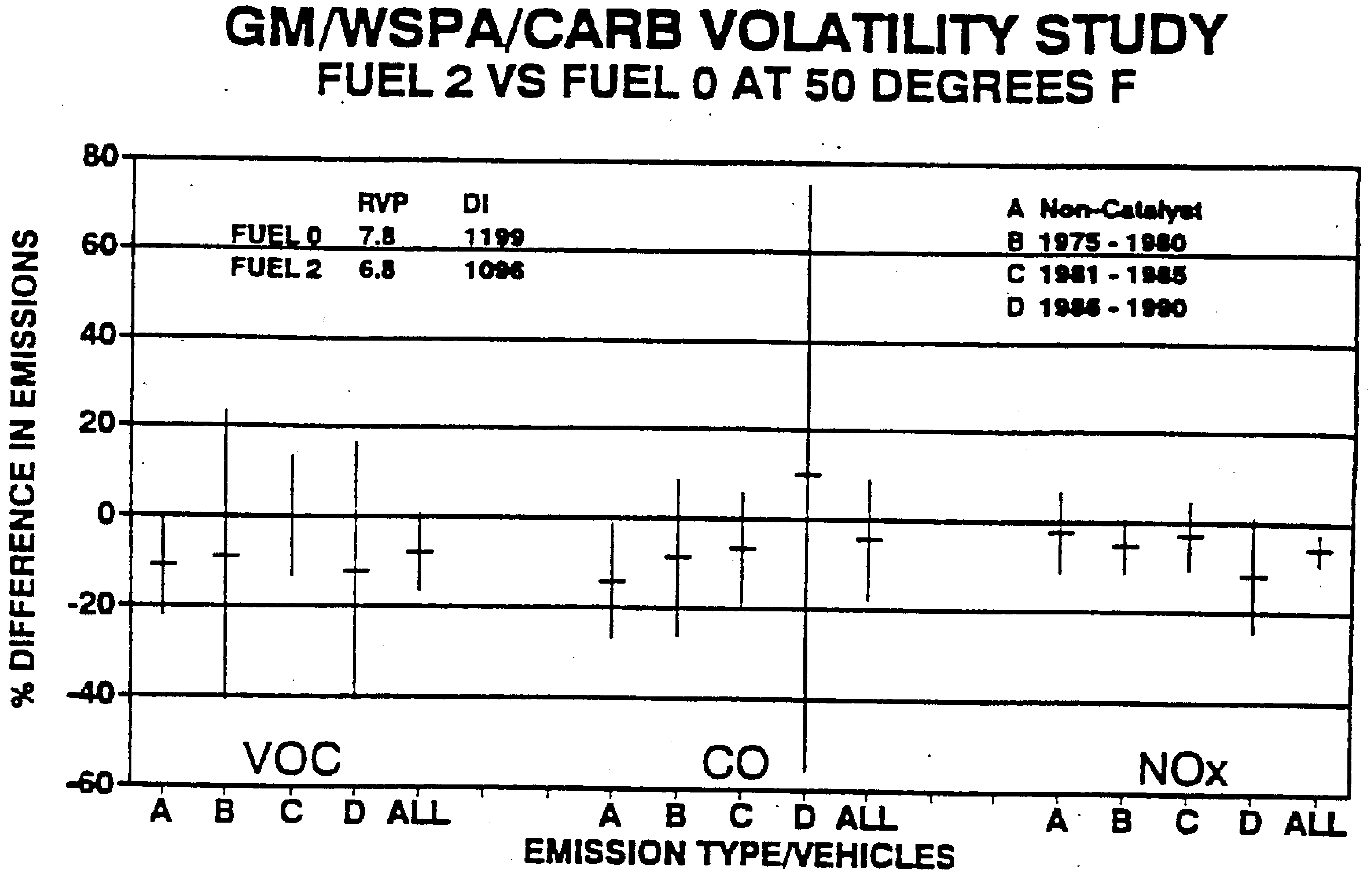
AVERAGE PERCENT DIFFERENCES IN EXHAUST NOX EMISSIONS

			50 DEGREE TESTS					75 DEGREE TESTS				
FUEL NO.	RVP	DI	A	B	C	D	ALL	A	B	C	D	ALL
0	7.8	1199.0	***	***	***	***	***	***	***	***	***	***
1	7.8	1090.0	-4.4	-0.1	-0.9	-8.0	-3.3	1.1	-0.8	-11.5	-3.1	-3.5
2	6.8	1096.0	-2.4	-5.2	-2.9	-11.6	-5.7	3.9	1.7	-6.8	-7.8	-2.1
3	7.7	1015.0	-5.5	-0.2	-6.2	-16.0	-7.1	3.0	-1.5	-6.7	-1.6	-1.7
4	7.0	1023.0	-8.8	-5.1	-4.0	-8.9	-6.6	-0.4	-0.8	-9.7	-0.1	-2.7
5	7.7	1266.0	-3.8	4.8	-2.7	1.7	0.2	4.7	4.5	-0.1	13.7	5.5

Source: ARB/GM/WSPA Volatility Study

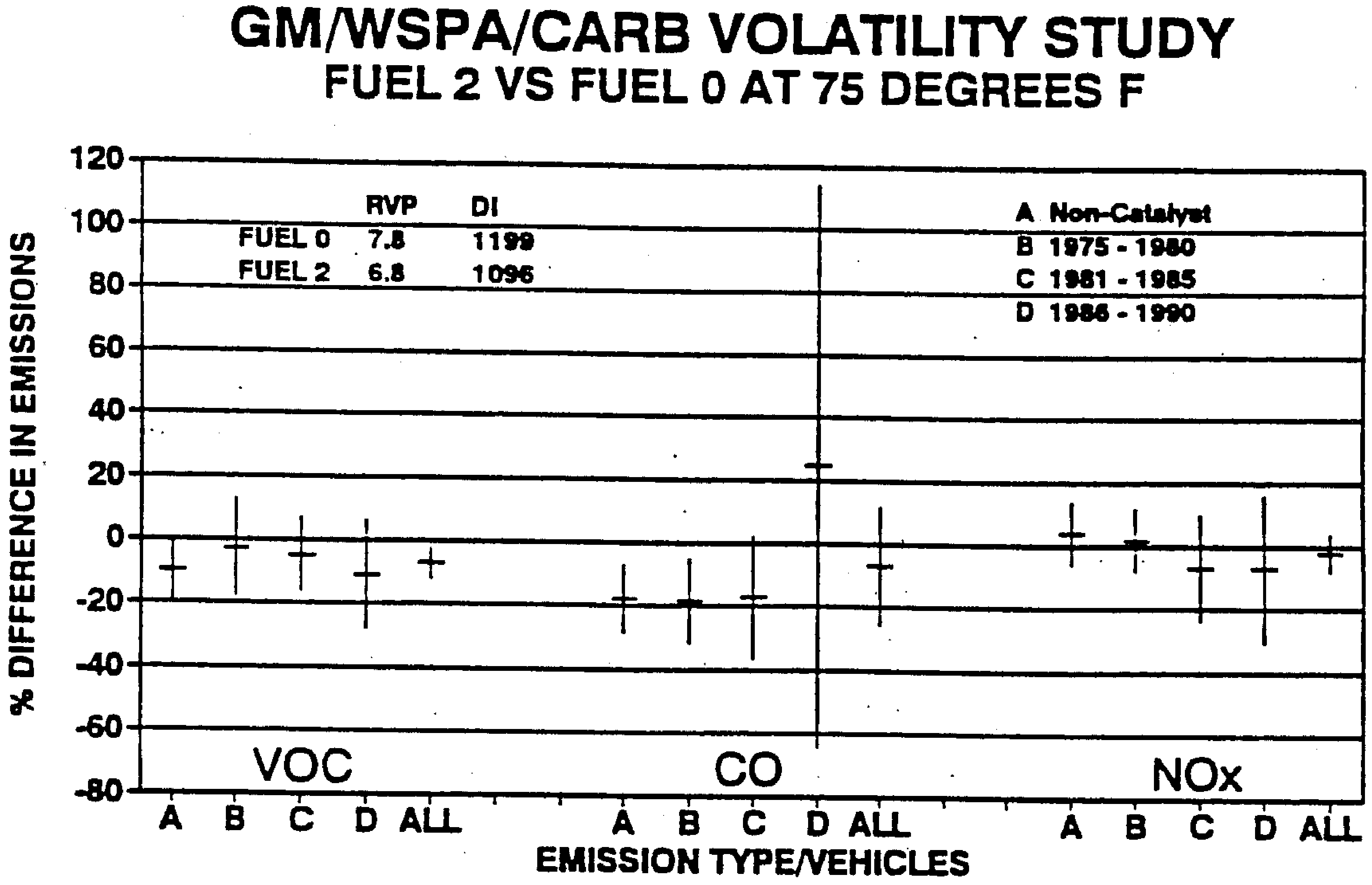
A = NON-CALTALYST VEHICLES
B = 1975 - 1980 VEHICLES
C = 1981 - 1985 VEHICLES
D = 1986 - 1990 VEHICLES
ALL = AVERAGE OF ALL VEHICLE GROUPS

Figure II-6



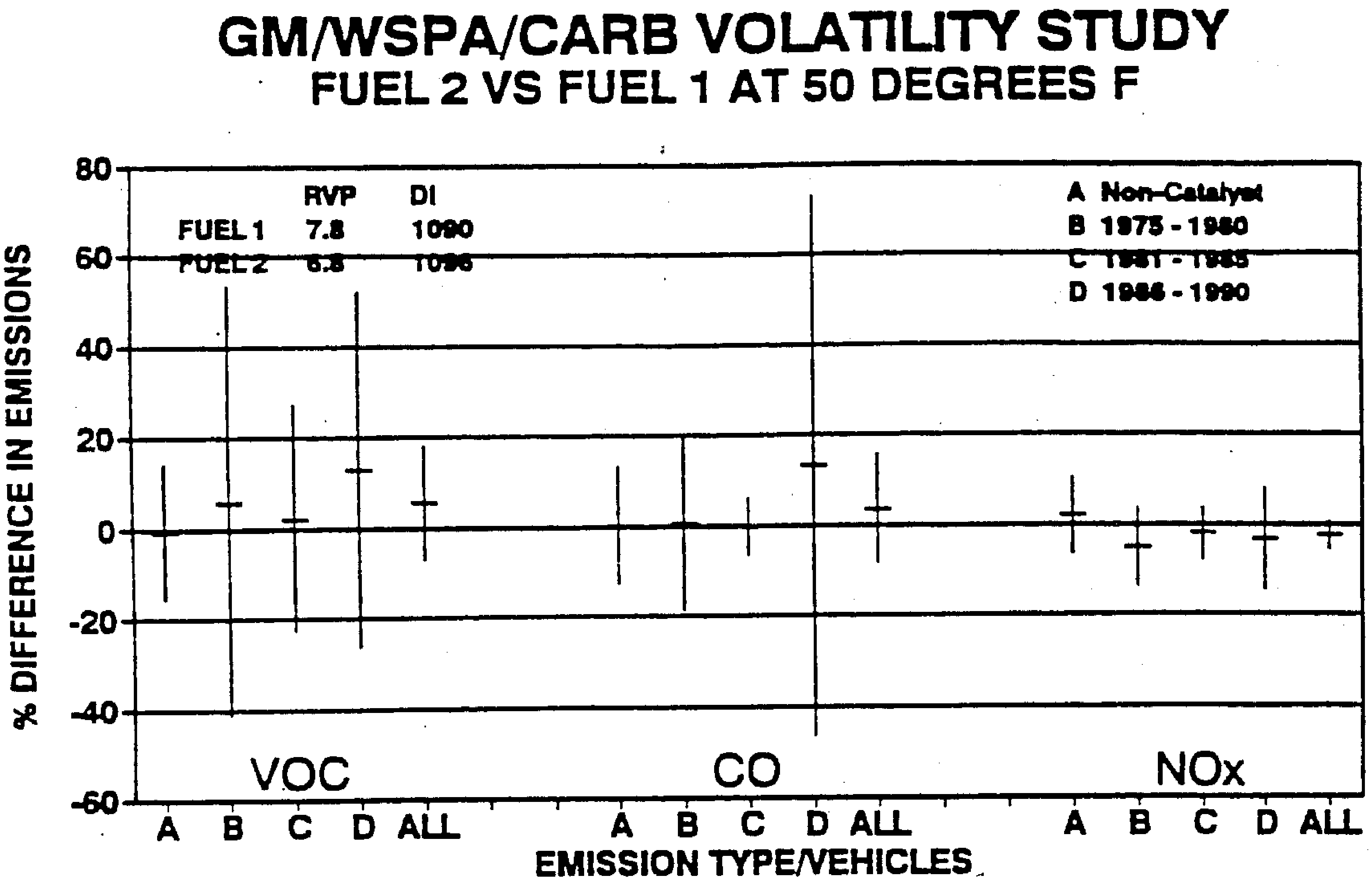
Source: ARB/GM/WSPA Volatility Study

Figure II-7



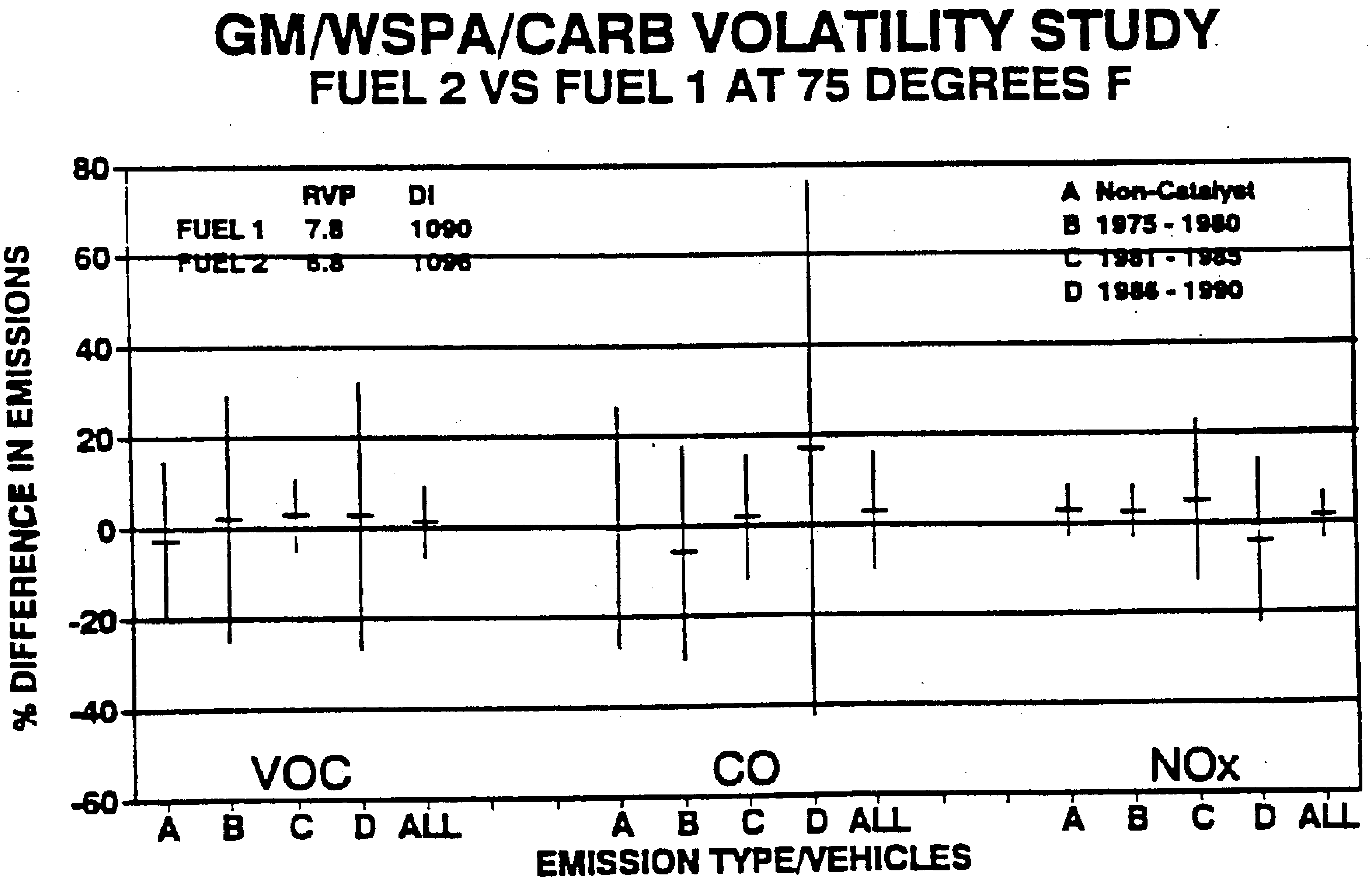
Source: ARB/GM/WSPA Volatility Study

Figure II-8


GM/WSPA/CARB VOLATILITY STUDY
FUEL 2 VS FUEL 1 AT 50 DEGREES F

Source: ARB/GM/WSPA Volatility Study

Figure II-9


GM/WSPA/CARB VOLATILITY STUDY
FUEL 2 VS FUEL 1 AT 75 DEGREES F

Source: ARB/GM/WSPA Volatility Study

the vehicles tested, lowering RVP and DI together will decrease exhaust emissions. Figures II-8 and II-9 compare the effects of RVP changes from 7.8 to 6.8 psi when DI is held constant a value of 1096. These figures show that there are small increases in VOC emissions when RVP is reduced, which seems to indicate that at a DI of about 1090 higher exhaust emission reductions can be achieved by a 7.8 psi RVP rather than from a 7.0 psi RVP. However, the changes in exhaust exhaust emissions are not statistically significant, and will most likely be out-weighed by the evaporative emission benefits resulting from reducing RVP to 7.0 psi.

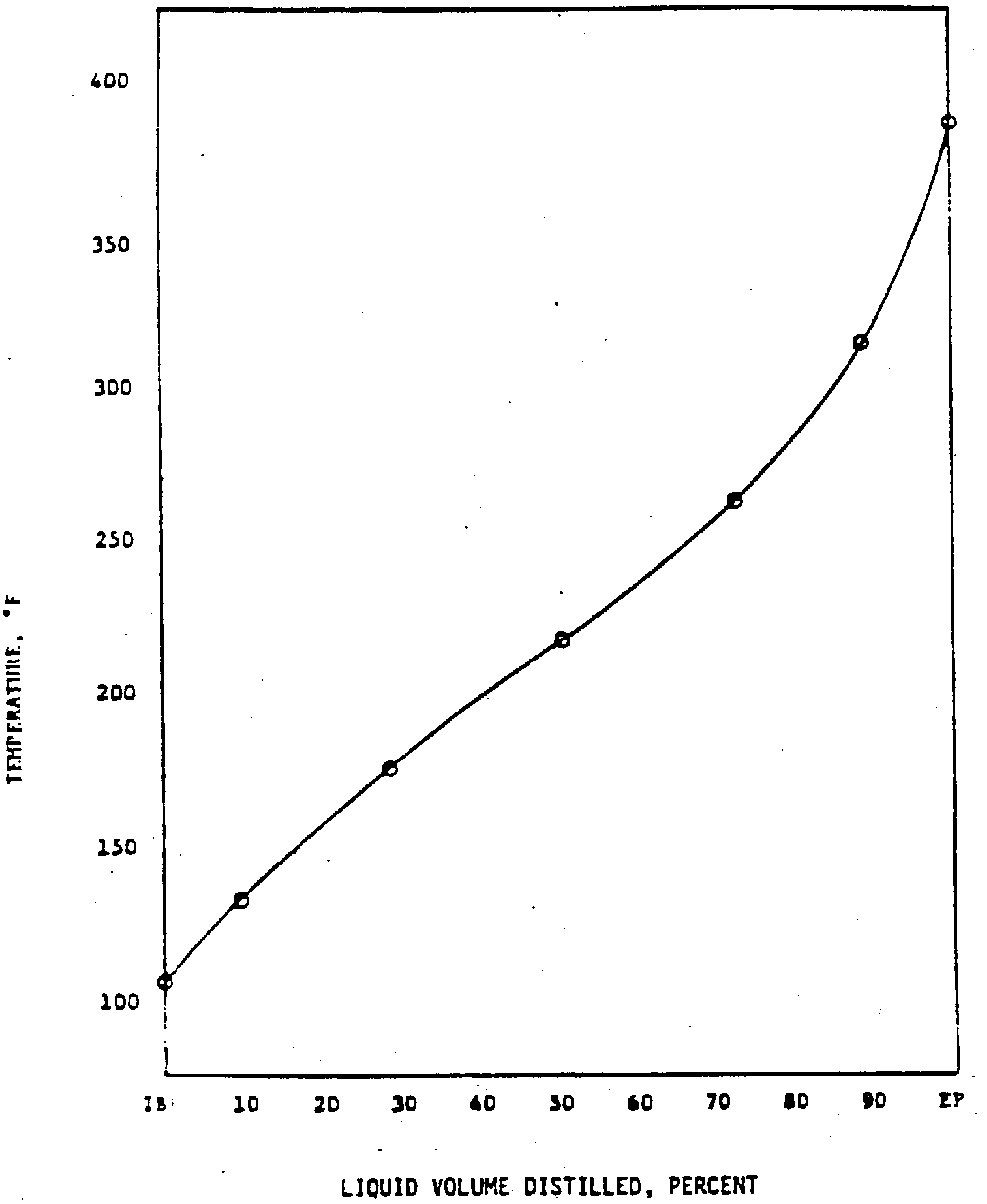
Preliminary results of this study, shown in Table II-10, confirm the hypothesis that the RVP can be reduced to 7.0 psi without causing a significant increase in exhaust emissions, with proper control of the DI. Because reductions in RVP are needed to achieve reductions in evaporative emissions, reductions in DI are necessary to eliminate any adverse impacts of RVP reductions on exhaust emissions. Additional benefits of controlling the DI by controlling distillation temperatures are discussed in the next section.

2. Distillation Temperatures

Gasoline contains a wide range of hydrocarbons containing from four to eleven carbon atoms and exhibits a wide boiling temperature range. A typical gasoline distillation curve, shown in Figure II-10, shows the percentage by volume of the gasoline that is volatilized at a given temperature and characterizes the tendency of the gasoline fuel to vaporize (volatility). The ASTM has established distillation point criteria (Table II-4) which vary with the area and the season and is based on ensuring adequate motor vehicle performance. The "front end" volatility of gasoline is the temperature at which 10 percent of the fuel evaporates (T10) and is important because it is related to cold-start, and vapor lock (hot-weather problem). The temperature at which 50 percent is evaporated (T50) has been related to short trip fuel economy, warm-up and cool weather driveability. The "back end" volatility expressed by the temperature at which 90 percent of the fuel is evaporated (T90) has been related to engine deposits and engine oil dilution.

Investigators looked at the effects of changing gasoline's distillation distribution on emissions by either changing individual distillation points such as T50 and T90 or by changing a distillation index such as the driveability index. The results of the GM/WSPA/ARB study discussed in the previous section in detail indicate that DI is important for the control of exhaust emissions.

Figure II-10



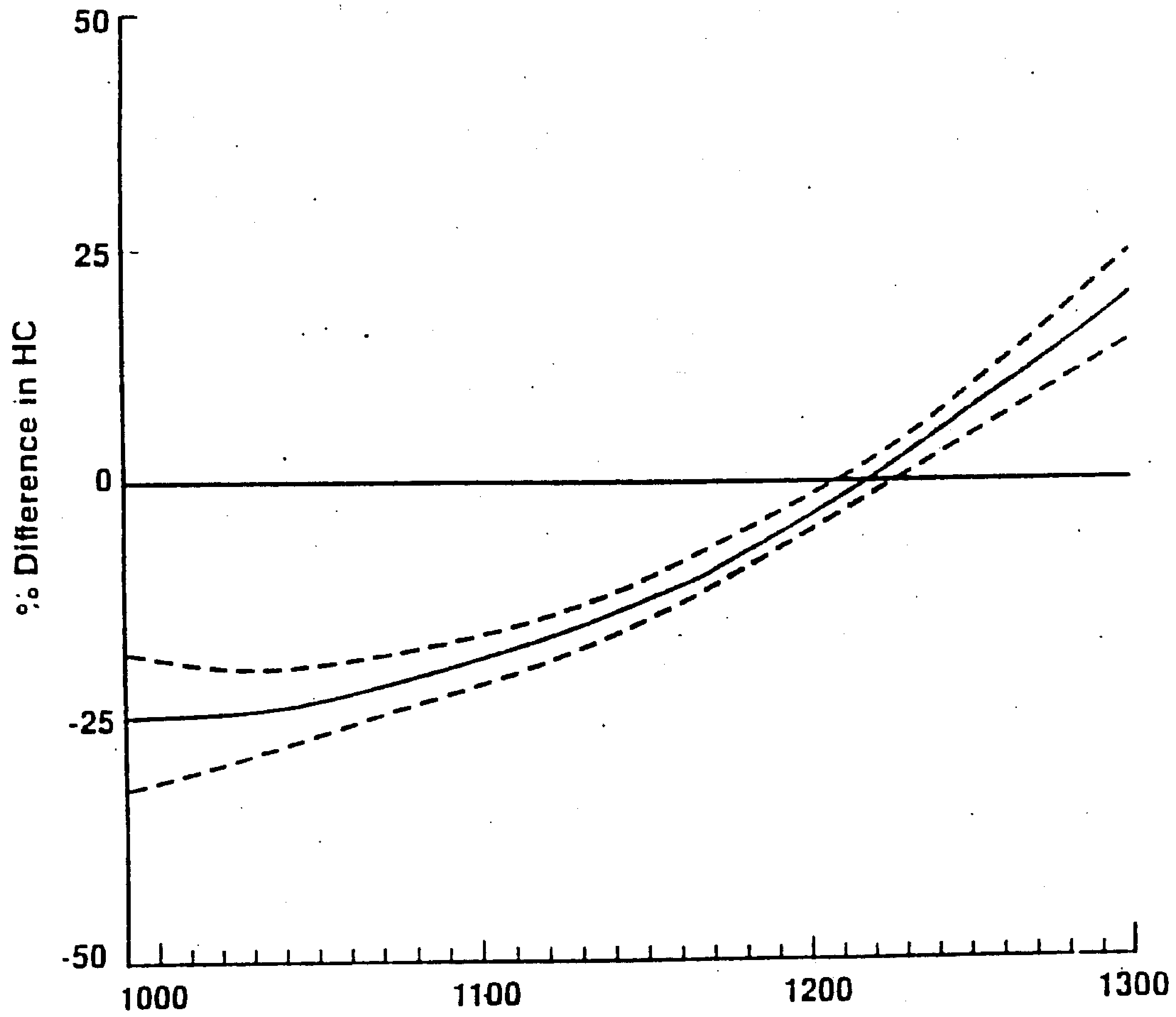
Distillation curve of a typical gasoline

Source: U.S. Dept. of Energy, "Octane Enhancement", July 1985.

The effects of reducing DI on exhaust VOC emissions has also been evaluated by Chevron Research. In a four program study, Chevron has evaluated the effects of DI reductions on different vehicle technologies. They have concluded that DI impacts exhaust emissions by affecting the cold transient phase of the federal test procedure (FTP) but no significant VOC emissions effects were found on the hot-transient phase. This conclusion strengthens the argument that the DI effect on VOC emissions is a cold start, warm-up phenomenon. Chevron's statistical analysis of the data indicated that exhaust volatile organic compounds decreased in a non-linear fashion with decreasing DI down to about 1100. Figure II-11 graphically presents the results of the Chevron study.

Figure II-11

QUADRATIC REGRESSION OF THE AVERAGE PERCENT DIFFERENCE IN FTP HC EMISSIONS BASED ON INDOLENE AND LA AVG WITH 95% CONFIDENCE INTERVALS, FOR ALL THE PROGRAMS COMBINED



Source: SAE paper 910352

The DI can be reduced from the current levels of about 1200 by reducing the T10, T50, and/or T90 distillation temperatures at the same time. Because the proposed RVP limit of 7.0 psi would constrain the front end of the gasoline volatility, it would limit the ability to change T10. Therefore, a refiner would have to reduce the T50 and T90 distillation temperatures to change the DI. The addition of the oxygenates in the fuel will reduce T50 values (Figure II-12) and help refineries in reducing DI, but oxygenates affect only slightly the T90 distillation temperature. To reduce T90, a refinery would need to separate the heavy hydrocarbon streams in the T90 distillation range and exclude them from their gasoline pool. The staff evaluated the benefits of reducing DI and the need for specifying limits on T50 and T90 independent of DI, as well as the possible impacts of such limits on the exhaust emissions. The staff's analyses indicate that specifying limits on T50 and T90 would be sufficient to exercise control over DI and at the same time allow flexibility to gasoline producers.

a. Impacts on Emissions of Changing the T50 Distillation Temperature

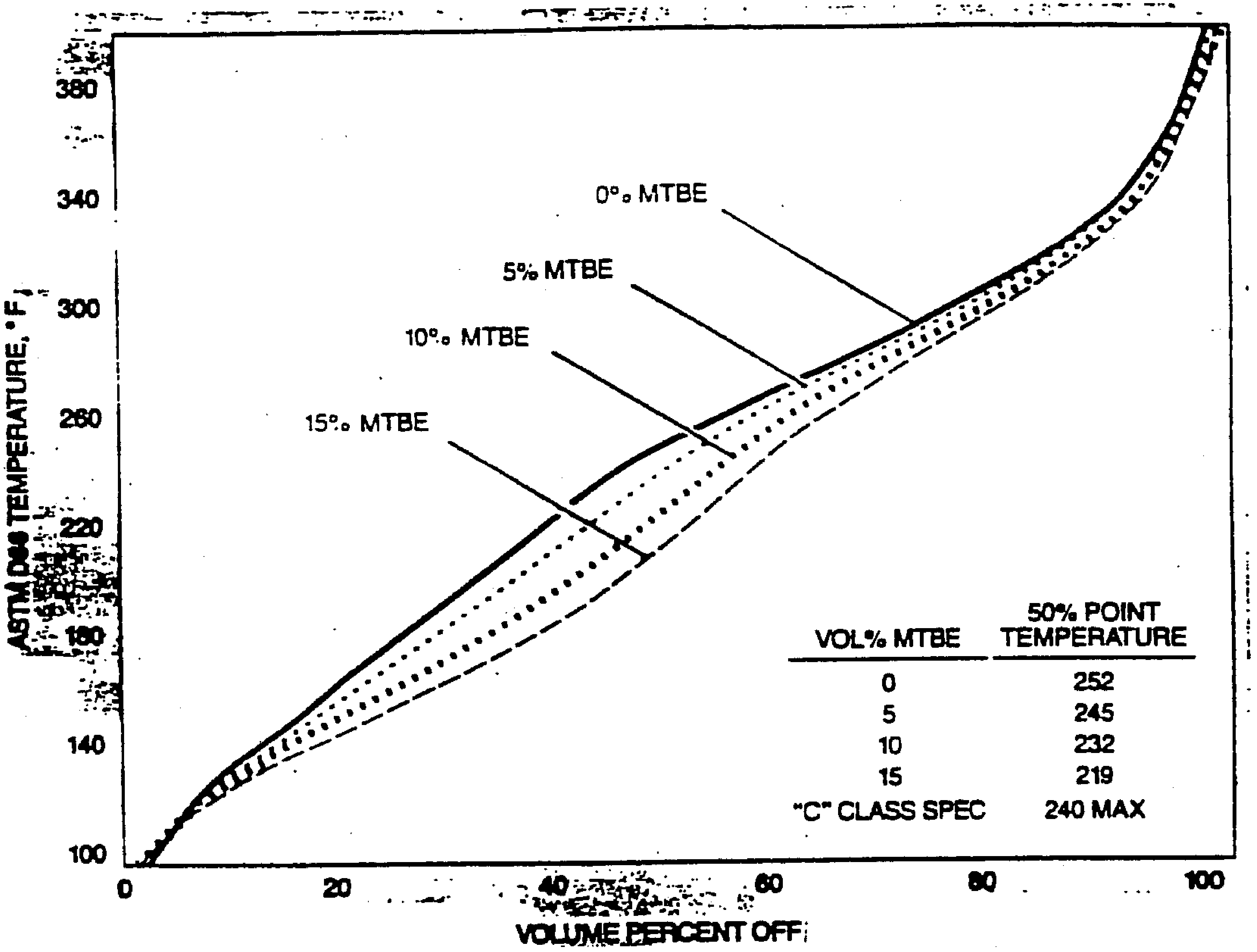
In a experimental set-up, Toyota has looked at the effects of T50 on throttle time response of port-fuel injected engines during the warm-up mode because it is believed that throttle response would affect the emissions performance of the engine. They have found that even an 18°F decrease in T50 makes a significant improvement in throttle response time during the warm-up period. Although, the Toyota data indicate that reducing T50 below 212°F, does not have significant benefits in throttle response time, the emissions test data collected by the same program indicate decreases in VOC emissions as T50 is reduced down to about 190°F (Figure II-13).

In an another study, Unocal Corporation tested an extensive fuel matrix which included T50 as one parameter. The tests were done on a number of post-1980 vehicles, and the study concluded that T50 reductions would result in reductions of both the VOC and carbon monoxide emissions. The results of Unocal's study are shown in Figures II-14 and II-15.

In order to evaluate the sensitivity of emissions to T50 changes, staff have used the Unocal regression equation (See Appendix 11) and assumed a baseline fuel that has Phase 1 gasoline properties. That fuel was evaluated against Phase 2 gasoline with different T50 values. Table II-11 shows the results of staff's sensitivity analysis.

Figure II-12

Distillation Benefits of MTBE in a High Octane, 9 RVP Fuel

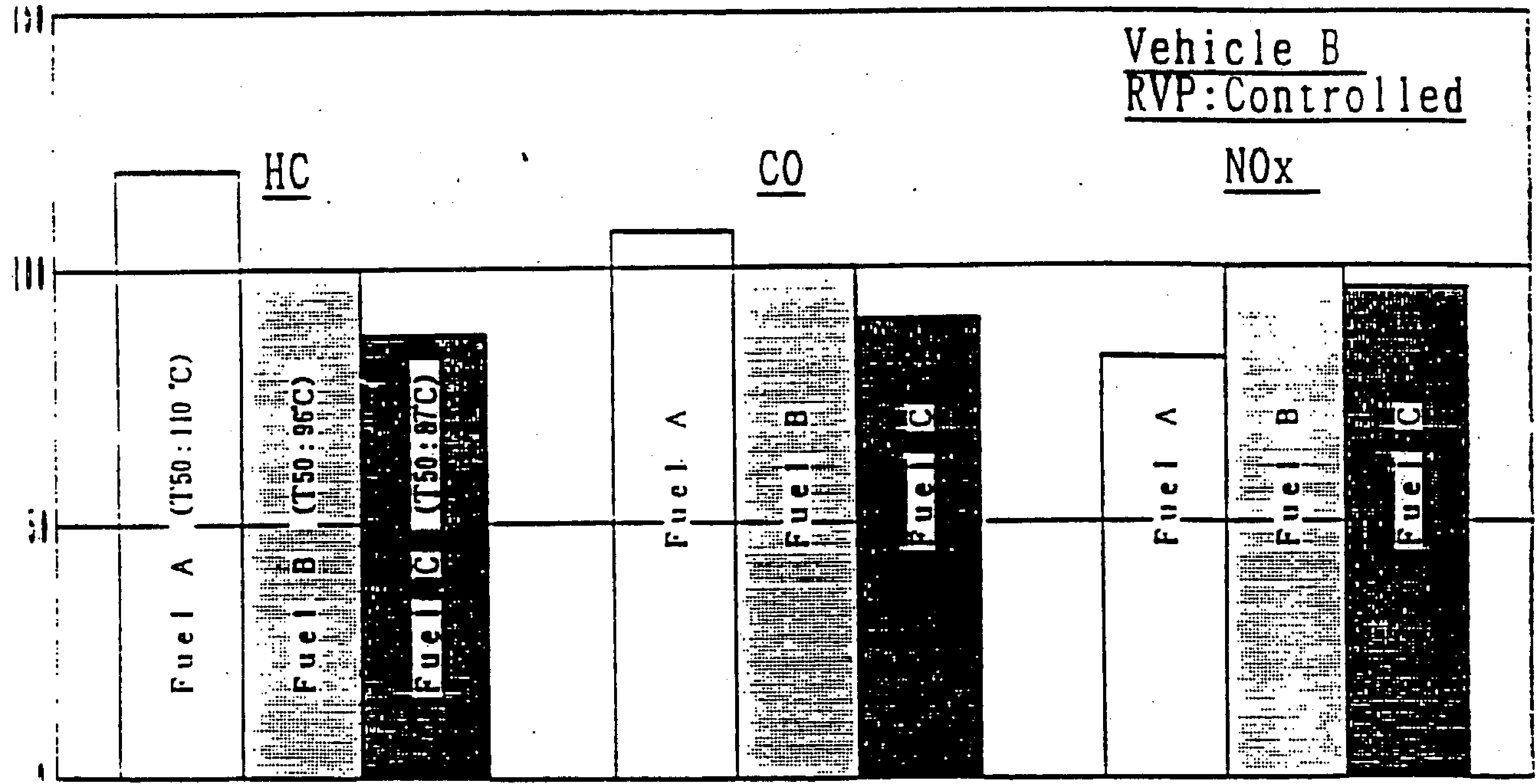


VOL% MTBE	50% POINT TEMPERATURE
0	252
5	245
10	232
15	219
"C" CLASS SPEC	240 MAX

Source: ARCO Chemical, "MTBE Octane Enhancer"

Figure II-13

Effect of T50 on Exhaust Emissions



Effect of T_{50} on Exhaust Emissions (Fuel B=100)

Fuel A T50: 230°F

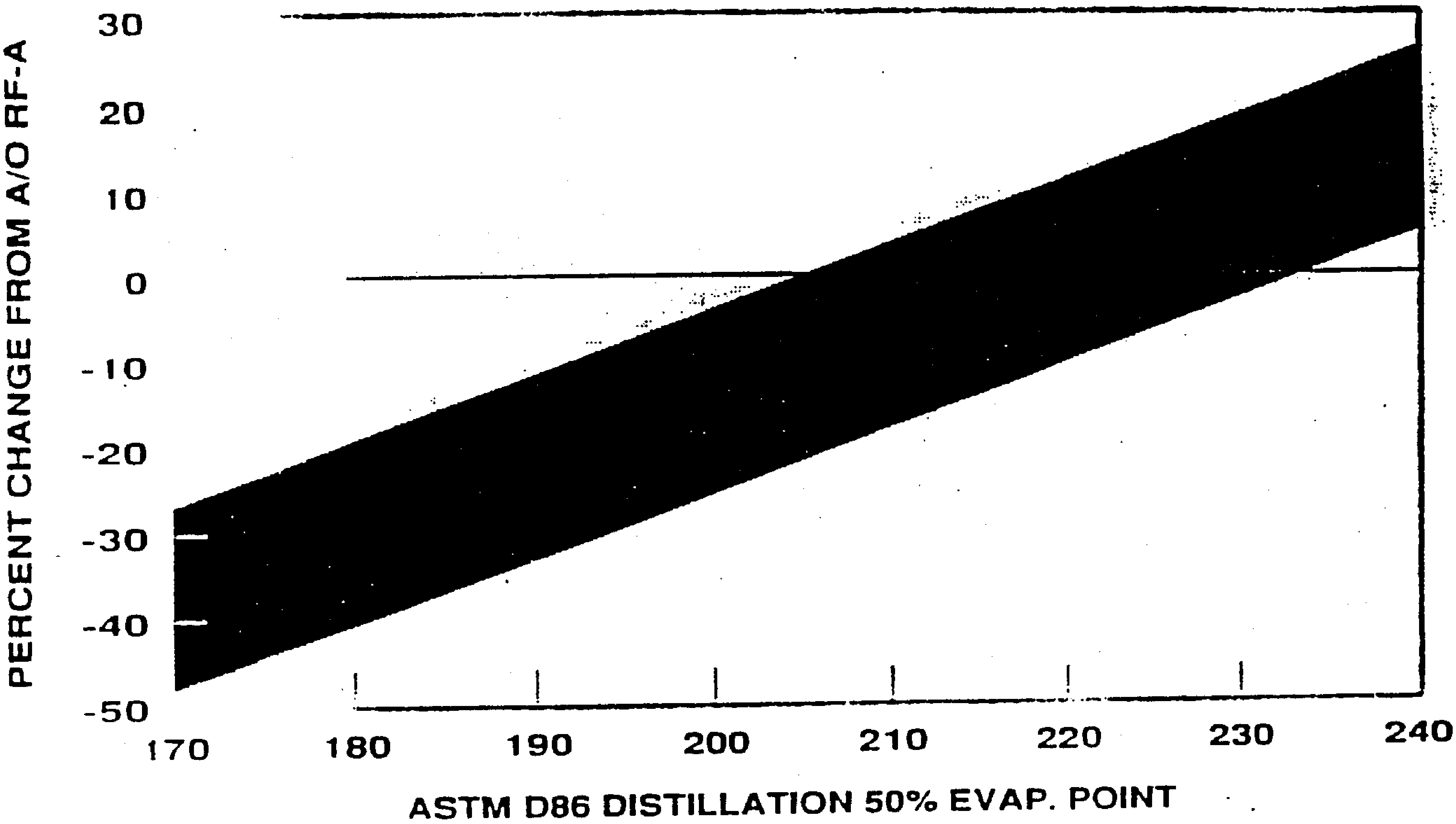
Fuel B T50: 205°F

Fuel C T50: 185°F

Source: Toyota, October, 1990.

Figure II-14

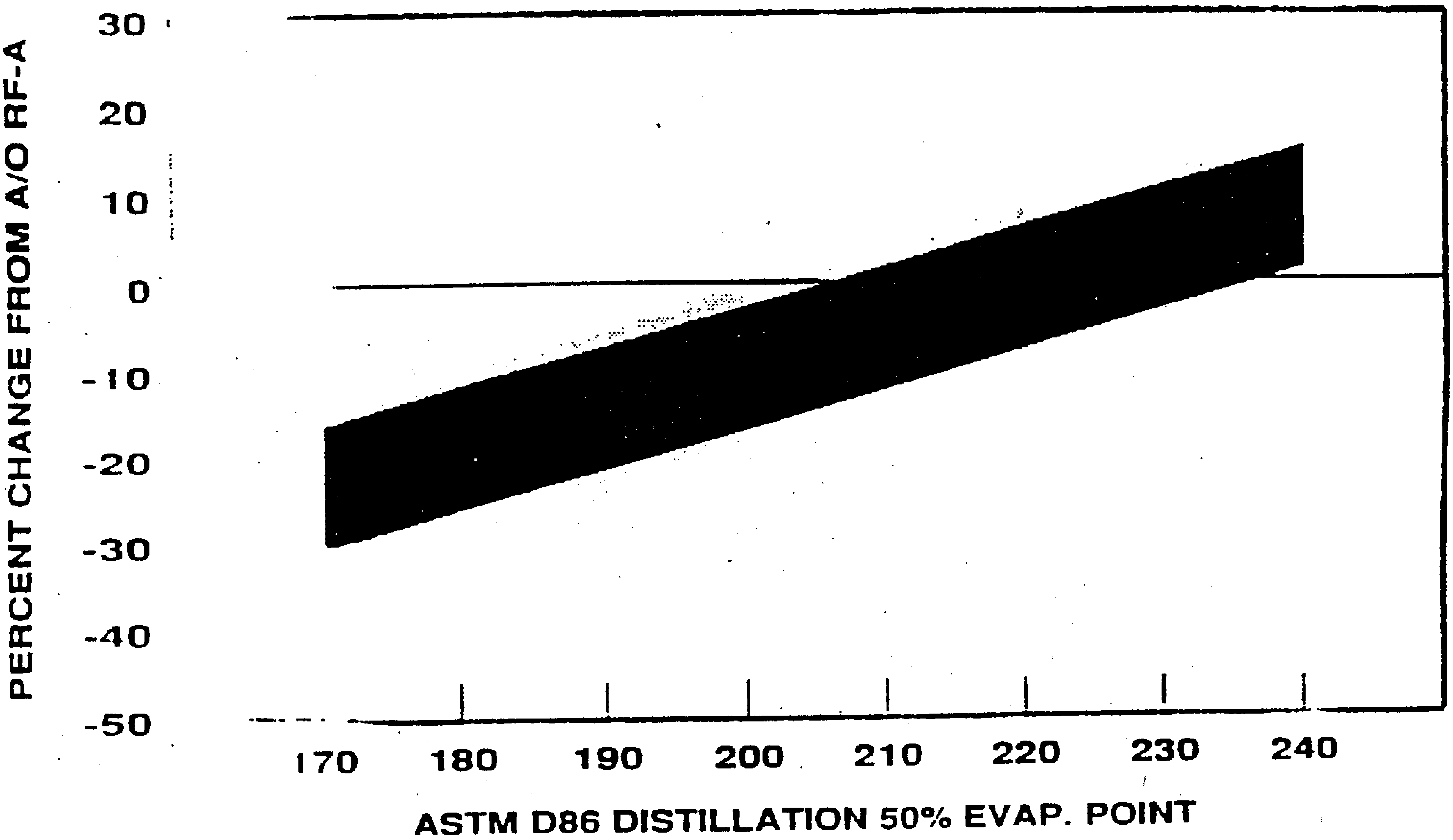
HYDROCARBON EMISSIONS
EFFECTS OF DISTILLATION T_{50}



Source: Unocal

Figure II-15

CO EMISSIONS
EFFECTS OF DISTILLATION T_{50}



Source: Unocal

Table II-11

Sensitivity Analysis of T50 Changes on Exhaust Emissions
Using Unocal Regression

	Percent Emissions Change-Current Vehicles		
T50 (°F)	HC	CO	NOx
240°	+25.8	+13.1	0
230°	+16.6	+ 8.4	0
220°	+ 7.4	+ 3.7	0
210°	- 1.8	- 0.9	0
200°	-11.0	- 5.6	0
190°	-20.3	-10.3	0
180°	-29.5	-14.9	0

Source: ARB/SSD.

The results of the analysis shown in Table II-11 indicate that the proposed standard of 210°F would result in small decreases in VOC and CO emissions from the baseline gasoline which has an average T50 value of 212°F. The proposed standard can be viewed as a cap on the T50 value at the current average level. The staff expects that refiners would have to consider the reproducibility of the test method and therefore have to produce a fuel that has a T50 of about 200°F in order to meet the standards. Staff expects benefits would be about 10 percent for VOC and about six percent for CO could be achieved. An argument can be made of having a standard of about 200°F which would result in an actual T50 value of 190°F with resulting higher VOC and CO emission benefits. However, the staff believes that such a limit would make the front end of the gasoline more volatile, and would make it more difficult and more expensive for the refineries to meet the RVP limit.

b. Impacts on Emissions of Changing the T90 Distillation Temperature

The effects of T90 on exhaust and evaporative emissions cannot be easily isolated from changes in other fuel parameters such as changes in the aromatic hydrocarbons content or the DI. To meet the aromatic hydrocarbon limit, a refinery would implement either volumetric reductions in streams that contribute to the aromatic hydrocarbon content of the gasoline pool such as reformate or reductions in the aromatic HC content in these streams. To reduce the aromatic hydrocarbons would require the treating of the blendstocks that contain aromatic hydrocarbons in order to reduce or separate the aromatic hydrocarbon components. This approach could reduce the heavy aromatic hydrocarbon component of the gasoline pool which would in turn result in reductions of T90 in the gasoline fuel. Conversely, reducing the T90 would require removal from the gasoline pool of components in the T90+ distillation range. Because the heavy aromatic hydrocarbons are in this range, reductions in T90 would create significant changes in aromatic hydrocarbons, especially heavy aromatic hydrocarbons. Because heavy aromatic hydrocarbons have high combustion temperatures and high reactivity, they are an important component of the total aromatic hydrocarbons. Total aromatic hydrocarbons also contribute to both exhaust reactivity and NOx emissions. Reductions of T90 could also be envisioned as reductions in the "back-end" of the gasoline volatility which would make the fuel more volatile, and would improve fuel vaporization and the air-fuel mixing. It is possible that T90 reductions reduce VOC emissions in the exhaust by both improving the fuel vaporization and by reducing species such as heavy aromatic hydrocarbons that have an adverse impact on the reactivity of the exhaust emissions.

The Auto/Oil study has evaluated the impacts of T90 reductions on VOC reactivity and on VOC, CO, and NOx emissions. This study concluded that T90 reductions would result in exhaust VOC emissions reductions for both current and older vehicles but that T90 reductions would have some marginal adverse effects on both CO and NOx emissions. The Auto/Oil work indicated that T90 reductions would benefit exhaust reactivity. The study also found significant interaction effects between T90, olefins, aromatic hydrocarbons, and MTBE content. The Auto/Oil group, in a new program that is starting soon, plan to further investigate the effects of T90.

The staff used the results of the Auto/Oil study and evaluated the impacts of reductions in T90 by conducting a sensitivity analysis on exhaust emissions. The results of staff's analysis for all vehicle groups are shown in Table II-12. Appendix 12 documents the regression equations.

Table II-12 shows the emissions reductions from a baseline gasoline which meets the Phase 1 gasoline specifications to a gasoline that would meet all other Phase 2 gasoline properties but has T90 values which vary from 330°F to 290°F. This analysis indicates that reducing T90 from 330°F, which is the current level of California gasoline, to 300°F would reduce VOC emissions from both the new and older vehicle groups and it would slightly increase NOx and CO.

From the results of the above discussed sensitivity analysis and data available from other studies, it appears that the most appropriate value for T90 is 300°F. Staff expects that refiners, in order to comply with the proposed standard, would need to produce fuel with a T90 of about 290°F. This is a level at which VOC emissions benefits for current vehicles are maximized but NOx and CO increases remain almost neutral. A further reduction in T90 would achieve higher VOC benefits but it would increase NOx and CO emissions.

Table II-12

Sensitivity Analysis of T90 Changes on Exhaust Emissions Using Auto/Oil Regression Equations

Percent Exhaust Emissions Reductions from California Base Fuel

T90 (°F)	Current Vehicles			Older Vehicles		
	HC	CO	NOx	HC	CO	NOx
330°	- 16.4	- 22.7	- 3.0	- 8.8	- 19.1	- 10.5
320°	- 19.8	- 22.4	- 2.1	- 9.7	- 17.6	- 10.2
310°	- 23.0	- 22.0	- 1.2	-10.6	- 16.1	- 10.0
300°	- 26.0	- 21.7	- 0.4	-11.4	- 14.6	- 9.7
290°	- 29.0	- 21.4	+ 0.5	-12.3	- 13.0	- 9.4

Source: ARB/SSD

3. Sulfur

The sulfur present in gasoline has been associated with many negative effects. Before high priority was placed on reducing vehicle emissions, the greatest concerns were related to the corrosive effects of sulfur on engine components. As environmental deterioration became recognized as an important concern and the public became more aware of this damage, reducing the emissions of sulfur dioxide, a precursor to sulfates, particulate matter, visibility reducing particles, and sulfuric acid became a major issue.

In the late 1970's there was a great deal of concern about sulfur dioxide emissions from gasoline motor vehicle engines being converted to sulfates and sulfuric acid by the oxidation catalysts which were then being installed on motor vehicles. The conversion was occurring at high rates because the oxidation catalysts required highly oxidizing atmospheres. With the advent of three-way catalysts, and the lowering of excess air levels, the concern shifted to the effects of fuel sulfur on catalyst activity.

a. Catalyst Deactivation

Catalytic converters consist of substrates coated with active catalyst material, usually platinum, palladium, or rhodium. Two important properties of catalytic converters are high catalyst activity and long catalyst life.

Oxidation catalysts function by oxidizing CO and VOC, and are optimized by setting the fuel mixture to lean, or by adding air after the engine, but before the catalyst. Reduction catalysts are optimized by limiting the excess air, allowing the reduction of oxides of nitrogen. Dual-bed catalyst systems place a reducing bed, where the excess air is limited for reduction of oxides of nitrogen first, followed by air injection and then the oxidizing bed. Three-way catalysts operating with closed loop control systems have proven to effectively decrease CO, VOC, and NOx, and operate in a narrow band of air-fuel ratio around stoichiometric. For the foreseeable future, it is expected that some form of improved three-way catalyst using a closed loop control system will be utilized on gasoline-powered vehicles.

The sulfur in the fuel would produce sulfur species in the exhaust such as hydrogen sulfide, sulfur dioxide, and sulfur trioxide. Formation is dependent upon the equivalence ratio and temperature. Interaction between these species and the exhaust catalyst most likely would induce adsorption and storage of sulfur, especially during lean conditions. It is believed that rich transient conditions would induce decomposition of the sulfur into gaseous phase as hydrogen sulfide.

In a paper presented at the Coordinating Research Council Reformulated Gasoline Workshop of March 26, 1991, Monroe et al, discussed catalytic deactivation of three-way catalysts by sulfur in the fuel. Among their conclusions were that feed sulfur reduces the performance of the catalysts, and that the level of impact is related to the sulfur concentration. The noble metals were found to be poisoned by the sulfur, though catalyst activity was found to recover when sulfur was removed from the feed.

Results of testing for the Auto/Oil study support the above findings. In the Summary of Auto/Oil Air Quality Improvement Research Program, Technical Bulletin No. 2, Effects of Fuel Sulfur Levels on Mass Exhaust Emissions, two fuel sulfur levels were tested in ten 1989 model vehicles. Certification gasoline with a low sulfur content of 49 ppm was used as the base low-sulfur fuel, and di-tertiary-butyl disulfide was added to the above gasoline to create the high sulfur fuel of 466 ppm sulfur. The low sulfur fuel represents the 10th percentile, and the high sulfur fuel the 65th percentile for commercial summertime gasoline. The use of high sulfur fuel increased the average mass exhaust VOC, CO, and NOx emissions 16 percent, 13 percent, and 9 percent, respectively, from the levels experienced when the low sulfur fuel was used. The results were determined to be significant at the 95 percent confidence interval. Decreased catalyst activity was determined by this study to be the cause of the higher emissions experienced with the high sulfur fuel. This conclusion was supported by the fact that no significant differences were found between engine out emissions at the two sulfur levels.

The decrease in catalyst activity was found to be immediately reversible when the use of high sulfur fuel was discontinued and low sulfur fuel was used. The short duration of the test prevents conclusions about the effects of long term high sulfur fuel use on catalyst activity, and the reversible nature of catalyst deactivation from the use of high sulfur fuel. Though the poisoning reactions have been shown to be ultimately reversible, some catalyst "memory" effects have been noted. In Phase II of the Auto/Oil study on sulfur effects, different sulfur compounds will be evaluated as well as multiple concentrations of sulfur, from 50 ppm to 450 ppm.

4. Oxygen Content

The addition of oxygenates in the gasoline fuels is expected to have different effects on exhaust emissions for different vehicles and the effects would depend on the vehicle's fuel control and emissions control system.

Older non-catalyst vehicles run typically lean. The addition of oxygenates in the fuel would further enlean the air-fuel mixture which would result in some carbon monoxide reductions. But the further enleanment of the air-fuel mixture could produce higher VOC emissions because of poor combustion. Open-loop vehicles are usually calibrated to run richer than stoichiometric and enleanment resulting from the presence of oxygenates in the fuel would result in VOC and CO emission reductions accompanied with possible increases in NOx emissions. Closed-loop vehicles are expected to be affected by the presence of oxygenates only when they are operated at open-loop, warm-up, and full power modes. The effect of oxygenates at those times would be similar to the effects on the open-loop vehicles which are VOC and CO emission reductions followed by NOx emission increases. It is believed that at other times, the closed-loop system/adaptive learning vehicles would have the capacity to compensate for stoichiometric differences between oxygenate blends and gasolines. Therefore, the effects of oxygenates on VOC, CO, and NOx emissions would be less pronounced.

Staff also expects that for all catalyst-equipped vehicles and for CO and VOC emissions during warm-up mode, the emission differences between gasolines and oxygenated-blends will be smaller when the exhaust goes through a functioning catalytic system. In the past, the effects of the oxygenates in emissions were pronounced because only small volumes of oxygenates were blended in the fuels. However, in the future, the reformulation of the other properties of gasolines would necessitate the use of oxygenates not only because of their emissions reductions potential but also as gasoline blending components in order to maintain gasoline quality and volumes.

First, the octane rating of gasoline would be affected by the proposed limits on RVP, aromatic hydrocarbons, and olefins content. The proposed RVP limit of 7.0 psi would result in the total elimination of butanes and possible reductions of pentanes from the gasoline pool with the associated loss of octane and volume value. Oxygenates with their high octane values are ideal for replacing butanes lost through RVP reductions. Also, reductions in the aromatic hydrocarbons of the fuel would result in significant reductions in gasoline octane value because aromatic hydrocarbons is the most significant source of octane in the gasoline pool. Table II-13 shows the octane values and RVP of ethers, alcohols, and various other gasoline components.

Figure II-16 also shows the incremental octane gains of adding alcohols and ethers in gasoline fuels. It is apparent from this figure that gasoline octane increases are dependent on the base octane of the gasoline fuel and the lower the base octane value the higher the incremental octane benefits can be achieved by the addition of oxygenates.

Another important benefit of the use of oxygenates in the gasoline fuel is the effect of oxygenates on the gasoline distillation characteristics of the gasoline. Gasoline distillation and especially T50 is important for the emissions performance of the fuel because it is used to control both hot and cold start driveability. The lower the T50 the better the fuel performance will be during cold engine operation. As shown in Table II-14, from all the gasoline blending components used in premium gasolines, only butanes, MTBE, and ethanol have T50 lower than 210°F. The removal of butanes for controlling RVP would necessitate the use of MTBE or ethanol for reducing T50 to the 210°F level.

Table II-13

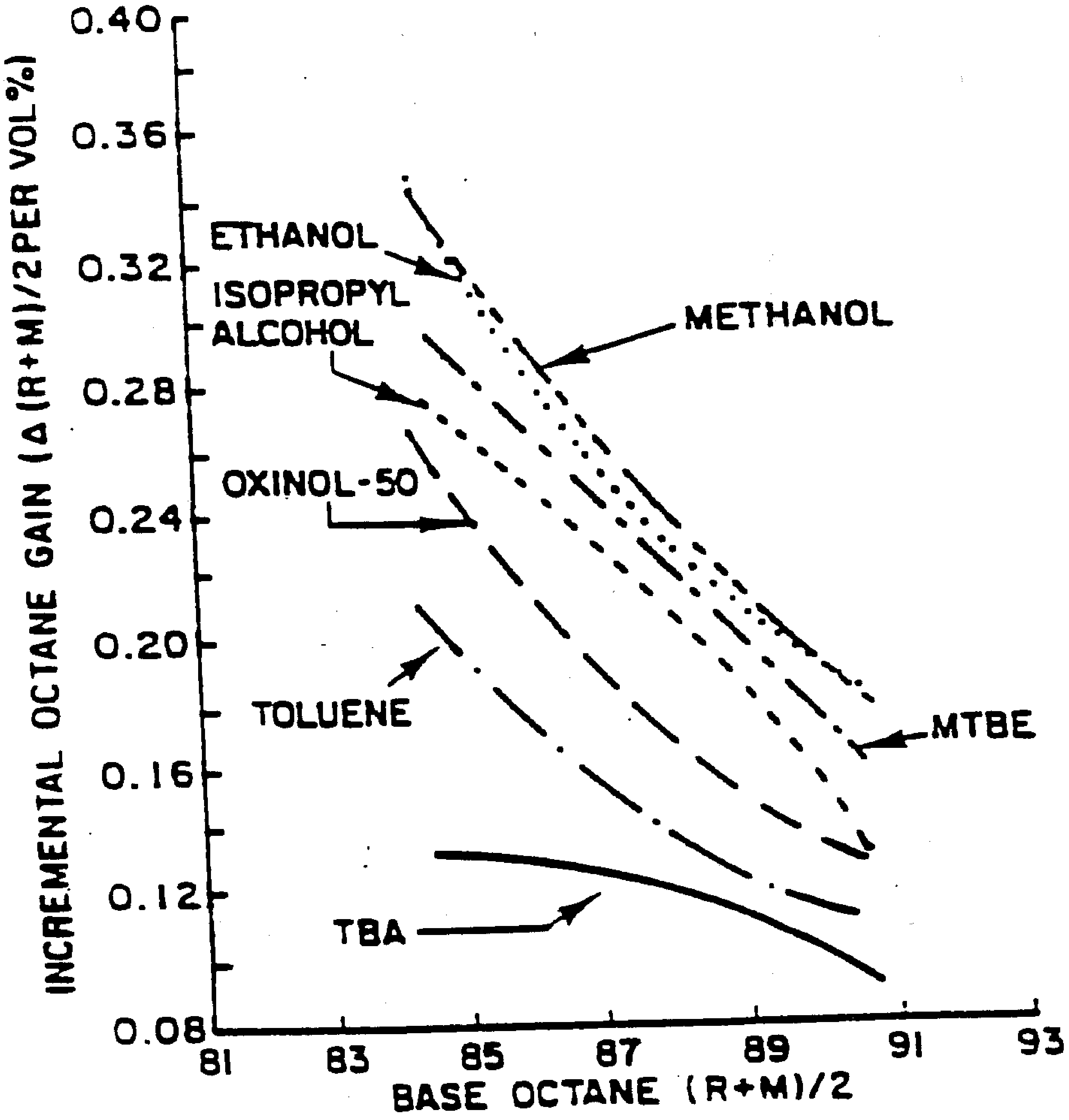
Gasoline Related Properties of Ethers, Alcohols, and Gasoline Components.

	Blending Octane		RVP	Concentration	
	RON	MON	(psi)	Oxygenate Concent. (Vol%)	Oxygen (wt. %)
Ethers					
MTBE	118	102	7.8	11	2.0
ETBE	119	112	4	12.7	2.0
TAME	112	99	1.5	12.4	2.0
Alcohols					
EtOH	120-135	100-106	2.3*	5.7	2.0
MeOH	127-136	99-104	4.6*	4.0	2.0
TBA	109	93	1.8	9.1	2.0
Gasoline Components					
Aromatic HC	104-120	87-100	<5	NA	NA
Paraffins	95-125	79-96	Vary	NA	NA
N-Butane	94-101	87-98	55	NA	NA

Source: W. J. Piel, "Technical Benefits aof MTBE and Other Fuel Ethers", 1989; API Publication 4261; "Gasoline Octane Enhancement", U.S. Dept. of Energy, 1985

Figure II-16

Effect of Base Fuel $\frac{R+M}{2}$ on Incremental Octane Gain for Various Oxygenates.



Source: SAE Paper 861178

Table II-14
Comparison of RVP, Octane, and T50 for Various High Octane Gasoline Blendstocks

Gasoline Blendstocks	Blending Octane $\frac{(R+M)}{2}$	Blending RVP (psi)	T50 (°F)
Reformate	92	5	270°
Heavy Reformate	95.5	2	310°
Alkylate	92	7	225°
Toluene	103	2	230°
Butane	94	55	31°
MTBE	113	8	131°
EtOH	108	2.3	173°
Phase 2 Limits		7.0	210°

Source: W.J. Piel, "Technical Benefits of MTBE and Other Fuel Ethers," 1989, API Publication 4261.

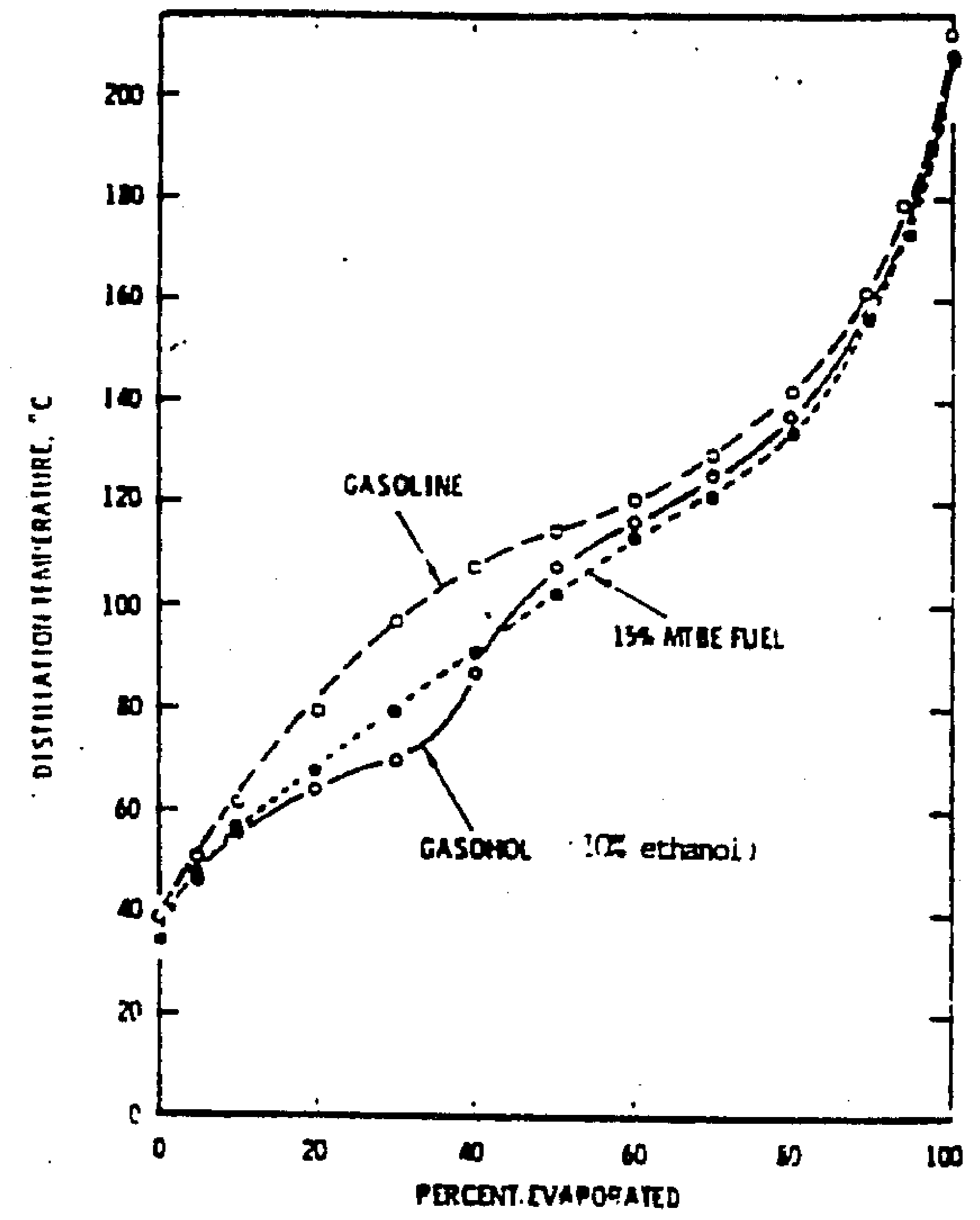
Figure II-17 shows the effects of MTBE and EtOH on the gasoline distillation characteristics. It is apparent that the addition of MTBE, and EtOH produce significant T50 reductions.

However, two important differences exist between MTBE and ETOH, the two types of oxygenates that have been historically used as gasoline blendstocks; their differences in the heat of vaporization and their different effects on RVP. As it is shown in Figure II-18, alcohols together with aromatic hydrocarbons have significantly higher heats of vaporization than ethers, paraffins, or olefins. This means that in a cold engine the heat required to vaporize gasoline fuel containing ethanol is higher than when ethers are present which in effect supercools the air and makes it more difficult to vaporize the higher boiling portion of the fuel. The resulting incomplete vaporization leads to incomplete combustion with higher VOC emissions.

The second notable difference between MTBE and ethanol is their difference on the effects on RVP. Unlike ethers, lower boiling point alcohols such as methanol or ethanol form azeotropes with lower boiling point hydrocarbons, and the azeotropes of hydrocarbons with the alcohols would have a boiling point nearer to that of the pure hydrocarbon. Because of this effect, the addition of alcohols to gasolines would create mixtures that have vapor pressures higher than the vapor pressure of the gasoline portion of the mixture. For example, the addition of 10 percent ethanol to a gasoline fuel could create an increase of about one psi in vapor pressure as measured by the Reid vapor pressure test method.

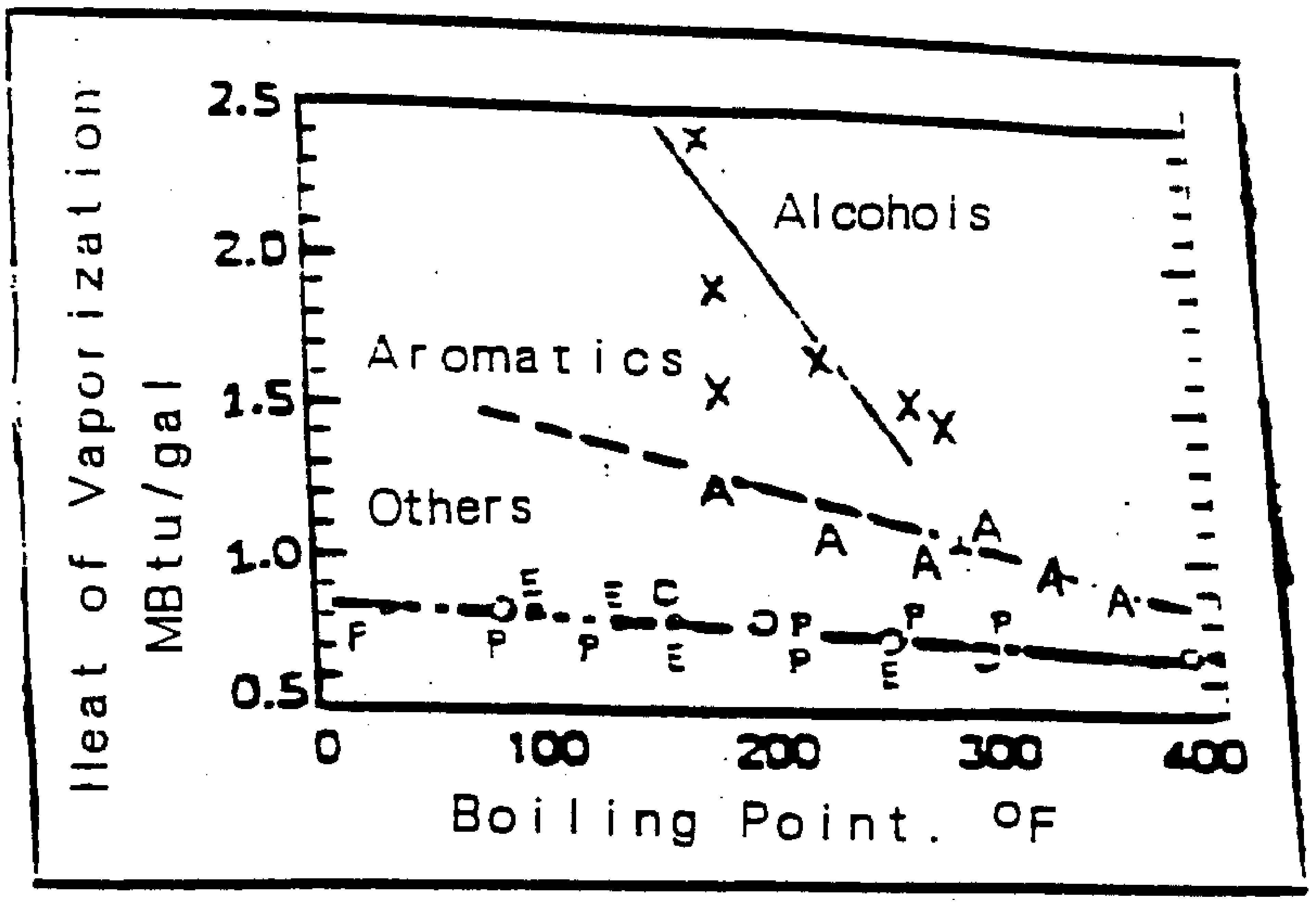
Figure II-17

ASTM Distillation Curves for Three Fuels



Source: SAE paper 800261

Figure II-18. Heat of Vaporization.



Heat of vaporization. Data indentity: X = alcohols; A = aromatics; P = parafins; O = olefins and E = others.

Source: William J. Piel, "Oxygenates for Reformulated Gasoline", 1990

In summary, the addition of oxygenates in the fuel is needed to facilitate meeting the requirements of the reformulated gasoline. The presence of oxygenates in the fuels benefits CO emissions but depending upon concentration and the type of vehicle could result in benefits or disbenefits on VOC and NOx emissions. The different oxygenates are also important because of the different effects on distillation, RVP, and combustion performance.

5. Olefins

Olefins (alkenes) are a class of HC having one or more double bonds which are mostly created by the refining process of cracking napthas or other petroleum fractions at high temperatures. The ARB in the past paid attention to limits on the olefins content of gasoline fuels because olefins have high ozone reactivity potential and contribute to the reactivity of the evaporative and running loss emissions. New information has recently become available on their contribution to exhaust emissions because of the olefins' effects on NOx formation. It is believed that because olefins have combustion temperatures higher than other saturated hydrocarbons their presence in the fuel would contribute significantly to NOx formation.

The importance of olefins on exhaust emissions was evaluated by the Auto/Oil study where olefins was one of the fuel parameters being studied. The results of the Auto/Oil study indicate that olefins reductions from 20 percent to 5 percent result in NOx reductions for both current and older vehicles but in VOC increases for both older and new vehicles. Another study conducted by Unocal Corporation confirmed the Auto/Oil benefits of the olefins reductions. In addition, the results of the Unocal study show some benefits on VOC emissions. An ARCO analysis of the Auto/Oil data confirms the NOx benefits of olefins reductions but contributes it to reductions in C3 - C5 olefins. Olefins with carbon numbers 3 through 5 are the highest reactive olefins of the olefinic species and represent a small component of the gasoline's olefinic pool. The staff has evaluated the impacts of olefins reductions on total exhaust emissions by using the Auto/Oil regressions. The results of the staff's sensitivity analysis of changes in olefins content are shown in Table II-15.

The base gasoline for the analysis shown in Table II-15 is Phase 1 gasoline. The table shows emission changes from the base case gasoline to gasoline fuels that meet the proposed properties of Phase 2 gasoline but have olefin values varying from 15 percent to 5 percent by volume.

The results of the analysis shown in the above table indicates that olefins reductions from the current levels of 10 percent to 5 percent would result in small benefits of NOx emissions for both the current and the older vehicle fleet. Emissions of HC would slightly increase and emissions of carbon monoxide would decrease.

Table II-15

Sensitivity of Exhaust Emissions to Gasoline Olefin Content

Olefins (Vol. %)	Percent Exhaust Emissions Reductions From California Base Case					
	Current Vehicles			Older Vehicles		
	VOC	CO	NOx	VOC	CO	NOx
15	- 27.8	- 21.0	- 2.7	- 14.9	- 12.7	- 5.9
10	- 27.0	- 21.4	- 1.2	- 13.2	- 13.6	- 7.8
5	- 26.0	- 21.7	- 0.4	- 11.4	- 11.4	- 9.7

Source: ARB/SSD

6. Aromatic Hydrocarbons

Aromatic hydrocarbons are hydrocarbons that contain one or more benzene rings and are a significant source of octane in the gasoline pool. Their presence in the fuel has been connected with the formation of NOx, HC, and toxic emissions in the exhaust. Because NOx production in a combustion engine is a time-temperature phenomenon and because aromatics have higher carbon content than other gasoline components, they have higher combustion temperatures. Therefore, their presence could increase engine-out NOx emissions. In addition, higher aromatic hydrocarbons levels in the fuel would result in higher aromatic hydrocarbon levels in the exhaust because the VOC composition of the engine-out emissions follows closely the fuel composition. It is expected that the presence of aromatic hydrocarbons in the exhaust could have an adverse impact on the reactivity of the exhaust emissions because some of the aromatic hydrocarbon components and especially heavy aromatic hydrocarbons (C8 + aromatic hydrocarbons) are highly reactive. However, the effects of fuel aromatic hydrocarbons on the VOC and NOx exhaust emissions could be masked by the presence of the vehicle emission control system. The effectiveness of catalysts on hydrocarbon destruction varies from compound-to-compound. It is possible that aromatic hydrocarbon compounds have different destruction efficiency than other hydrocarbons and therefore tailpipe emissions could be affected differently by different catalytic system technology. Because of these reasons, it is possible that when emissions from different emissions control technology vehicles are examined the effects of the fuel aromatic hydrocarbons on the tailpipe VOC emissions appear different.

Investigators in a number of studies have looked at the effects of fuel aromatic hydrocarbons on exhaust emissions. First, the Auto/Oil study has evaluated the impacts of fuel aromatic changes on two groups of vehicles: Group A which is composed of current technology, and Group B which is composed of older technology vehicles. This study concluded that reductions in fuel aromatic hydrocarbons have a marginal adverse effect on NOx emissions for the new vehicle group but a statistically significant beneficial impact for the older vehicle group. The same study also shows that fuel aromatic hydrocarbons reduction has a weak benefit on VOC emissions for the new vehicle group and an adverse impact for the older vehicle group. However, a very important finding of the Auto/Oil study is that the interaction effects between aromatic hydrocarbons and other fuel parameters such as T90, olefins, or MTBE could reverse or strengthen the benefits of changes in the fuel aromatic hydrocarbons content. The interactions are critically important because from a refinery perspective a reduction in the fuel aromatic hydrocarbons content could also involve significant changes on T90 or the olefins content and could increase the need for the addition of oxygenates in the fuel. The parameter interaction effects are important from the staff's perspective because in order to optimize the fuel's emissions behavior the synergistic effects of changing other fuel properties together with aromatic hydrocarbons must be evaluated.

Second, in a number of studies, the Chevron Corporation (Chevron) has also investigated the emissions effects of changing fuel aromatic hydrocarbons by testing fuels composed of 10 percent, 20 percent, and 30 percent by volume aromatic hydrocarbons on a number of current and older technology vehicles. These studies have also looked at the effect of changes in the distillation characteristics of the fuel in addition to changes in the aromatic hydrocarbons content. In summary, the Chevron studies did not find any statistically significant effect of fuel aromatic hydrocarbons on vehicle exhaust emissions.

A common difficulty in both the Auto/Oil and the Chevron studies arises from the methodology that was used to change the aromatic hydrocarbons levels in the test fuels. In both studies certain aromatic hydrocarbons streams were added or removed to make the necessary fuel changes in an attempt not to affect other fuel properties. However, in a real balanced refinery situation the changes in fuel aromatic hydrocarbons would necessitate other changes in fuel properties which were difficult to incorporate in the design of the Auto/Oil or the Chevron fuels.

In a third study conducted by ARCO, the fuel aromatic hydrocarbons content evaluated as one of the fuel parameters by testing a number of current technology vehicles. The ARCO fuels were made in a balanced refinery configuration where aromatic hydrocarbons reductions were followed by the necessary changes in other fuel properties. The fuels had a low sulfur and olefins content, and incorporated the use of MTBE. The ARCO generated fuels evaluated the fuel aromatic hydrocarbons levels of about 10 percent, 20 percent, and 30 percent by volume at two different Reid vapor pressure (RVP) levels. The results of this study indicate that the aromatic hydrocarbons reduction combined with changes in other fuel properties could result in significant reductions of VOC, CO, and NOx emissions. ARCO staff has also evaluated the Auto/Oil data and developed their own correlations which are different from the Auto/Oil correlations and which indicate that aromatic hydrocarbons and especially heavy aromatic hydrocarbons have a significant impact on carbon monoxide and VOC emissions.

The staff evaluated the effects of different levels of fuel aromatic hydrocarbons by using the results of the Auto/Oil and the ARCO study on a combined emissions analysis for both the older and the new vehicles. The results of the staff's sensitivity analysis are shown in Table II-16.

Table II-16

Sensitivity of Exhaust Emissions to the Aromatic Hydrocarbon Content in the Fuel

Aromatic	Percent Emissions Reductions from a Base Case California Fuel					
	Current Vehicles			Older Vehicles		
Hydrocarbons(%)	VOC	CO	NOx	VOC	CO	NOx
35	- 23.1	- 17.0	- 2.1	- 18.3	- 14.6	- 5.4
30	- 24.6	- 19.4	- 1.2	- 14.9	- 14.6	- 7.6
25	- 26.0	- 21.7	- 0.4	- 11.4	- 14.6	- 9.7
20	- 27.5	- 24.0	+ 0.5	- 7.8	- 14.6	-11.8
15	- 28.9	- 26.3	+ 1.4	- 4.1	- 14.6	-13.8

Source: ARB/SSD

The staff's aromatic hydrocarbons sensitivity analysis shown in Table II-16 assumes a California baseline fuel that complies with the Phase 1 regulatory criteria and compares it with other fuels which have the proposed Phase 2 Reformulated Gasoline properties but the aromatic hydrocarbons levels varies from 35 percent to 15 percent by volume. Current California gasolines have an average aromatic hydrocarbons level of about 32 percent by volume. The staff's analysis indicates that the effect of aromatic hydrocarbons reductions on emissions would depend upon the type of vehicle. It appears that in older vehicles, the aromatic hydrocarbons reductions could have NOx benefits and adverse impacts on VOC. In the current vehicles, the aromatic hydrocarbons reductions would achieve overall reductions in the VOC and small increases in NOx.

III.

EMISSION BENEFITS FROM REDUCING CRITERIA POLLUTANTS

In a single measure, the proposed California Phase 2 reformulated gasoline specifications will achieve significant reductions in emissions of volatile organic compounds, oxides of nitrogen, carbon monoxide, and sulfur dioxide. These emission reductions will be obtained by reducing exhaust and evaporative emissions from on-road mobile sources. Additional reductions will be achieved by reducing evaporative emissions from other mobile sources and petroleum marketing operations. The proposed specifications also will reduce the reactivity of emissions.

In the first year of implementation, staff estimates that the Phase 2 gasoline specifications will reduce emissions from gasoline-powered motor vehicles by about 15 percent for volatile organic compounds, six percent for oxides of nitrogen, 17 percent for carbon monoxide, and 80 percent for sulfur dioxide. Staff estimates that there will be about a six percent reduction in evaporative emissions of volatile organic compounds from other mobile sources, and a 12 percent reduction in evaporative emissions of volatile organic compounds from petroleum marketing operations. Overall, in the first year of implementation, the Phase 2 gasoline specifications will reduce volatile organic compound emissions from all sources by four percent, oxides of nitrogen emissions by about two percent, and carbon monoxide emissions by about 10 percent.

This Chapter presents the technical basis for projecting the emission reductions of volatile organic compounds, oxides of nitrogen, carbon monoxide, and sulfur dioxide from the use of California Phase 2 reformulated gasoline.

A. EMISSION REDUCTIONS FROM ON-ROAD GASOLINE-POWERED MOTOR VEHICLES

1. Methodology

In summary, staff used the following methodology for determining the reductions in emissions of volatile organic compounds, oxides of nitrogen, and carbon monoxide that will result from the use of Phase 2 reformulated gasoline.

Step 1. Separate the light duty passenger cars and trucks into vehicle model year groups that reflect a dominant emission control technology. Medium duty and heavy duty trucks are included but are categorized simply as non-catalyst or catalyst-equipped vehicles.

Step 2. For the groups of vehicles in any given year, calculate the emission rates for running exhaust emissions, cold start exhaust emissions, hot start exhaust emissions, hot soak evaporative emissions, diurnal evaporative emissions, and running losses.

Step 3. Determine the vehicle activities of each vehicle group. Vehicle activity is represented by vehicle miles travelled (VMT), number of cold start trips, and number of hot start trips, and is used to calculate the amount of running exhaust emissions, cold start emissions, hot start emissions, hot soak evaporative emissions, diurnal evaporative emissions, and running losses.

Step 4. Determine the baseline emissions for the vehicle groups.

Step 5. For the different vehicle groups, calculate emission reduction factors for total exhaust and total evaporative emissions.

Step 6. Calculate emission reductions.

The following discussion presents the detailed information.

a. Step 1-Breakdown of the Vehicle Groups

The vehicle fleet of any particular year is separated into groups according to model years. The selection of the vehicle groups is based on the prevalent vehicle emission control technology. For the purpose of this analysis, the vehicle fleet is separated into the following groups:

Non-Catalyst	Without catalytic converters
1975 - 1980	Open loop oxidizing catalyst
1981 - 1985	Early closed loop three way catalyst
1986 - 1990	Current closed loop three way catalyst
1991 - 1995	Closed loop three way catalyst
Post 1995	Includes vehicle certified on Phase 2 reformulated gasoline and low emission vehicles

b. Step 2-Determine Baseline Emission Factors

The baseline emissions factors are calculated with the EMFAC7EP emission model. For different vehicles and different vehicle activities, EMFAC7EP calculates a set of emission factors for volatile organic compounds, oxides of nitrogen, and carbon monoxide. An emission factor is an estimate of the rate at which a pollutant enters the atmosphere per unit of activity (e.g. miles driven).

EMFAC7EP produces emission factors that take into account the implementation of California phase 1 gasoline, low emission vehicles, the new evaporative emission test procedure, and the reclassification of medium duty vehicles.

The types of emission factors produced by EMFAC7EP are listed below:

<u>Exhaust Emission Factors</u>

- Running Exhaust Emission Factors

  The running exhaust emission factor is expressed in grams per mile. Running exhaust emission factors for volatile organic compounds, oxides of nitrogen, and carbon monoxide are determined at an ambient temperature of 75 degrees Fahrenheit (^{o}F) and various speeds. Temperature factors are used to adjust the running emission factors for ambient temperatures other than 75^{o}F. These emission factors vary with vehicle speed and apply after the vehicle is warmed up and in a stabilized mode of operation. Running exhaust emissions includes emissions emerging from the tailpipe or through the crankcase as engine blowby.

- Cold Start Emission Factors

  The cold start emission factor is expressed in grams per trip. Cold start emissions occur from the time the engine starts, in the cold start mode, until it is fully warm. Cold start mode occurs after a long engine-off period, one or more hours for a catalyst equipped vehicle and four or more hours for a non-catalyst equipped vehicle.

o Hot Start Emission Factors

The hot start emission factor is expressed in grams per trip. Hot start emissions occur after a short engine-off period, less than one hour for a catalyst equipped vehicle and less than four hours for a non-catalyst equipped vehicle.

Both the cold start and hot start emission factors are modeled in EMFAC as being the emissions that are in excess of the emissions that would occur if the vehicle was driven in the warmed-up condition over a distance of 3.59 miles at an average speed of 25.6 mph.

<u>Evaporative Emission Factors</u>

Emission factors are needed for hot soak losses, diurnal losses, and running losses. These emission factors are described below.

o. Hot Soak Emission Factors

The hot soak emission factor is expressed in grams per trip, the trip having any speed or length. Hot soak emissions are losses of gasoline vapor from the vehicle after the vehicle's engine has been turned off at the end of a trip. Hot soak emissions originate primarily from the vehicle's fuel system and occur immediately after the engine is turned off. In older vehicles with carburetors, gasoline in the carburetor bowl vaporizes due to the temperature increase in the carburetor. The introduction of fuel-injected vehicles into the California market in place of carbureted vehicles in recent years has resulted in reduced hot soak emissions from newer cars.

Hot soak testing is currently performed at an ambient temperature between 68°F and 86°F. The ARB's newly-adopted evaporative procedure will require hot soak testing to be performed at 105°F.

o Diurnal Emission Factors

The diurnal emissions factor is expressed in grams per vehicle per day. Diurnal emissions are evaporative emissions resulting from the daily changes in the ambient temperature. In a partially-filled fuel tank, the air-fuel mixture expands and gasoline vapor is released into the atmosphere.

Currently, the test procedure for diurnal emission incorporates a single 60-84°F heat build following a cold soak. This diurnal test is performed over a one hour period during which the fuel tank is heated, simulating a linear ambient air temperature excursion. The new ARB test procedure requires:

- Real time diurnal testing to be performed over three days consisting of three 24-hour cycles.

- Diurnal heating to be performed by heating the ambient air in the shed rather than by heating the fuel in the tank.

- A diurnal heat build of 65-105°F during each cycle followed by a cool down period of 12 hours.

o Running Loss Emission Factors

The emission factor for running losses is expressed in grams per mile. Running losses are evaporative emissions that occur due to gasoline vaporization while the vehicle is operating. The losses occur as the vehicle's fuel tank temperature increases during operation. Test data indicate that running losses can account for a significant portion of vehicular evaporative emissions.

The new evaporative test procedure requires that the running loss testing be performed at an ambient temperature of 105°F.

c. Step 3-Determine Vehicle Activity

The activities of a vehicle define how the vehicle is operated. The activities of a vehicle are separated into vehicle miles travelled (VMT) per day, number of daily trips, number of cold trips, and number of hot trips. To determine the emissions by any given group of vehicles, it is necessary to know the activities of the vehicle groups. The ARB uses aggregated activity data and pro-rate the contribution of each model year by weighting the fraction of each activity by model year through EMFAC's composite emission factor. Thus, the emission factor accounts for a certain fraction of each activity and when multiplied by the aggregated activity for a vehicle class the emission inventory for that activity category is produced.

d. Step 4-Determine the Baseline Emissions

Baseline emissions are defined as those emissions from vehicles operating on Phase 1 reformulated gasoline. Baseline emissions of a particular group or fleet of vehicles in any given area are estimated by multiplying the activities of the vehicles in the area by their emission factors. For example, the running exhaust emissions of a group of vehicles are determined by multiplying its EMFAC7EP running emission factor by its daily VMT. The ARB determines the baseline emissions for different areas in the state using the BURDEN computer model.

The baseline emissions are determined for the fleets of light duty vehicles, medium duty vehicles, and heavy duty vehicles in the years 1996, 2000, 2005, and 2010.

For the purposes of this analysis, staff has relied on the ozone planning inventory. The ozone planning inventory for motor vehicle emissions is designed for those areas of the state that are not in attainment of the state ambient air quality standard for ozone. The ozone planning inventory has been developed for most of California, since most areas are not in attainment of the ozone ambient air quality standard. The ozone planning emission inventory is based on the temperature of the ten worst air quality days over the last three years.

e. Step 5-Calculate Emission Reduction Factors

An emission reduction factor is the ratio of the amount of emissions reduced from the baseline emissions to the baseline emissions. For the purpose of this analysis, staff have developed emission reduction factors for composite exhaust emissions, hot soak evaporative emissions, diurnal evaporative emissions, and running loss evaporative emissions for each vehicle group listed in Step 1, except for the post 1995 vehicles. Staff assumed that past-1995 vehicles will be certified on Phase 2 gasoline; therefore, no credit will be taken for reductions from these vehicles.

f. Step 6-Determination of Emission Reductions

The reductions in emissions from each of the vehicle groups, for each pollutant, are determined by multiplying its baseline emission inventory by its emission reduction factor. The total emissions reductions are calculated for the fleet by summing the individual group reductions.

2. Emissions Inventory of On-road Gasoline-Powered Motor Vehicles

The ozone planning inventory has been produced by separating listing emissions for exhaust emissions of volatile organic compounds, oxides of nitrogen, and carbon monoxide, and evaporative emissions of volatile organic compounds. The evaporative emissions are separated into hot soak emissions, diurnal emissions, and running loss emissions. The ozone planning inventory for light duty vehicles, medium duty vehicles, and heavy duty vehicles for all nonattainment areas and the South Coast Air Basin are presented in Tables III-1, III-2, and III-3 for the years 1996, 2000, 2005, and 2010.

For light duty cars and trucks within each of the nonattainment areas, staff have classified the inventories for each year according to the dominant vehicle technology group. Figures III-1 through III-3 graphically show how emissions of volatile organic compounds, oxides of nitrogen, and carbon monoxide change over time as a function of the dominant emission control technology. The figures show that the dominant vehicle class in the year 1996 are the vehicles equipped with closed loop three way catalysts represented by vehicles produced in the 1986 to 1995 time frame. However, earlier model year vehicles still are a significant source of emissions, accounting for about 40 percent of the emissions of volatile organic compounds, oxides of nitrogen, and carbon monoxide.

Table III-1

Summary of Emissions From Light Duty Vehicles Based on the Ozone Planning Inventory

Area/Pollutant	Emissions (tons/day) 1996	2000	2005	2010
<u>All Nonattainment Areas</u>				
Carbon Monoxide	6,454	5,145	4,005	3,299
Oxides of Nitrogen	611	514	391	308
Volatile Organic Compounds				
Exhaust VOC	434	323	211	128
Evaporative VOC				
Hot Soak	78	55	38	26
Diurnal	60	47	28	13
Running Loss	32	19	10	5
Total VOC	603	445	287	172
<u>South Coast Air Basin</u>				
Carbon Monoxide	2,647	2,132	1,666	1,389
Oxides of Nitrogen	246	210	162	130
Volatile Organic Compounds				
Exhaust VOC	183	138	92	58
Evaporative VOC				
Hot Soak	30	21	15	10
Diurnal	22	18	11	4
Running Loss	15	10	5	17
Total VOC	250	187	122	75

Source: Ozone Planning Inventory, ARB, 1990

Table III-2

Summary of Emissions From Medium Duty Trucks Based on the Ozone Planning Inventory

Area/Pollutant	Emissions (tons/day) 1996	2000	2005	2010
All Nonattainment Areas				
Carbon Monoxide	486	405	371	339
Oxides of Nitrogen	77	77	80	83
Volatile Organic Compounds				
Exhaust VOC	46	38	31	24
Evaporative VOC				
Hot Soak	5	3	2	2
Diurnal	4	3	2	2
Running Loss	2	1	1	0
Total VOC	57	45	36	28
South Coast Air Basin				
Carbon Monoxide	190	161	150	138
Oxides of Nitrogen	30	30	32	34
Volatile Organic Compounds				
Exhaust VOC	19	16	13	11
Evaporative VOC				
Hot Soak	2	1	1	1
Diurnal	1	1	1	0
Running Loss	1	1	0	0
Total VOC	23	19	15	12

Source: Ozone Planning Inventory, ARB, 1990

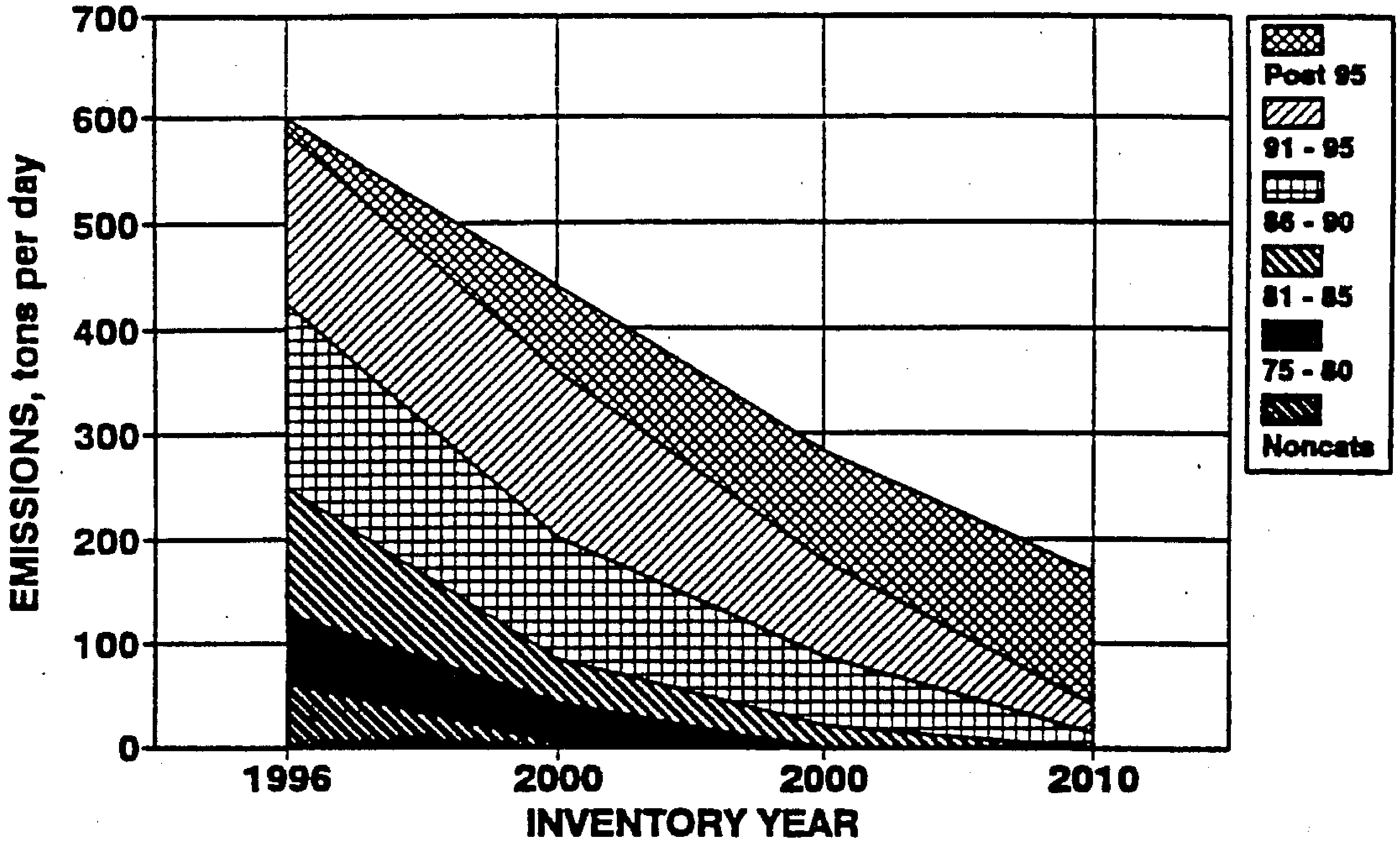
Table III-3

Summary of Emissions From Heavy Duty Trucks Based on the Ozone Planning Inventory

Area/Pollutant	Emissions (tons/day) 1996	2000	2005	2010
All Nonattainment Areas				
Carbon Monoxide	767	545	440	337
Oxides of Nitrogen	160	142	140	138
Volatile Organic Compounds				
Exhaust VOC	30	25	22	18
Evaporative VOC				
Hot Soak	6	6	6	6
Diurnal	3	2	2	3
Running Loss	0	0	0	0
Total VOC	39	33	30	27
South Coast Air Basin				
Carbon Monoxide	313	226	186	145
Oxides of Nitrogen	60	52	50	49
Volatile Organic Compounds				
Exhaust VOC	14	12	10	9
Evaporative VOC				
Hot Soak	2	2	2	2
Diurnal	1	1	1	1
Running Loss	0	0	0	0
Total VOC	17	15	13	12

Source: Ozone Planning Inventory, ARB, 1990

Figure III-1


TREND OF VOC EMISSIONS FROM LIGHT DUTY VEHICLES
OZONE PLANNING INVENTORY FOR ALL NONATTAINMENT AREAS

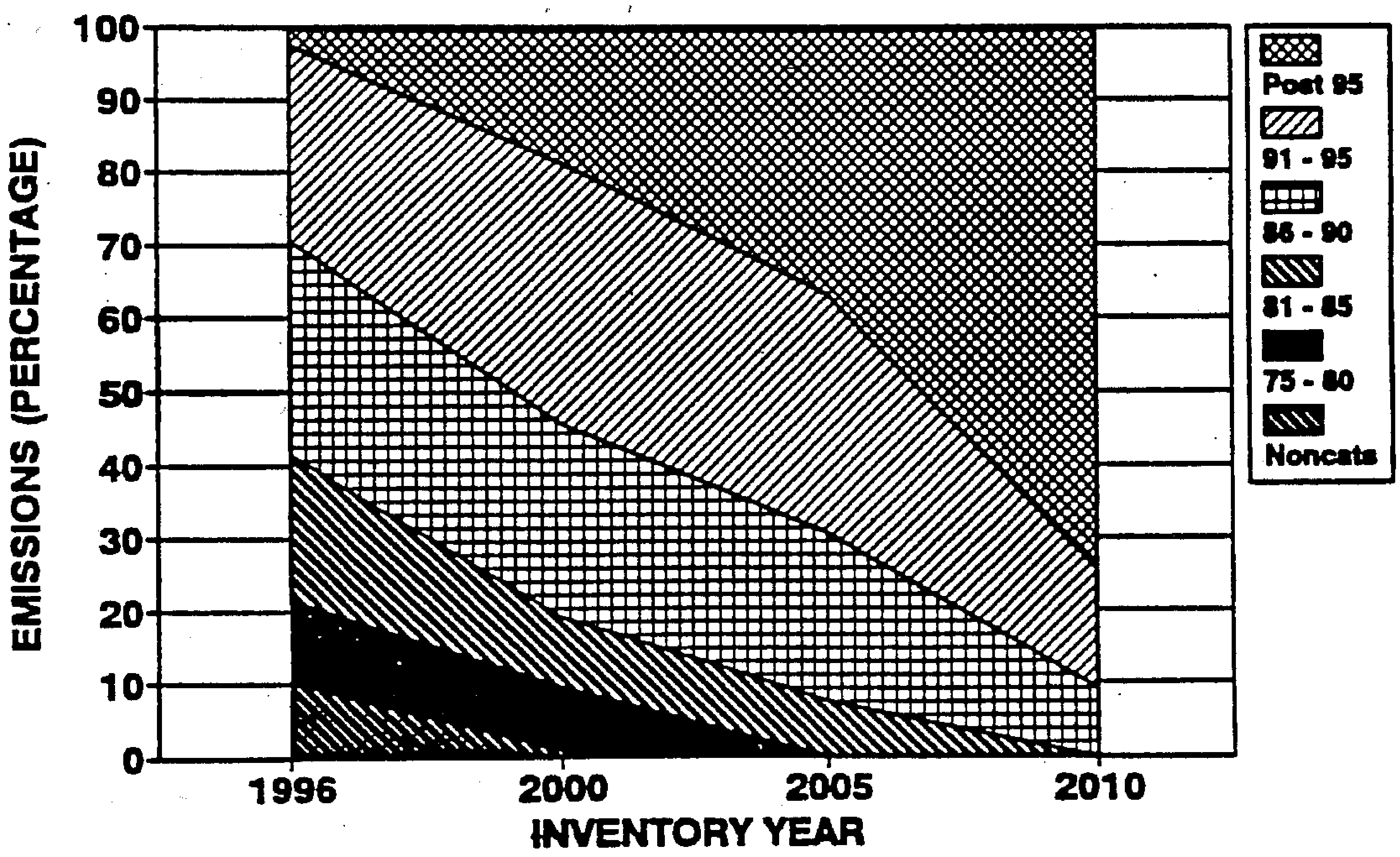
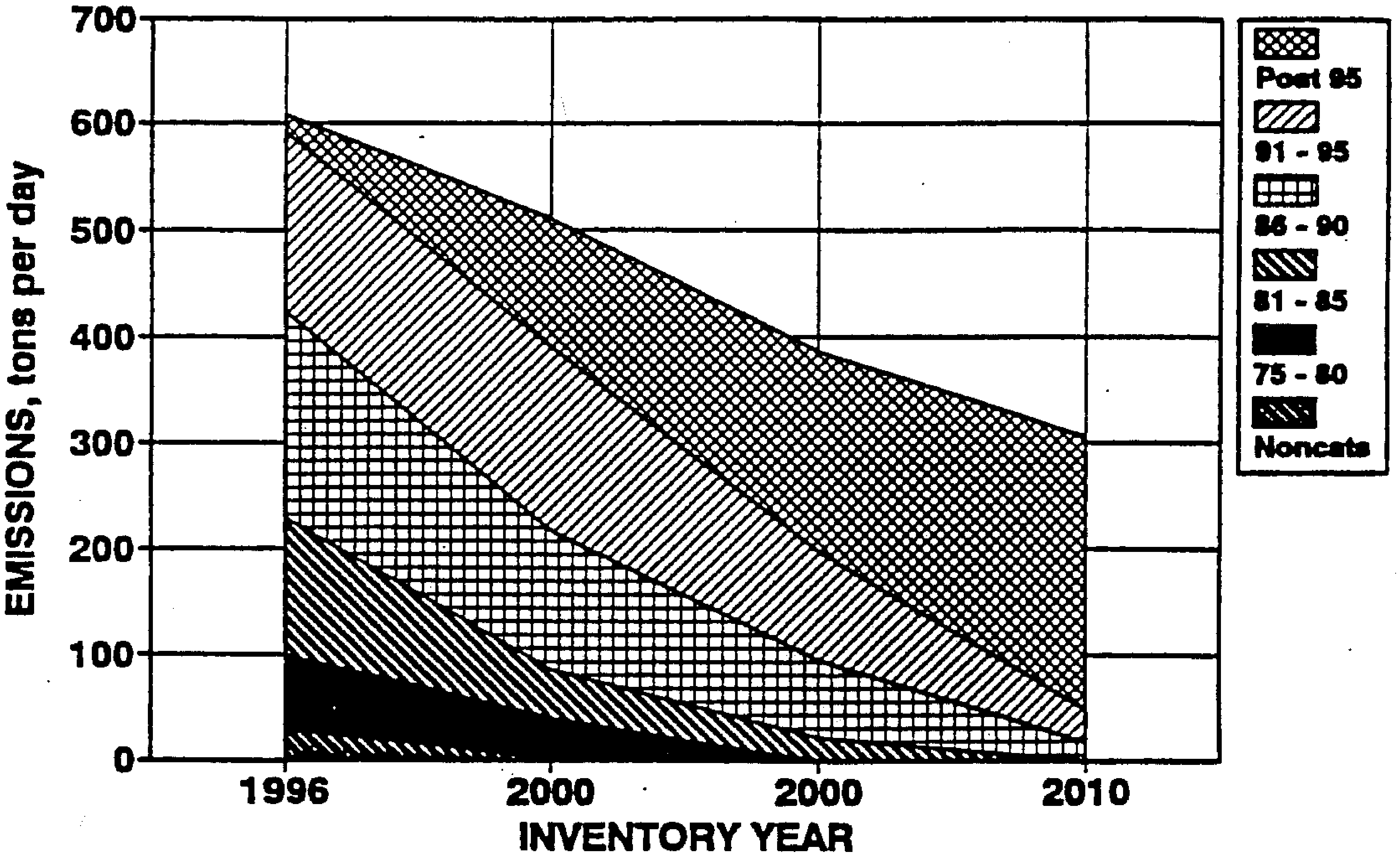
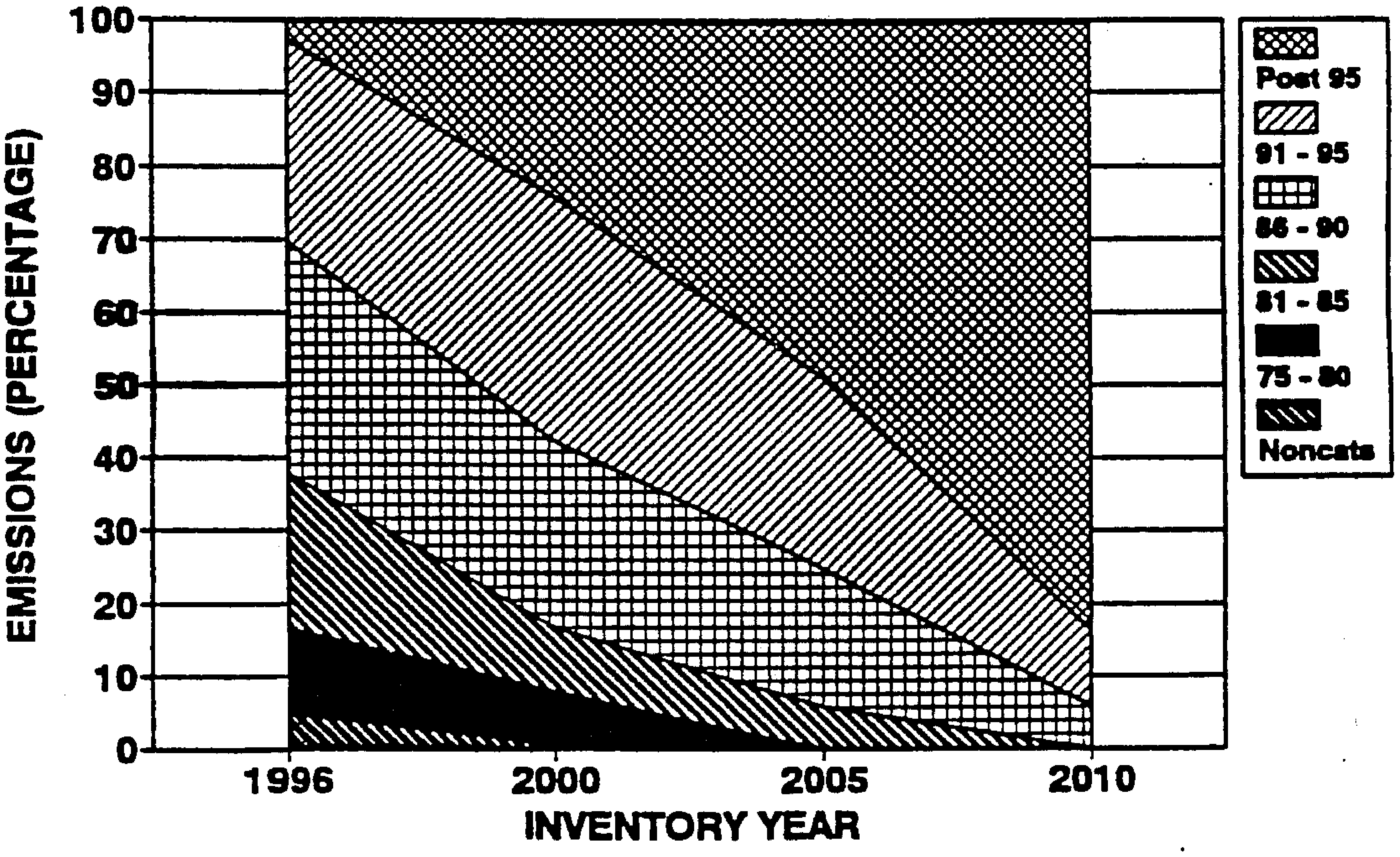

PERCENTAGE OF VOC EMISSIONS FROM LIGHT DUTY VEHICLES
OZONE PLANNING INVENTORY FOR ALL NONATTAINMENT AREAS

Figure III-2



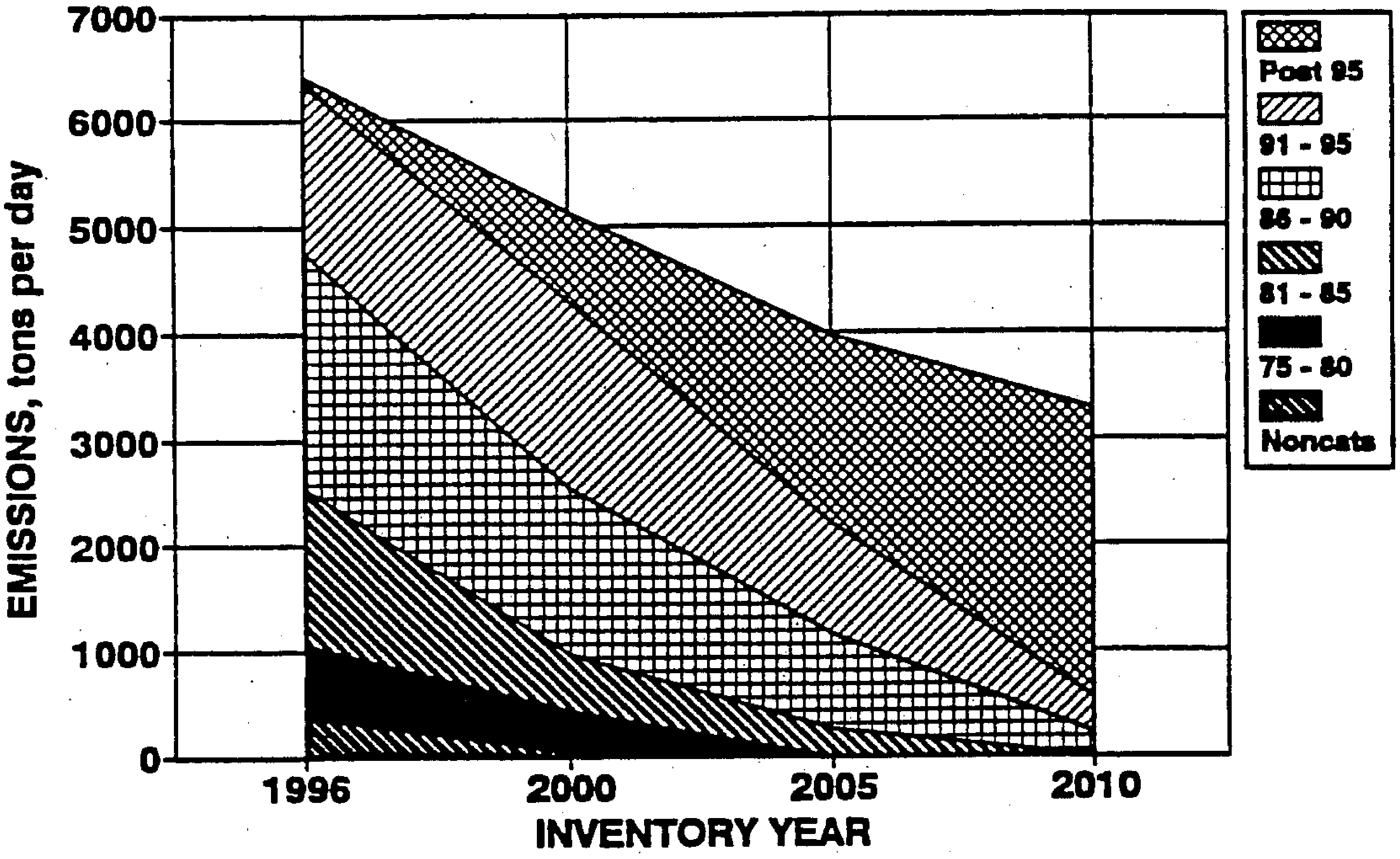
TREND OF NOx EMISSIONS FROM LIGHT DUTY VEHICLES
OZONE PLANNING INVENTORY FOR ALL NONATTAINMENT AREAS



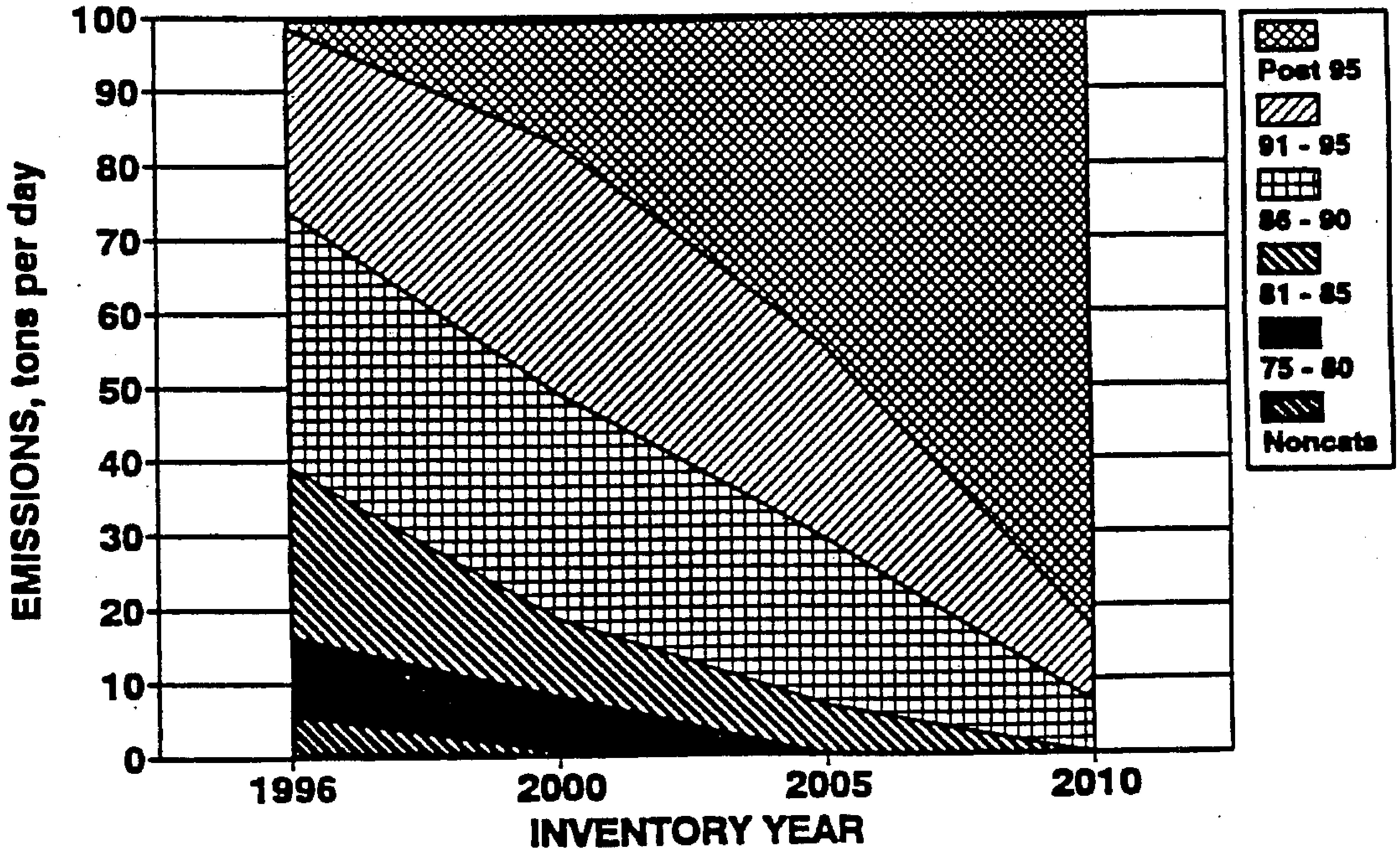
PERCENTAGE OF NOx EMISSIONS FROM LIGHT DUTY VEHICLES
OZONE PLANNING INVENTORY FOR ALL NONATTAINMENT AREAS

Figure III-3

TREND OF CO EMISSIONS FROM LIGHT DUTY VEHICLES
OZONE PLANNING INVENTORY FOR ALL NONATTAINMENT AREAS



PERCENTAGE OF CO EMISSIONS FROM LIGHT DUTY VEHICLES
OZONE PLANNING INVENTORY FOR ALL NONATTAINMENT AREAS



3. Calculating Reductions in Exhaust Emissions

a. Exhaust Emissions

The range of exhaust emission reductions resulting from the Phase 2 reformulated gasoline specifications have been estimated using the results of various test programs. These test programs allow for the estimate of the emissions from vehicles using fuels with different compositions. Some test programs have been designed to allow for the development of predictive models. Other test programs have been conducted using fuels with similar specifications to the proposed Phase 2 reformulated gasoline specifications. Each of these approaches is discussed below.

i. Predictive Models

Staff have used the regression equations developed as part of the Auto/Oil Study as one basis for projecting emission reductions from Phase 2 reformulated gasoline. The Phase 1 Auto/Oil Study looked at the effects of aromatic hydrocarbons, MTBE, olefins, and the 90 percent distillation temperature on current model vehicles (1989) and on older vehicles (1983-1985). The range of properties addressed in the Auto/Oil Study, and which are included in the regression equations are presented in Table III-4. The regression equations for both the current vehicles and the older vehicles are presented in Appendix 12.

Table III-4

Range of Variables Considered in the Phase 1 Auto/Oil Study

Variable	Range
Aromatic Hydrocarbons	20 - 45 volume %
MTBE	0 - 15 volume %
Olefin	0 - 5 volume %
90 % Distillation Temp.	280 - 360 degrees F

The sulfur content of the fuel has also been identified as an important variable to be considered in evaluating the results of predictive models. As discussed in Chapter II, sulfur adversely affects the catalyst efficiency. The Auto/Oil Study equations do not include a factor for sulfur. The Auto/Oil Study is currently evaluating the effects of sulfur at levels from 50 ppm to 450 ppm in increments of 100 to evaluate the linearity of the effects of sulfur on emissions. These results are expected in early October. For the purposes of this analysis, the ARB staff have assumed that the reduction of sulfur results in a linear decrease in emissions based on the Auto/Oil sulfur study.

These fuel sulfur factors are calculated assuming a change in sulfur content from 466 ppm to 49 ppm with corresponding carbon monoxide, VOC, and NOx benefits of -12.9 percent, -16.1 percent, and -9.0 percent. The resulting fuel sulfur factors used in the regression analysis for CO, VOC, and NOx are -0.031 percent/ppm reduced, -0.022 percent/ppm reduced, and -0.039 percent/ppm reduced.

Using the Auto/Oil Study regression equations modified to include the sulfur effects, staff calculated the emission reductions expected for the Phase 2 reformulated gasoline. The baseline gasoline used represents typical California properties as reported in Chapter II. The baseline fuel specifications, the Phase 2 reformulated gasoline specifications, and the regression results are presented in Table III-5.

Table III-5

Percent Emission Reductions from the Use of the California Phase 2 Reformulated Gasoline Versus California Phase 1 Reformulated Gasoline Based on the Auto/Oil Regression Equations

	Predicted Percent Emissions Change	
Pollutant	Auto/Oil 1990 Fleet	Auto/Oil 1983-1985 Fleet
Carbon Monoxide	-18.1	-10.9
Oxides of Nitrogen	1.2	- 9.6
Hydrocarbons	-19.6	- 3.5

Assumptions:

Fuel Specifications	Units	Baseline Fuel	Phase 2 Fuel
Reid Vapor Pressure	psi	7.8	7.0
Aromatic Hydrocarbons	% volume	32.4	20
Olefins	% volume	9.9	5
Sulfur	ppmw	150	30
Distillation Temperatures			
T10	degrees F	135	135
T50	degrees F	212	200
T90	degrees F	329	300
Oxygenates	% volume	0	11.3

These results show that significant emission reductions are predicted by changing the specifications of the fuel. For the purposes of calculating emission reductions from the use of Phase 2 reformulated gasoline, staff assumed that the Auto/Oil regression equation for the 1983-1985 model year vehicles, modified to include the sulfur effects, is applicable to the 1975-1980 vehicle class. Staff also assumed that the older vehicle regression, with the fuel sulfur factor removed, is applicable to the non-catalyst vehicles. Finally, the Auto/Oil regression analysis for the current vehicles was assumed to apply to the 1991-1995 model year vehicles. Table III-6 presents the emission reduction factors, expressed as percent changes, that were used to calculate the reductions in exhaust emissions from light duty vehicles.

Table III-6

Emission Changes Predicted by Auto/Oil Study Regression Equations

Vehicle Class	Percent Emissions Change CO	NOx	VOC
Non-catalyst Vehicles	- 7.1	-7.0	-1.1
1975-1980 Vehicles	-10.9	-9.6	-3.5
1981-1985 Vehicles	-10.9	-9.6	-3.5
1986-1990 Vehicles	-18.1	1.2	-19.6
1991-1995 Vehicles	-18.1	1.2	-19.6
Post 1995 Vehicles a/	0.0	0.0	0.0

a/ No changes taken for this class of vehicles since it was assumed that these vehicles would be certified on Phase 2 reformulated gasoline.

For medium duty trucks and heavy duty trucks, staff assumed that an average of the non-catalyst vehicles and the 1975-1980 model year vehicles would be representative of the benefits for these vehicles.

ii. Emission Testing Programs

There have been several vehicle emission testing programs that have tested fuels which have characteristics similar to the Phase 2 reformulated gasoline. These fuels have been tested against a nationwide industry average fuel which has been blended in large quantities as part of the Auto/Oil Study. There have been three fuels tested which approximate the Phase 2 reformulated gasoline specifications. The three test programs have been conducted by ARCO, Ford, and as part of the Auto/Oil RVP/Oxygenates Study. These three studies have been conducted using current model year vehicles. In addition, the ARB, in cooperation with General Motors (GM), has conducted testing of the ARCO EC-X fuel. The ARB/GM test results were done on four classes of vehicles. Table III-7 presents the fuel specifications for the baseline fuel and the tested fuel. As you can see, the fuels differed somewhat from the proposed Phase 2 reformulated gasoline. The results of the four test programs for current model year vehicles are shown in Table III-8. Table III-9 presents the ARB/GM tests for all vehicle classes.

Table III-7

Summary of Exhaust Emission Tests With Fuel Specifications Similar to Phase 2 Reformulated Gasoline

Study	RVP psi	Arom HC Content Vol %	Fuel Composition Oxygen Content Wt %	Olefin Content Vol %	Dist. T90 deg F	Temps T50 deg F	Sulfur ppmw
CARB Proposed Phase 2 Specs	7.0	20.0	1.8-2.2	5.0	300	210	30
ARCO Base Fuel/ RF-A	8.6	34.4	0.0	9.7	323	213	349
Test Fuel/ EC-X2	6.7	21.6	2.7	5.5	293	201	41
GM/CARB Base Fuel/ RF-A	8.6	34.4	0.0	9.7	323	213	349
Test Fuel/ EC-X2	6.7	21.6	2.7	5.5	293	201	41
Auto/Oil/ Base Fuel/ RF-A	8.7	32.0	0.0	9.2	330	218	339
Test Fuel/ Fuel MM	8.0	22.2	2.7	5.4	289	167	355
Ford/ Base Fuel/ RF-A	8.7	32.0	0.0	9.2	330	218	339
Test Fuel/ CF1	7.1	18.3	1.2	0.2	280	194	81

Table III-8

Percent Difference in Exhaust Emissions Based on Vehicle Emission Tests

STUDY	PERCENT DIFFERENCE FROM THE BASE FUEL VOC	CO	NOx
ARCO Test Fuel: EC-X2	-31.3	-26.0	-25.7
GM/CARB Test Fuel: EC-X2	-20.7	-41.3	-8.6
AUTO/OIL Test Fuel: A/O-MM	-15.5	-12.9	-0.8
FORD Test Fuel: CF1	-35.2	-7.6	-26.7

Note, in all cases the base fuel represents a national industry average fuel.

Table II-9

Summary of Exhaust Emissions from General Motors Testing of ARCO's EC-X Blend 2 Reformulated Gasoline

		Emissions			Percent Differences		
Vehicle Type	Fuel Type	VOC (g/mi)	CO (g/mi)	NOx (g/mi)	VOC pct	CO pct	NOx pct
65 Valiant	RF-A	4.629	49.341	2.172			
	EC-X	4.893	49.841	2.2286	5.7	- 0.6	5.2
71 Ford LTD	RF-A	3.571	49.825	4.192			
	EC-X	2.975	37.868	4.045	-16.7	-22.8	-3.5
			Average	NON-CAT	- 5.5	-11.7	0.9
75 Chrysler Cordoba	RF-A	0.771	13.881	4.31			
	EC-X	0.723	11.455	3.999	- 6.2	-17.5	- 7.2
77 Ford Mustang	RF-A	0.821	6.047	3.221			
	EC-X	0.75	6.153	3.15	- 8.6	1.8	- 2.2
77 Olds Omega	RF-A	1.591	29.371	3.17			
	EC-X	1.782	23.047	3.645	12.0	-21.5	- 1.8
			Average	1975-1980	- 1.4	-18.6	- 5.6
83 Olds Ciera	RF-A	1.244	8.268	2.247			
	EC-X	1.198	7.839	2.197	- 3.7	- 5.2	- 2.2
85 Ford LTD	RF-A	1.471	5.246	0.902			
	EC-X	1.217	2.853	0.847	-17.3	-45.6	- 6.1
			Average	1981-1985	-10.5	-25.4	- 4.2
90 Buick LeSabre	RF-A	0.161	2.728	0.263			
	EC-X	0.113	1.119	0.235	-29.8	-59.0	-10.6
90 Ford Taurus	RF-A	0.356	5.917	0.41			
	EC-X	0.315	4.516	0.383	-11.5	-23.7	- 6.6
			Average	1986-1990	-20.7	-41.3	- 8.6

SSD 9/11/91

These data can be used to estimate the emission reductions that can be achieved by using Phase 2 reformulated gasoline, modified by using the predictive equations discussed above to reflect differences in gasoline properties. This was done using the Auto/Oil regressions and comparing the nationwide industry average fuel to the California average fuel. Additional corrections were made to account for differences between the test fuel and the Phase 2 reformulated gasoline. The ARCO EC-X data was used for the 1986-1995 vehicle classes since the testing was done on more vehicles than the confirmation testing. The GM/CARB confirmation testing was used for the other vehicle classes in the absence of other test data. The resulting emission reduction factors that were used to project emission reductions are presented in Table III-10.

Table III-10

Emission Changes Based on the Emission Testing Programs

Vehicle Class	Percent Emissions Change		
	CO	NOx	VOC
Non-catalyst Vehicles	-15.0	2.0	- 9.5
1975-1980 Vehicles	-15.8	- 0.3	+ 2.3
1981-1985 Vehicles	-22.6	1.1	- 6.8
1986-1990 Vehicles	-22.1	-20.4	-26.6
1991-1995 Vehicles	-22.1	-20.4	-26.6
Post 1995 Vehicles a/	0.0	0.0	0.0

a/ No changes taken for this class of vehicles since it was assumed that these vehicles would be certified on Phase 2 reformulated gasoline.

The ARB, again in cooperation with General Motors, is testing a version of the EC-X fuel which has a lower oxygen content than the original EC-X test fuel. The baseline fuel for this study will be a California average fuel, which was available from the GM/WSPA/CARB volatility study. The results from this study are expected in mid-October.

For medium duty trucks and heavy duty trucks, staff assumed that an average of the non-catalyst vehicles and the 1975-1980 model year vehicles would be representative of the benefits for these vehicles.

c. Sulfur Dioxide Emission Reductions

For sulfur dioxide emissions, staff assumed that 100 percent of the sulfur in the fuel is converted to sulfur dioxide, and calculated the emissions based on a reduction of 150 ppm by weight to 30 ppm by weight using the gasoline consumption values presented in Table III-11.

Table III-11

Gasoline Consumption in All Nonattainment Areas and the South Coast Air Basin

Year	Fuel Consumed (million gallons/day)	
	South Coast Air Basin	All Nonattainment Areas
1996	14.0	34.6
2000	14.4	35.1
2005	15.4	36.7
2010	16.3	38.3

4. Calculating Reductions in Evaporative Emissions

The methodology for estimating evaporative emissions for on-road vehicles generally follows the methodology used to determine emission reductions for California Phase 1 reformulated gasoline. The methodology has been modified to include the effects of reducing RVP on running losses.

Staff calculated emission reduction factors for diurnal emissions, hot soak emissions, and running losses. These emission factors were then applied to the emissions inventory to calculate emission reductions. A detailed discussion of the methodology for determining the evaporative emissions is presented in Appendix 13. Table III-12 presents the emission reduction factors as a function of vehicle group and type of evaporative emission for light duty passenger cars. Table III-13 presents similar information for light duty trucks.

Table III-12

Emissions Change in Evaporative Emissions By Vehicle Class From Light Duty Passenger Cars

Vehicle Class	Percent Emissions Change Hot Soak	 Diurnal	 Run. Loss
Non-catalyst Vehicles	-16.3	-28.6	-34.0
1975-1980 Vehicles	-16.1	-26.9	-35.6
1981-1985 Vehicles	-15.4	-22.8	-39.4
1986-1990 Vehicles	-14.1	-16.5	-45.2
1991-1995 Vehicles	-13.6	-13.5	-48.0
Post 1995 Vehicles a/	0.0	0.0	0.0

a/ No changes taken for this class of vehicles since it was assumed that these vehicles would be certified on Phase 2 reformulated gasoline.

Table III-13

Emissions Change in Evaporative Emissions By Vehicle Class From Light Duty Trucks

Vehicle Class	Percent Emissions Change Hot Soak	 Diurnal	 Run. Loss a/
Non-catalyst Vehicles	-16.3	-28.6	-34.0
1975-1980 Vehicles	-16.2	-28.2	-34.4
1981-1985 Vehicles	-16.0	-27.4	-35.1
1986-1990 Vehicles	-14.3	-17.5	-44.2
1991-1995 Vehicles	-13.6	-13.5	-48.0
Post 1995 Vehicles a/	0.0	0.0	0.0

a/ No changes taken for this class of vehicles since it was assumed that these vehicles would be certified on Phase 2 reformulated gasoline.

For medium duty trucks and heavy duty trucks, staff assumed that an average of the non-catalyst vehicles and the 1975-1980 model year vehicles would be representative of the benefits for these vehicles.

5. Summary of Emission Reductions from On-Road Gasoline-Powered Motor Vehicles

Using the ozone planning inventory and the emission reduction factors presented in the previous section, staff calculated the emission reductions of volatile organic compounds, oxides of nitrogen, carbon monoxide, and sulfur dioxide expected from the use of the Phase 2 reformulated gasoline in light duty vehicles, medium duty vehicles and heavy duty vehicles. These results are summarized in Table III-14.

Table III-14

Reductions in Emissions From On-road Gasoline-Powered Motor Vehicles Resulting from the Use of Phase 2 Reformulated Gasoline

	Emission Reductions (tons/day)							
	1996		2000		2005		2010	
Nonattainment Area	A/O	Test	A/O	Test	A/O	Test	A/O	Test
All Nonattain. Areas								
VOC Exhaust	52	76	43	59	25	35	7	11
VOC Evaporative								
Hot Soak	18	18	11	11	6	6	3	3
Diurnal	9	9	6	6	3	3	1	1
Running Loss	13	13	7	7	4	4	1	1
Total VOC	92	116	67	83	38	48	12	16
NOx Exhaust	37	71	23	60	18	34	18	8
Total 03 Precursors	129	187	90	143	56	82	30	24
CO Exhaust	1070	1540	794	1075	456	618	164	230
S02 Exhaust	30	30	30	30	30	30	30	30
South Coast Air Basin								
VOC Exhaust	22	32	19	25	11	15	3	5
VOC Evaporative								
Hot Soak	7	7	4	4	2	2	1	1
Diurnal	4	4	2	2	1	1	0	0
Running Loss	6	6	4	4	2	2	2	2
Total VOC	39	49	29	35	16	20	6	8
NOx Exhaust	14	29	9	25	7	14	7	4
Total 03 Precursors	53	78	38	60	25	34	13	12
CO Exhaust	430	630	331	448	191	259	72	100
S02 Exhaust	10	10	10	10	10	10	10	10

B. EMISSION REDUCTIONS FROM OTHER MOBILE SOURCES

1. Emissions Inventory

Off-road mobile sources include motorcycles, snowmobiles, pleasure boats, light and heavy duty farm equipment and residential and commercial utility engines. Table III-15 presents the emissions inventory for other mobile sources for all ozone nonattainment areas. Table III-16 presents similar information for the South Coast Air Basin.

Table III-15

Emissions of Volatile Organic Compounds From Emissions of Other Gasoline-Powered Mobile Sources for All Ozone Nonattainment Areas

	Emissions (tons/day)			
Source	1996	2000	2005	2010
Motorcycles	5.5	5.8	6.2	6.5
Snowmobiles	0.8	0.10	0.1	0.10
Four-wheel Drives	2.7	2.8	3.0	3.2
Boats	112.2	120.4	129.4	138.5
Transportation Refrigeration	4.9	5.1	5.4	5.6
Light-duty Industrial	10.9	11.5	6.2	12.5
Heavy-duty Farm	15.1	15.9	17.0	18.0
Heavy-duty Non-farm	7.0	7.5	8.0	8.5
Residential Utility Equipment	20.4	21.8	23.4	24.9
Commercial Utility Equipment	50.7	55.0	60.0	65.0
TOTAL	230.2	245.9	258.7	282.8

Source: Ozone Planning Inventory, ARB 1990.

Table III-16

Emissions of Volatile Organic Compounds from Other Gasoline-Powered Mobile Sources for the South Coast Air Basin

Source	Emissions (tons/day) 1996	2000	2005	2010
Motorcycles	2.1	2.2	2.3	2.4
Snowmobiles	0.0	0.0	0.0	0.0
Four-wheel Drives	1.1	1.2	1.3	1.4
Boats	26.0	28.1	30.5	32.9
Transportation Refrigeration	1.7	1.7	1.7	1.7
Light-duty Industrial	7.2	7.5	7.3	8.1
Heavy-duty Farm	0.4	0.5	0.5	0.6
Heavy-duty Non-farm	3.0	3.2	3.4	3.6
Residential Utility Equipment	7.1	7.6	8.0	8.5
Commercial Utility Equipment	14.4	15.8	17.9	19.9
TOTAL	63.0	67.8	72.9	79.1

Source: Ozone Planning Inventory, ARB 1990.

3. Calculating Reductions in Evaporative Emissions

The evaporative emissions from other mobile sources are assumed to be directly propotional to the true vapor pressure of the gasoline. Staff also assumed that 50 percent of the volatile organic emissions are due to evaporative losses.

4. Summary of Emission Reductions from Other Mobile Sources

The emissions from other mobile sources are presented in Table III-17.

Table III-17

Summary of Evaporative Emission Reductions
from Other Gasoline-Powered Mobile Sources

	Emission Reductions (tons/day)[a]	
Year	South Coast Air Basin	All Nonattainment Areas
1996	3.8	13.8
2000	4.1	14.7
2005	4.4	15.5
2010	4.7	17.0

[a] Based on assumption that 50 percent of total volatile organic compound emissions from these sources are evaporative emissions.

C. EMISSION REDUCTIONS FROM STATIONARY SOURCES

1. Emissions Inventory

Evaporative hydrocarbon emissions occur from a number of stationary sources. Most of the emissions that can be reduced by reducing RVP occur from vehicle fueling operations, gasoline storage and transfer operations, and storage tank working losses and breathing losses. Table III-18 presents the emissions of volatile organic compounds for petroleum marketing operations.

Table III-18

Emissions of Volatile Organic Compounds from Petroleum Marketing and Other Petroleum Processes, Storage, and Operations

	Emissions (tons/day)			
Air Basin	1996	2000	2005	2010
Lake Tahoe	0.4	0.4	0.4	0.4
North Central Coast	1.8	1.7	1.7	1.7
Sacramento Valley	12.7	12.1	12.3	12.6
San Diego	10.7	11.7	12.5	13.2
San Francisco	35.0	37.1	38.1	39.1
San Joaquin Valley	6.4	6.1	5.9	5.6
South Central Coast	8.1	8.0	8.1	8.1
South Coast	52.7	54.5	54.2	53.8
South East Desert	7.8	9.1	10.4	11.7
GBV/Mono County	0.2	0.3	0.3	0.3
TOTAL STATE	135.8	141.0	143.9	146.2

Source: Ozone Planning Inventory, ARB, 1990.

3. Calculating Reductions in Evaporative Emissions

For the purposes of this study, we assumed that the evaporative losses from these sources is directly proportional to the true vapor pressure of the gasoline. Table III-19 shows the adjustment factors that were used to adjust emissions from stationary sources for changes in RVP. In calculating the true vapor pressure, a temperature of 75° F was assumed.

Table III-19

Adjustment Factors for Vehicle Refueling, Gasoline Storage and Transfer, Working Losses and Breathing Losses

RVP	TVP	Adjustment Factor[1/]	Emission Reduction
7.8	5.2	1.00	0
7.6	5.1	0.97	0.03
7.4	4.9	0.94	0.06
7.2	4.8	0.91	0.09
7.0	4.7	0.88	0.12

[1/] Adjustment factors are based on True Vapor Pressure (TVP) at 75°F.

4. Summary of Emission Reductions in Stationary Sources

The emission reductions from petroleum marketing operations are presented in Table III-20.

Table III-20

Summary of Evaporative Emission Reductions from Petroleum Marketing Operations

Year	Emission Reduction (tons/day) South Coast Air Basin	Emission Reduction (tons/day) All Nonattainment Areas
1996	6.3	16.3
2000	6.5	17.0
2005	6.5	17.2
2010	6.4	17.6

D. SUMMARY OF EMISSION REDUCTIONS

For all nonattainment areas and the South Coast Air Basin, Table III-21 presents the emission reduction estimates for volatile organic compounds and oxides of nitrogen due to the implementation of the Phase 2 reformulated gasoline specifications. Table III-22 presents estimates of emission reductions for carbon monoxide and sulfur dioxide for both areas. For this analysis, we have assumed that the emissions from on-road gasoline-powered motor vehicles is equal to the average of the estimates from the predictive model analysis and the emissions testing analysis.

Actual emission reductions are expected to be greater than shown in the table. During the past few years, a number of independent investigators have conducted studies that assert that the inventory of volatile organic compounds in urban areas may be underestimated by substantial amounts. Investigations conducted during the last year by the ARB staff have shown that these underestimates are in the neighborhood of 50 to 100 percent. Staff believes that the on-road motor vehicle portion of the inventory is underestimated by at least as much as the overall inventory; however, studies to date have not been able to establish error bands for specific categories of the inventory. Efforts towards improving both the mobile and stationary source portions of the inventory continue and a major effort is underway to obtain improved emission rates and vehicular activity data for the on-road motor vehicle emission estimates.

To the extent the motor vehicle emissions inventory is underestimated, the emission reductions for the proposed specifications are underestimated. The actual emission reductions could be 50 to 100 percent greater, or more than currently estimated. This would mean that the emission reductions could increase from about 200 to 250 tons per day for volatile organic compounds, 75 to 100 tons per day for oxides of nitrogen, and 2000 to 2500 tons per day for carbon monoxide.

Staff also believes that the Phase 2 gasoline specifications will reduce exhaust emissions from other gasoline-powered mobile sources such as off-road vehicles, trains, ships, aircrafts, and utility equipment. Estimates of emission reductions from these sources are not addressed here because of a lack of emission test data on which to base emission reduction estimates, so they are not included in the tables.

Table III-21

Reductions in Ozone Precursor Emissions (VOC and NOx) Resulting from the Use of California Phase 2 Reformulated Gasoline (Based on the Ozone Planning Inventory a/)

Ozone Nonattainment Area	Emission Reductions (tons/day)			
	1996	2000	2005	2010
All Nonattainment Areas				
Volatile Organic Compounds				
Evaporative Emissions				
On-road Vehicles	40	25	15	5
Other Mobile Sources	14	15	15	20
Stationary Sources	16	20	20	20
Exhaust Emissions	60	50	30	10
Total VOC	130	110	80	55
Oxides of Nitrogen				
Exhaust Emissions				
On-road Vehicles	50	40	30	10
Total Ozone Precursors	180	150	110	65
South Coast Air Basin				
Volatile Organic Compounds				
Evaporative Emissions				
On-road Vehicles	20	10	5	2
Other Mobile Sources	4	5	5	5
Stationary Sources	6	10	10	6
Exhaust Emissions	30	20	10	4
Total VOC	60	45	30	17
Oxides of Nitrogen				
Exhaust Emissions				
On-road Vehicles	20	20	10	5
Total Ozone Precursors	80	65	40	22

a/ The ozone planning inventory represents typical summertime episodic day emissions in a nonattainment area. These days are typically hot days when motor vehicle evaporative control systems tend to fail.

Table III-22

Reductions in Sulfur Dioxide and Carbon Monoxide Emissions Resulting from the Use of California Phase 2 Reformulated Gasoline Based on the Ozone Planning Inventory a/

Ozone Nonattainment Area	Emission Reductions (tons/day)			
	1996	2000	2005	2010
All Nonattainment Areas				
Sulfur Dioxide	30	30	30	30
Carbon Monoxide	1,300	930	540	200
South Coast Air Basin				
Sulfur Dioxide	10	10	10	10
Carbon Monoxide	530	390	220	90

In addition to reductions in mass emissions, the proposed Phase 2 gasoline specifications would reduce the reactivity of the exhaust and evaporative emissions. Exhaust reactivity would be affected by reductions in olefins, aromatic hydrocarbons, and T90. The preliminary results of the GM/WSPA/ARB study show that the reactivity potential of the exhaust expressed in grams of ozone per gram of exhaust volatile organic compounds is reduced by approximately five percent when a fuel similar to current average California gasoline is replaced by a gasoline approximating the Phase 2 gasoline specifications. Similarly, the results of the ARCO study show a reduction of about eight percent when the industry average fuel is replaced by a fuel similar to Phase 2 gasoline. The results of the Auto/Oil AQIRP relate reduction of reactivity in the exhaust to reductions in T90. On a grams ozone per mile basis, staff expects the Phase 2 specifications will result in a 30 to 40 percent reduction in the reactivity of exhaust emissions.

The limits proposed for olefins and aromatic hydrocarbon content would reduce these compounds from the evaporative emissions which contribute disproportionately to the reactivity. Although the benefits cannot be quantified at this time, we expect that they would be proportional to the reductions.

E. REACTIVITY BENEFITS

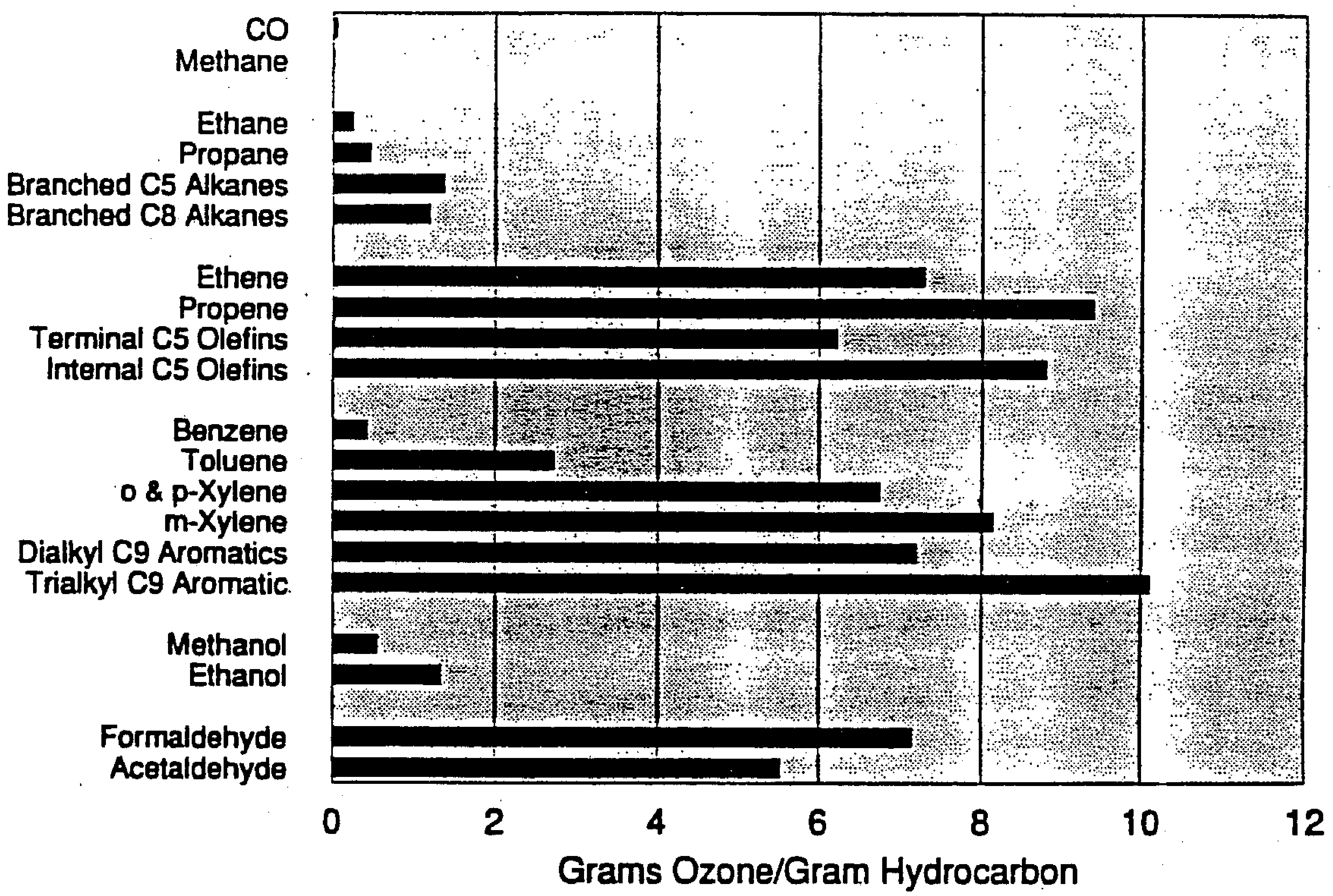
In the past, emissions from motor vehicles have been viewed as non-methane organic gases (NMOG), NOx, and CO emitted. Non-methane organic gases are composed of many different hydrocarbon and other organic species which vary significantly in ozone forming potential. The changing of the composition of the fuels by adding oxygenates, changing the distillation characteristics, and reducing the aromatic hydrocarbon and olefin content would drastically change the hydrocarbon and organic species composition of the exhaust. Therefore, there is a need to evaluate the effects of changing fuel composition on the ozone forming potential of the exhaust to ensure that the proposed phase 2 fuel specifications in addition to mass VOC emission benefits would also achieve benefits in the ozone forming potential of the exhaust.

Figure III-4 shows the maximum incremental reactivity of some common exhaust hydrocarbons. As Figure III-4 shows, olefins and high molecular weight aromatic hydrocarbons have significantly higher reactivity potential than paraffins (alkanes). Because aromatic hydrocarbons and olefins in the fuel are related to aromatic hydrocarbons and olefins in the exhaust and because the proposed Phase 2 gasoline specifications would reduce aromatic hydrocarbons and olefinic species in the fuel the proposed regulation would reduce the ozone forming potential of the exhaust emissions.

Exhaust emissions data collected by ARCO for a fuel that has specifications similar to the specifications of the Phase 2 gasoline show a 39 percent reduction in the Carter Ozone Per Mile (COPM) reactivity potential of the exhaust. This reduction of reactivity includes the benefits of reductions in mass emissions and represent a reduction of about eight percent in grams of ozone per gram of hydrocarbon emission in the exhaust. This reduction was from the Industry Average Fuel. The reactivity reductions can be compared to a 31 percent reduction in the mass hydrocarbon emissions in the exhaust. The results of these tests indicate that the proposed gasoline specifications would result in significant reactivity benefits over the base fuel.

General Motors in their analysis of the Auto/Oil data has also looked at the changes in ozone forming potential of the exhaust when fuel composition changes are made and has contributed a large fraction of the exhaust reactivity potential to high molecular weight aromatic hydrocarbons in the fuel. Their analysis indicated that when di- and tri-alkylbenzenes are removed from the fuel, a significant reactivity benefit in the exhaust would result. However, some disbenefits could occur because replacement of these aromatic hydrocarbons with alkanes could result in reactivity increases since alkanes are precursors of highly reactive olefins. The proposed specifications which limit the T90 to 300°F, combined with the proposed 25 percent limit in aromatic hydrocarbons, is expected to result in reductions of the heavy aromatic hydrocarbons content of the fuel and therefore, according to GM analysis would reduce exhaust reactivity. The results of the GM/WSPA/ARB study also indicate that the proposed fuel specifications would result in about a five percent reduction in the

Figure III-4



Maximum Incremental Reactivity
of Common Exhaust Hydrocarbons

ARB/RD (1991)

reactivity potential of the exhaust as measured in grams of ozone per gram of exhaust hydrocarbon. The staff expects that if the mass benefits are include, the overall COPM reactivity benefits would be similar to the benefits shown by the ARCO study.

The staff is evaluating further the contribution of the high molecular weight aromatic hydrocarbons to the ozone forming potential of the exhaust by analyzing all data available in order to determine if there is a need to specify limits on the heavy aromatic hydrocarbons. The staff is also evaluating the refinery process changes that are needed to reduce heavy aromatic hydrocarbons from the fuel and to determine if additional benefits in reactivity can be achieved in a cost-effective manner.

In addition, to the benefits on the exhaust reactivity, the proposed Phase 2 gasoline specifications would also benefit the reactivity of the evaporative emissions. The proposed reductions in the aromatic hydrocarbons content from 32 percent to 25 percent by volume and the proposed reductions in the total olefins content would significantly improve the reactivity of the evaporative emissions because aromatic hydrocarbons and olefins are the main contributors to the reactivity of evaporative emissions. The proposed limit of 5 percent on olefin content combined with the 7.0 psi RVP limit and the 30 ppm sulfur content would require of refiners to remove from the gasoline pool and process gasoline blendstocks which contain C3 to C5 olefins. Such processing would probably eliminate C3 to C5 olefins which are major contributors to the reactivity of the evaporative emissions.

IV.

BASIS FOR ADOPTING GASOLINE SPECIFICATIONS AFFECTING TOXIC POLLUTANTS

A. OVERVIEW OF TOXIC POLLUTANTS FROM GASOLINE-POWERED VEHICLES

Toxic pollutants are air pollutants suspected of causing (or known to cause) cancer in people. Of the 62 toxic and potentially toxic substances listed in the 1990 ARB document "Toxic Air Contaminant Identification List", 28 are believed to be emitted from gasoline vehicles. Of the 28 substances, 10 are likely to be emitted from gasoline vehicles in quantities of at least one ton per year, statewide. (One of the ten is asbestos, which is emitted through the wear of brake and clutch linings, not from the use of gasoline.) The Motor Vehicle Toxics Control Plan of July 1990 quantified and ranked the risks from emissions of these substances from gasoline vehicles.

Table IV-1 lists these 10 toxic substances, the estimates of emissions in tons per year, and the estimated contribution that gasoline vehicles make to total emissions of each substance in the state. Table IV-2 shows the potential cancer incidence associated with these emissions, based on typical ambient concentrations measured between 1987 and 1989. (The estimates of cancer incidence differ from those reported in the Motor Vehicle Toxics Control Plan due to some new information on ambient air concentrations, unit risks, and emission inventories, as detailed in Appendix 7.) The potential cancer incidence values are calculated with unit risk values from the Department of Health Services, where available. Otherwise, unit risk values are from the California Association of Air Pollution Control Officers (CAPCOA) risk assessment guidelines.

Tables IV-1 and IV-2 show that benzene and 1,3-butadiene are predominantly emitted by motor vehicles and they account for over 95 percent of the total gasoline vehicle-related risk. Thus, any evaluation of the impact of Phase 2 gasoline specifications on toxic emissions must include both benzene and 1,3-butadiene. Two other substances, formaldehyde and acetaldehyde, make up considerably less of the total gasoline vehicle toxic risk. However, they have been included in the evaluation of Phase 2 gasoline toxic pollutant specifications because of the potential impact oxygenated fuels may have on emissions of these compounds and because of the wealth of information provided by the Air Quality Improvement Research Program (AQIRP) study regarding these compounds.

Table IV-1

Statewide Toxic Emissions from Gasoline Vehicles

Substance	Tons/Year(a)	Percent of Total Emissions(c)
(1) benzene	25,000	91%
(2) 1,3-butadiene	2,900	78%
(3) formaldehyde	8,900 (b)	5%
(4) acetaldehyde	2,600-6,000 (b)	5-21%
(5) styrene	1,600-1,700	63-65%
(6) asbestos	1	5%
(7) ethylene dichloride	9	16%
(8) cadmium	3	18%
(9) benzo[a]pyrene	0.4-2	4-22%
(10) ethylene dibromide	3	1%

(a) The year for which the estimate applies varies by substance from 1981 to 1991.

(b) Formaldehyde and acetaldehyde emission estimates exclude amounts formed in the atmosphere by photo-oxidation of organic gases from vehicles.

(c) Emissions expressed as percent of total emissions of the substance from all sources.

Table IV-2

Statewide Potential Cancer Incidence Due to Gasoline Vehicles

Substance	Potential Cases/yr(b)	% of Total (129 Cases/Year)
(1) benzene	89	69%
(2) 1,3-butadiene	34	26
(3) formaldehyde	2.5	1.9
(4) acetaldehyde	0.70	0.5
(5) styrene	1.1	0.9
(6) asbestos	0.84	0.7
(7) ethylene dichloride	0.56	0.4
(8) cadmium	0.43	0.3
(9) benzo[a]pyrene	0.071	0.06
(10) ethylene dibromide	0.014	0.01
Total	129	~100

(a) based on typical ambient concentrations measured in 1986 to 1989 and a population of 26.8 million

(b) lifetime cases at typical ambient concentration divided by 70 years

The following sections of this chapter discuss why the four main toxic pollutants from gasoline vehicles occur in the exhaust and evaporative emissions and how Phase 2 gasoline specifications would affect the emission rates and the potential cancer incidence due to those emissions. The discussions are divided into (1) sections on benzene emissions, the associated cancer risk, and the proposed limit on benzene in gasoline, (2) sections on the other three toxic pollutants, and (3) a section on the effect of the entire set of Phase 2 specifications on the overall risk from all four pollutants. This organization reflects the status of benzene as the only toxic pollutant whose origin and relationship to gasoline properties is understood well enough for the staff to propose a gasoline specification (on the benzene content) for the sole purpose of controlling toxic emissions.

While it is not clear how emissions of 1,3-butadiene, formaldehyde, and acetaldehyde might be controlled specifically by adjusting gasoline properties, the effects of the proposed Phase 2 specifications on the emissions of these pollutants can be estimated. Although emissions of the two aldehydes are expected to increase somewhat, the total mass of all four toxic pollutants is expected to decrease. This is, in part, because all four toxic pollutants are organic gases (NMOG), which the specifications are designed to control. More importantly, the Phase 2 specifications would sharply decrease benzene and butadiene emissions, thereby effecting a distinct decrease in risk from vehicular emissions despite the minor increase in aldehyde emissions.

B. BENZENE EMISSIONS

This section relates benzene emissions from the use of gasoline to total benzene emissions. It shows estimates of future ambient air concentrations of benzene and of the potential numbers of cancer cases attributable to benzene emissions from the use of gasoline.

1. Gasoline as a Cause of Benzene Emissions

Gasoline-powered vehicles are the dominant source of benzene emissions in California. About 90 percent of benzene emissions in California are from gasoline-powered vehicles. Benzene is also emitted from diesel-powered vehicles and from stationary sources such as gasoline stations, stationary engines, and gasoline storage tanks. In every emission category involving gasoline, the emission rate of benzene increases with the benzene content of the gasoline. The relationships are approximately linear.

Benzene is emitted by a gasoline vehicle in three ways: benzene evaporating from the fuel in the tank and the carburetor (evaporative and "running loss" emissions), benzene in the fuel passing through the engine and catalyst without destruction, and other aromatic compounds in gasoline converting to benzene in the engine or catalyst. Two experimental studies [1,2] involving late-model passenger vehicles indicate that about 40 percent of the exhaust benzene is due to the benzene in gasoline and about 60 percent is due to the other (non-benzene) aromatic content. About half of the total benzene emissions from gasoline-powered vehicles (evaporative plus exhaust) are attributable to the benzene in gasoline.

2. Emission Trends

The average benzene content of gasoline has increased in recent years as refiners have increased the aromatic content (which includes benzene) of gasoline to provide the octane value that was once provided by tetraethyl lead.

Despite the increase in the benzene and other aromatic contents of gasoline, vehicular benzene emissions have been declining as hydrocarbon emissions (which include benzene) have declined in response to emission standards for new vehicles and programs to reduce in-use hydrocarbon emissions from vehicles. Benzene emissions will continue to decline as vehicles emitting less hydrocarbons (0.25-gm/mile and low-emission vehicles) replace older vehicles in the on-road fleet. Overall, benzene emissions between 1986 and 1996 will decline by about 30 percent. The rate of decline of benzene emissions will also be influenced by how much gasoline is replaced by other fuels in response to the low-emission vehicle and clean-fuel regulations (see Figure IV-1). However, the magnitude of benzene emissions from gasoline vehicles and other gasoline-related sources (about 27 tons per day in the year 2010) will continue to be significant for the forseeable future.

3. Emission Estimates

The staff has estimated benzene emissions from vehicles as hydrocarbon (HC) emissions multiplied by appropriate values of the benzene fraction of HC. For on-road vehicles, the HC emission estimates are based on ARB's standard models (EMFAC and BURDEN) for various classes of vehicle. HC emissions from other mobile sources (e.g., boats and recreational vehicles) are from ARB's emission inventory system.

The benzene fractions are based on the results of studies on late-model vehicles [1,2,3] and regression equations developed by the ARB staff from various published data on older vehicles [4]. The benzene fractions for non-catalyst on-road vehicles are applied to other mobile sources as well. All the fractions are linear in the benzene content of gasoline. Appendix 1 provides the details of the calculations.

The benzene emission estimates for future years include the effects of all regulations adopted to date, including the low-emission vehicle standards adopted in 1990.

Table IV-3 and Figure IV-1 show the staff's estimates of recent and future benzene emissions in California for the two cases just described. Emissions in 2000 are expected to decrease by about 40 percent relative to 1986 because of increasingly stringent HC emission standards and fleet turnover. They are expected to continue to decrease through 2010.

Figure IV-2 shows the distribution of emissions by source type. In 1994, the use of gasoline will cause about 88 percent of all estimated benzene emissions and will continue to cause over 75 percent through 2010. By 2000, emissions from "other mobile" sources (boats, agricultural vehicles, off-road recreation, construction equipment, etc.) will cause a major part of the gasoline-related benzene emissions. Some "other mobile" emissions would be reduced by control measures now under development.

Table IV-3
Estimated Benzene Emissions in California
(tons/day)

	1986	1994[a]	If all LEVs use gasoline 2000	If all LEVs use gasoline 2010	If 1/2 of LEVs use gasoline 2000	If 1/2 of LEVs use gasoline 2010
Gasoline						
on-road vehicles	62	36	28	13	28	10
other vehicles[b]	8	11	11	13	11	13
gasol. storage & marketing; stationary engines	1	1	1	1	1	1
total	71	48	41	27	40	24
Diesel						
on-road vehicles	1	1	1	1	1	1
other vehicles	2	2	2	2	2	2
Stationary Sources[c]	4	4	4	5	4	5
TOTAL[d]	77	55	47	34	47	31

[a] The proposed regulation would go into effect in 1996. Since an emission inventory is not available for 1996, 1994 is used as a surrogate.

[b] off-road vehicles, utility equipment, and mobile equipment

[c] except gasoline-related sources

[d] apparent addition errors are due to rounding to nearest ton

Figure IV-1

Estimated Benzene Emissions in California

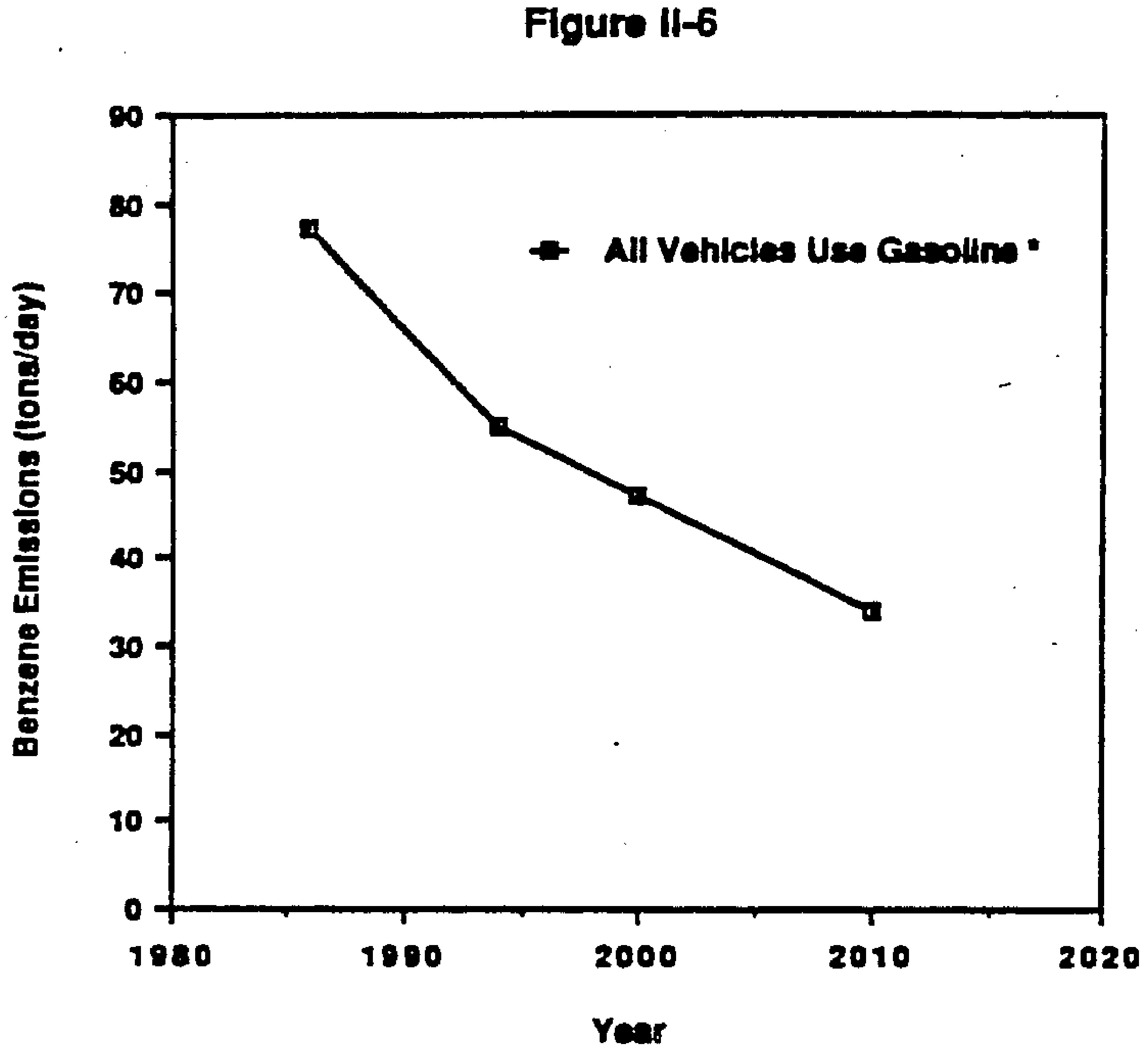
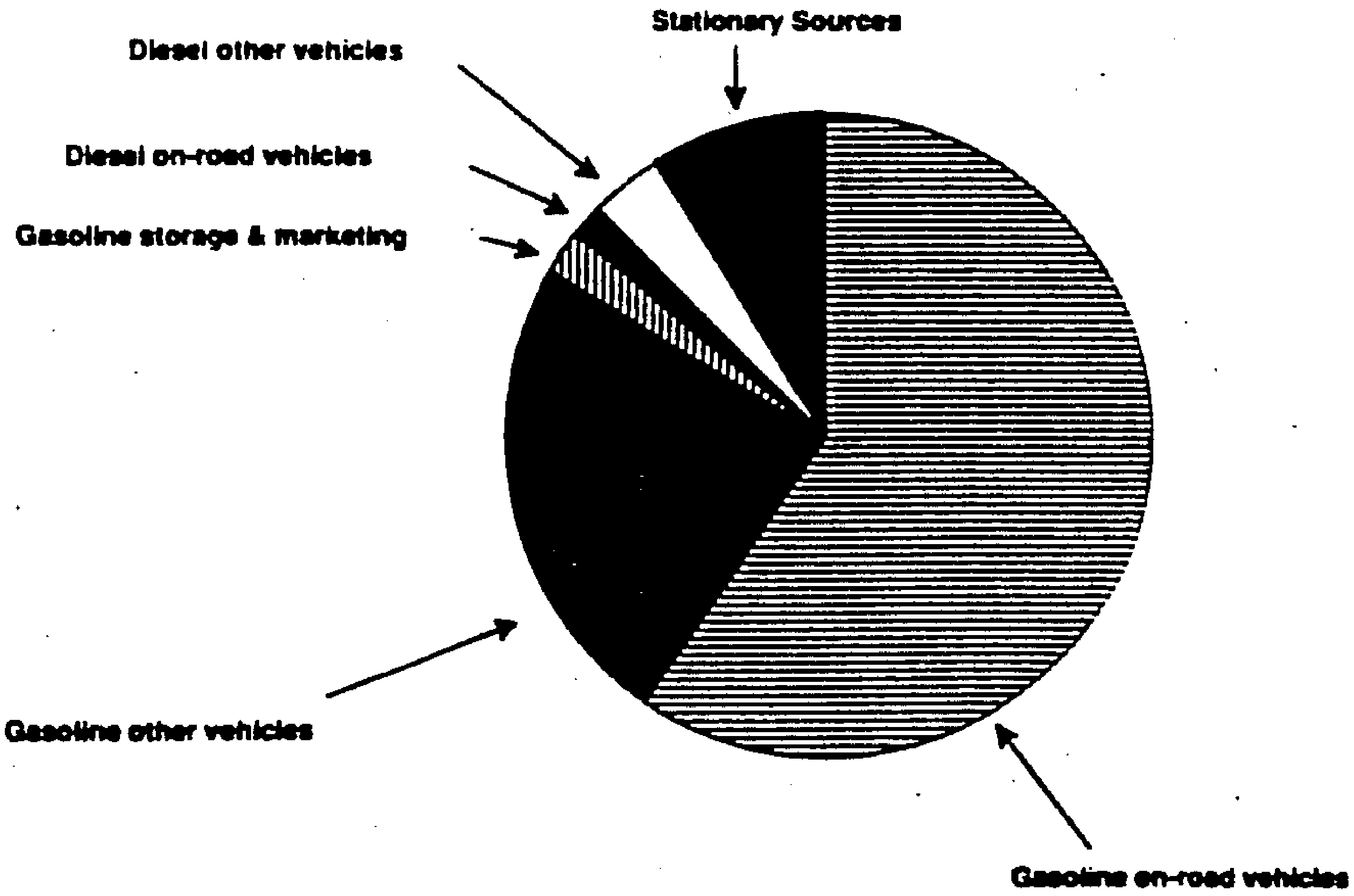


Figure IV-2

Source Distribution of Benzene Emissions in 2000



C. AMBIENT BENZENE CONCENTRATIONS; RISK OF CANCER

Since most benzene is emitted from gasoline-powered vehicles, it is present in the air everywhere there is traffic. Thus, virtually everyone in the state is exposed to some concentration of benzene. Because the emissions are widespread, benzene concentrations do not exhibit the very large variations over short distances that often characterize pollutants emitted exclusively from stationary sources.

In 1986, the ARB measured benzene in the air periodically at 18 locations in the state. The staff has augmented the information from these locations with benzene estimates based on the much more numerous and widespread data on carbon monoxide (CO) measurements. Because benzene and CO are both stable air pollutants emitted mostly from vehicles, their concentrations closely track each other. The staff has applied the correlation between benzene and CO data developed from 1986 data to estimate a statewide population-weighted average benzene concentration of 2.7 parts per billion (ppb) in 1986. (Appendix 4 presents the entire analysis.) The corresponding value for the South Coast Air Basin is 3.6 ppb. Table IV-4 shows the concentrations estimated for various future years on the assumption that the concentration will be proportional to the total benzene emission inventories presented in Table IV-3.

Table IV-4

Estimated Ambient Benzene Concentrations
(ppb, population-weighted mean in state)

	1986	1994	2000	2010
If all LEVs use gasoline	2.71	1.92	1.65	1.19
If 1/2 of LEVs use gasoline	2.71	1.92	1.63	1.08

According to the Department of Health Service's (DHS) analysis of the carcinogenic potency of benzene, the best estimate for an individual's potential risk of cancer during a lifetime of exposure is 93 chances in a million per part per billion (ppb) of benzene concentration. Table IV-5 shows risks corresponding to the ambient concentrations in Table IV-4. The individual risk at the average benzene concentration in 1986 is (if the concentration were maintained over 70 years) about 250 chances in a million, which is equivalent to 250 lifetime cases among a million people. The individual risk corresponding to the concentration estimated for 2000 is about 150 per million, 86 percent of which is attributable to the use of gasoline.

Table IV-5

Risk of Cancer Due to Benzene Emissions

	1986	1994	2000	2010
		If all LEVs use gasoline		
total risk[a]	252	179	153	111
% due to gasoline	91	88	86	79
		If 1/2 of LEVs use gasoline		
total risk[a]	252	179	150	100
% due to gasoline	91	88	86	77

[a] average risk among state's population over a 70-year lifetime of exposure to the benzene concentration estimated for the indicated year; per million people exposed

D. POTENTIAL CANCER INCIDENCE DUE TO BENZENE EMISSIONS

By integrating the local estimates of benzene concentrations with census data, the staff has estimated the potential number of cancer cases if the state's population in 1986 were to breathe the 1986 benzene concentrations over a lifetime (70 years). (See Appendix 4.) This estimate has been adjusted for future base years in proportion to the concentrations in Table IV-4 and the predicted populations for the future years. Details of the estimates for the future years are in Appendix 1.

Table IV-6 shows the estimates of potential cancer incidence. The estimate based on the year 2000 is 5,570 cases in 70 years if gasoline is the only low-emission vehicle fuel. About 86 percent of these potential cases are due to the use of gasoline. If gasoline is the fuel for half of the low-emission vehicles, the estimate is 5,500, still about 86 percent due to gasoline.

Table IV-7 compares the gasoline-related cancer incidence on the 1986 basis with estimates of cancer incidence due to other pollutants from other types of source. It shows the importance of addressing benzene emissions from the use of gasoline. These emissions correspond to a much greater potential cancer incidence than other toxic emission sources for which the Board has adopted control measures.

Table IV-6
Potential Cancer Cases Due to Benzene Emissions
(all emission sources)

base year:	1986	1994	2000	2010
	If all LEVs use gasoline			
total cases[a]	6,820	5,850	5,570	4,530
% from gasoline	91	88	86	79
	If 1/2 of LEVs use gasoline			
total cases[a]	6,820	5,850	5,500	4,100
% from gasoline	91	88	86	77

[a] potential cases over 70 years of exposure to benzene for the concentration and population in the base year

Table IV-7
Potential Cancer Incidence, Various Pollutants and Sources

Pollutant	Toxic Emission Source	Potential[a] Cases
benzene	gasoline vehicles	6,200
1,3-butadiene	mobile sources[b]	4,300
chromium	chrome plating *	2,700
chromium	cooling towers *	900
ethylene oxide	sterilizers *	360 to 510

[a] over 70 years, before toxic pollutant control measures; base year: late 1980's (varies by pollutant)

[b] No control measures specifically for 1,3-butadiene have been adopted. However, vehicular control measures for hydrocarbons have reduced emissions of 1,3-butadiene.

* Control measure has been adopted by ARB.

E. REDUCING BENZENE EMISSIONS

1. Why Gasoline Contains Benzene

Gasoline is required by law to meet over a dozen physical and chemical specifications. There are also additional constraints on the nature of gasoline needed for customers' satisfaction. To meet these specifications, the refining industry has developed a very complex process for making gasoline. The typical refiner blends at least a half dozen different intermediate products ("blend stocks") from different refinery processes to provide gasoline meeting the specifications.

Some of these blend stocks contain benzene. Some of the benzene was present in the crude oil, but most of it results from chemical processes used to improve the octane value* of the blend stocks. Refiners process to increase the aromatic content of gasoline as a means of improving octane. Benzene has a high octane value and thus is not undesirable from the refiners' point of view. However, it is only a minor part of the total aromatic content and has the lowest octane value among the aromatic compounds.

Providing enough octane in gasoline is often a limiting factor and a determinant of cost in making gasoline. Recent regulations, such as the elimination of lead and lower limits on the volatility (Reid vapor pressure) of gasoline, tend to disallow or discourage the addition of certain components that were formerly used to provide octane improvements. Until recently, increased demand for gasoline and for octane value was met by more severe processing of liquids derived from crude oil. Now, refiners are beginning to use oxygen-bearing materials, primarily MTBE (methyl tert-butyl ether) and ethanol. To the extent that use of oxygen-bearing additives increases (especially in response to the proposed limits on the minimum oxygen content of gasoline), it will provide an alternative source of the octane value now provided by benzene.

Table IV-8 shows data on the composition of gasoline from the respondents to a 1988 ARB survey. Slight increases in the benzene and total aromatic contents of gasoline are expected by 1995, along with a substantial increase in the use of MTBE. (The data do not reflect any changes that may occur in response to ARB's "Phase 1" or "Phase 2" regulations or to EPA's expected regulations.)

---

* The octane value of a gasoline (or a constituent of gasoline) is an empirical measure of its ability to prevent knocking in the engine. Knocking is destructive to the engine.

Table IV-8
Properties of Gasoline in California[a]

	1987	1995
Volume produced, million gallons per day	33.6	40.1
Average octane ((R+M)/2)	88.5	88.7
Average % benzene	1.87	1.96
Average % aromatic	32.5	34.4
MTBE used, million gallons per day	.09	.65

[a] results of 1988 survey of refiners supplying 90% of gasoline used in California

2. How Benzene in Gasoline Can be Reduced

The benzene in gasoline can be reduced substantially by standard processing techniques. Most refiners have suggested that they would distill certain blending stocks to isolate most of the benzene into smaller volumes of liquid. These distillates would then be either reacted with hydrogen (hydrotreated) to convert benzene to cyclohexane or extracted with a solvent to remove the aromatic material. In the latter case, the aromatic material would be distilled to separate the benzene from the other aromatic compounds, which would be returned to gasoline blending. The benzene would then be shipped to purchasers, probably in the Gulf Coast. In either case, the volume and octane value that had been provided by the benzene would have to be replaced. This could be done by adding an oxygen-bearing additive and/or by "isomerizing" (a process that increases the octane of certain feeds) the liquids that had undergone extraction or hydrotreating. Details on refiners' choices of process techniques are in Appendix 3. Diagrams of the processes are in Appendix 9.

Extraction or hydrotreating can be done readily to blending stocks such as naphtha and reformate. However, if applied to other gasoline blend stocks, such as those from catalytic crackers or cokers, these processes destroy more octane value than just the octane provided by the benzene. Also, the removal of benzene from stocks other than reformate and naphtha is not a commercial practice. Thus, a benzene limit set low enough to force processing of stocks other than reformate and naphtha would be more expensive per unit of benzene removed than would higher limits, and the ability for refiners to comply would be less certain.

From information supplied by refiners on measures needed to reduce benzene in their gasolines, it appears that all refiners could reduce their benzene contents to 0.80 volume percent. For lower limits, the feasibility is uncertain for several refiners, and the costs per unit of benzene removed increase sharply. Chapter VI and Appendix 6 show the costs.

To offer gasoline with low benzene content, blenders and importers would have to obtain such gasoline or low-benzene blend stocks from their suppliers. Importers who buy gasoline from outside the U.S. would be dependent upon the willingness of refiners outside the U.S. to make complying gasoline, unless the importers would be able to enter the refining business to some extent.

All the information presented in this subsection 2. applies to gasoline produced as it is produced today. If other regulations are adopted and put into effect at or near the the same time as a benzene limit, different measures might be employed to meet a benzene limit. Reducing benzene might be a natural result of a new refinery design adopted to meet all regulations simultaneously, or it might be provided by special equipment added onto a new refinery design. In any case, the types of regulations being considered, with the minor exception of a lower limit on volatility (RVP), should not make meeting a given benzene limit more complex or expensive than discussed above. If significant reduction of the overall aromatic content is required, the incremental cost of meeting a benzene limit is likely to be less than the cost of meeting the same limit alone.

3. What Benzene Content Limit Should Be

The proposed regulation contains three limits on the benzene content of gasoline: 1) the "basic limit", which is essentially a standard for a refiner's average benzene content over a long period, (2) the "batch limit", which is a never-exceed limit that a refiner could choose as an alternative to the basic limit, and the "absolute limit", which would apply at all levels of producing and marketing gasoline.

a. 0.80 v% for the basic limit

From the results of the 1988 survey of refiners, follow-up workshops and discussions, the staff believes that achieving a benzene content of less than 0.80 v% could force some refiners to turn to methods that are not commercially demonstrated and that would have technical drawbacks. This has been discussed in section VII. A. Also, if the basic limit were set at--say--0.60 v%, some refiners would be unable to produce batches with significantly less benzene. Therefore, they would not be able to bank benzene* to offset batches with significantly more than 0.60 v% benzene, and the flexibility offered by the basic limit approach would be lost.

---

* "Banking" is the mechanism by which benzene contents exceeding 0.80 v% in some batches of gasoline would be offset by lesser benzene contents in other batches. Chapter V explains banking.

Furthermore, as seen in Chapter VI, the cost of the basic limit per unit of benzene removed from gasoline is approximately constant down to 0.80 v%, but increases at 0.60 v%. It thus appears that 0.80 v% is a "break point" in terms of technical feasibility, utility of the banking concept, and cost-effectiveness.

b. 1.00 v% for the batch limit

The optional batch limit cannot be set much higher than the basic limit without a danger of the resulting average benzene content being higher than what the staff believes is the reasonable target--0.80 v%. This option may be impractical for some refiners, who might have to design for a typical benzene content less than 0.80 v% so as to never exceed 1.00 v%. Such refiners would be expected to select the basic limit option instead.

c. 1.20 v% for the absolute limit

The absolute limit, applicable at all points in the market system that delivers gasoline from the refiner to the user, would deter the "dumping" of high-benzene material into gasoline that had initially complied with the producer's limit. The lower the absolute limit, the greater would be its potential effectiveness. On the other hand, if set too low, the absolute limit would harm the flexibility offered to the refiner by the basic limit option. The staff has selected 1.20 v% for the absolute limit as the lowest value that we believe would not seriously restrict the refiner's flexibility.

F. BUTADIENE FROM GASOLINE VEHICLES

Mobile sources account for approximately 80 percent of all 1,3-butadiene emissions in California. 1,3-butadiene is not present in gasoline, except in trace quantities. It is produced as a result of incomplete combustion of petroleum fuels, although its precursors compounds are not precisely known. Thus, the staff is not able to propose specifications on gasoline for the sole purpose of reducing 1,3-butadiene emissions. However, the Phase 2 specifications proposed for reducing criteria pollutant emissions are expected to reduce 1,3-butadiene emissions, also. This effect is discussed in Section H of this chapter.

G. FORMALDEHYDE AND ACETALDEHYDE FROM GASOLINE VEHICLES

Formaldehyde and acetaldehyde are not present in gasoline. As products of combustion, they are emitted directly into the atmosphere from vehicle exhaust. However, greater amounts of both compounds are formed in the air from photochemical reactions of other organic gases from vehicles and stationary sources.

The addition of some oxygenated compounds to gasoline has been shown to increase formaldehyde emissions in exhaust. However, we recommend the addition of oxygenated compounds as part of the Phase-2 specifications because of the beneficial effect on hydrocarbon and carbon monoxide emissions. The increase in formaldehyde emissions would add only a minor part to the risk from vehicular emissions.

Staff is unable to propose specifications for the specific purpose of reducing formaldehyde and acetaldehyde emissions.

H. EFFECTS OF PHASE 2 SPECIFICATIONS ON TOXIC POLLUTANT EMISSIONS

This section presents estimates of the effects of the proposed Phase-2 specifications on emissions of toxic pollutants and the associated potential cancer incidence. Data on which to base estimates are available for most, but not all, of the gasoline properties that have specifications.

Subsection 1 presents information on the effect of the proposed benzene limit on benzene emissions and the associated potential cancer incidence. This information was develeloped as if the benzene limit would be the only agent to reduce benzene emissions from vehicles. If a limit on the aromatic content is also adopted, as the staff proposes, it also will reduce benzene emissions, both by a presumed reduction of the benzene content of gasoline (as part of the aromatic content) and by reducing the amounts in gasoline of aromatic precursors to benzene emissions. Therefore, the effects of the benzene limit as part of the overall set of Phase 2 specifications would be somewhat less than what subsection 1 shows. Subsection 3 shows the overall effect of the benzene and aromatic limits combined.

1. Reductions of Potential Risk and Incidence of Cancer by the Proposed Benzene Limit

Reducing the benzene content of gasoline would decrease the benzene in vehicular hydrocarbon emissions. The staff has used data in three research studies [1,2,3] to estimate the relationship between benzene in gasoline and benzene emissions from late-model vehicles. The relationships for older vehicles are based on various other data reported [4]. Benzene emissions from other mobile sources (e.g., off-road vehicles) are assumed to behave as do emissions from non-catalyst on-road vehicles. Appendix 1 shows the derivations.

Table IV-9 shows the effects on potential cancer risk of alternative values for the basic benzene limit for all gasoline. The table shows the effects both with and without gasoline as the fuel for low-emission vehicles. The effects are calculated for three base years: 1994, 2000, and 2010. Each value of risk applies to a lifetime of exposure to the concentration estimated for the corresponding year. On each basis, the measure of the effect is generally different. For example, if a person experienced for his lifetime the reduction in ambient benzene concentration estimated for 2000 under the limit of 0.80 v.% (and if gasoline is the only low-emission vehicle fuel), his lifetime risk would decrease by about 23 percent. If his lifetime experience were the reduction in concentration estimated for the same limit in 2010, his lifetime risk would decrease by about 20 percent.

Table IV-9

Effect of Basic Benzene Limit on Potential Cancer Risk

Base Year	Baseline Risk (a)	Percent reduction from baseline provided by benzene limit at: 0.6%	0.8% *	1.0%	1.2%
1994	180	27	23	19	16
2000					
If all LEVs use gasoline	150	27	23	19	15
If 1/2 of LEVs use gasoline	150	26	23	19	15
2010					
If all LEVs use gasoline	110	23	20	16	13
If 1/2 LEVs use gasoline	100	22	19	16	13

[a] individual's risk over a lifetime (70 years) at the ambient benzene concentration estimated for the indicated year

* proposed value

Table IV-10 shows the reductions in the potential cancer incidence for the 0.80 v.% basic limit. The numbers show, for a particular year the reduction in potential lifetime cancer incidence on a per year basis assuming the ambient benzene concentration and the population remain constant. For gasoline as the only low-emission vehicle fuel, at 0.80 v.% benzene in gasoline, the lifetime cancer incidence would be reduced by about 18 cases per year if both the ambient benzene concentration and the population in 2000 would remain constant for 70 years. This is a 23 percent reduction of the baseline (no-regulation) incidence. The analogous number on the 2010 basis is 13 potential cases avoided per year, a 20 percent reduction from the baseline. If only half of low-emission vehicles will use gasoline, the reductions from the corresponding baselines would be about the same.

Table IV-10

Effect of Basic Benzene Limit on Potential Cancer Incidence

Base year	Population (million)	Baseline Incidence (cases/year) (a)	Reduction of incidence by basic benzene limit of 0.80% (cases/year)
1994	32.8	84	19
2000			
If all LEVs use gasoline	36.3	80	18
If 1/2 of LEVs use gasoline	"	79	18
2010			
If all LEVs use gasoline	41.0	65	13
If 1/2 of LEVs use gasoline	"	59	11

[a] cases among a constant population over 70 years of exposure to the ambient benzene concentration in the indicated year, divided by 70

The numbers in Table IV-10 differ significantly for different base years because of the different average risks (Table IV-9) and the different populations in those years. To provide an average measure of the effect of the proposed basic benzene limit (0.80 v%), taking into account the changing rate of effect, the staff has integrated the annual equivalent of the 70-year risk reduction in each year with the annual population estimate for the year, over the period 1996 to 2010 (calculations are as shown in Appendix 6). The result is 244 potential cases avoided through 15 years of application of the proposed benzene limit for the case of gasoline as the only low-emission vehicle fuel and 234 potential cases avoided if gasoline is half of all low-emission vehicle fuel. These are each about 22% of their respective baseline cancer incidence values over the 15-year period.

Besides the exposure to benzene in the ambient air, reducing the benzene in gasoline would reduce exposures that have not been quantified here. For example, employees and customers in service station would breathe less concentrated benzene during vehicle fueling, and people who contact gasoline directly (for example, while filling fuel tanks on their lawn mowers) would be expected to contact less benzene.

2. Effects of Other Phase 2 Specifications on Toxic Emissions

This section discusses the effects on vehicular toxic emissions of the proposed Phase-2 specifications for the aromatic content, oxygen content*, T-90 distillation temperature, sulfur content, RVP, and olefin content. The staff has no information on the effects on toxic emissions from changes to T-50 distillation temperature, drivability index (DI) or oxygen content using compounds other than MTBE. No effect is expected for the RVP limit.

Subsection a. presents the effect of the proposed limit on the aromatic, olefin, and oxygen (as MTBE) contents. Subsection b. presents the effect of the sulfur limit. Section 3. presents the combined effect of all five of these limits plus the benzene limit.

The staff has used the information reported by the Air Quality Improvement Research Program (AQIRP or "Auto/Oil") to comparing the emission rates of benzene, 1,3-butadiene, formaldehyde, and acetaldehyde from using Phase 1 gasoline (gasoline meeting the specifications already adopted by the ARB) to the predicted emission rates from using Phase 2 gasoline. Table IV-11 lists the values of the aromatic content, oxygen content, olefin content, sulfur content, and distillation temperatures that were used to compare the emissions between the gasolines.

Table IV-11

Values of Gasolines Properties Used in Comparison

	Proposed Phase 2	Baseline Phase 1
Aromatics (vol.%)	20	32
Oxygen (wt.%)	2[a]	0
Olefins (vol.%)	5	10
90% Distillation Temperature (°F)	300	330
Sulfur (ppm)	30	150

[a] expressed as 11% MTBE

---

* The discussion on oxygen content reflects data taken with MTBE, only.

a. Effects of Limits on Aromatics, Oxygen, Olefins, and T-90

The staff has used the AQIRP regression models to estimate emissions of benzene, 1,3-butadiene, formaldehyde, and acetaldehyde as a function of the first four variables in Table IV-11. [Technical Bulletin No. 5] (The effects of the proposed limit for benzene are addressed in subsection 1 of this section, while the effects of the proposed sulfur limit is discussed later in this subsection. The effects of the proposed limits for T-50, DI and non-MTBE oxygenate content are not addressed, due to lack of data.) One set of AQIRP models estimate emissions for the 1989 model year vehicles, while the other set estimates emissions for older (1983-1985) vehicles. We have used only the statistically significant (per AQIRP) regression equation coefficients.

Table IV-12 shows how the AQIRP models predict changes in toxic emissions for the individual Phase 2 specification and the changes for all four Phase 2 limits combined. The common effects of individual variables in both 1989 vehicles and the older vehicles are:

- Reducing the aromatic content of gasoline reduces benzene emissions (an effect previously seen in several studies) but increases formaldehyde and acetaldehyde emissions.
- Reducing the olefinic content of gasoline reduces 1,3-butadiene emissions but not the other three pollutants.
- Decreasing T-90 reduces 1,3 butadiene emissions.
- Increasing MTBE has no significant effect on acetaldehyde emissions but increases formaldehyde emissions.

When all four fuel variables are changed simultaneously (last column of the table), the following effects are predicted by the models.

- Benzene and 1,3 butadiene emissions are each reduced by more than 25 percent. (This does not include the effect of reducing the benzene content in gasoline.)
- Formaldehyde emissions increase by 17 percent in the 1989 vehicles and by 53 percent in the older vehicles.
- Acetaldehyde emissions increase by 15 percent in the older vehicles, but increase only slightly in the newer vehicles.

Table IV-12

Percent Changes in Emissions of Toxic Compounds from Implementing Phase 2 Specifications

Specification:	20% Aromatics	2% Oxygen*	5% Olefins	300°F T90	All Four
			1989 Vehicle Model		
Benzene	-24	0	0	- 4	-29
1,3-Butadiene	+ 2	-5	-11	-17	-26
Formaldehyde	+11	+18	0	-11	+17
Acetaldehyde	+11	0	0	- 9	+ 4
			Older Vehicle Model		
Benzene	-17	- 7	- 3	+ 3	-26
1,3-Butadiene	- 1	+ 3	-13	-10	-28
Formaldehyde	+ 9	+40	0	0	+53
Acetaldehyde	+15	0	0	0	+15

* as 11 vol.% MTBE

Table IV-13 shows the effect of the four Phase 2 limits on the potency-weighted sum of toxic emissions. The potency-weighted sum is calculated by multiplying each compound's percent change in emissions by its unit value of cancer risk (risk per concentration) and summing the four values. This gives a more meaningful measure of the overall change in emissions. The overall reduction in potency-weighted emissions is estimated to be 25 percent for the 1989 vehicles and 8 percent for the older vehicles. (The total change when all four fuel variables are changed is greater than the sum of the changes due to individual variables because the models contain interactive effects among the variables.)

Table IV-13

Percent Changes in Potency-Weighted* Emissions of Toxic Compounds Resulting from Four Phase 2 Specifications

Specification:	20% Aromatics	2% Oxygen	5% Olefins	300°F T90	All Four
1989 Vehicle Model					
	-14	0	-3	-8	-25
1983-1985 Vehicle Model					
	- 7	+7	-5	-1	- 8

* Sum of (% change in emissions) x (unit risk value for compound)
Unit risks, per ug/m3, are 1,3-butadiene: 1.4×10^{-4} (ARB, 1991); benzene: 2.9×10^{-5} (DHS, 1989); formaldehyde: 2.4×10^{-5} (ARB, 1991); acetaldehyde: 2.2×10^{-6} (CAPCOA, 1988)

b. The Effect of Phase 2 Limit on Sulfur on Toxic Emissions

The AQIRP study found a 16 percent reduction of hydrocarbon emissions when the sulfur content of gasoline was changed from 466 to 49 ppm [Technical Bulletin 2]. Because AQIRP compared only two sulfur contents in gasoline, the functional relationship of exhaust emissions to the fuel sulfur level is not known. It is assumed here that the relationship of exhaust emissions and sulfur content is linear. The reduction in hydrocarbon mass emissions resulting from lowering gasoline sulfur content from 150 ppm (Phase 1) to 30 ppm (Phase 2) is estimated at 5 percent.

AQIRP has not published emission data for toxic compounds for this study. However, it is commonly seen in other studies that the toxic emissions are reduced by about the same factor as the HC emissions. Therefore, it can be assumed that reductions of about 5 percent in benzene, formaldehyde, and acetaldehyde would result from a reduction of sulfur content in gasoline. However, staff does not make this assumption for 1,3-butadiene. 1,3-butadiene appears to be formed exclusively during the period before a cold catalyst becomes warm enough to function. Since the effect of sulfur on emissions is due to its role as a catalyst poison, the staff has assumed that butadiene emissions would not be reduced by reducing the sulfur in gasoline.

3. Total Effect of Phase 2 Specifications

The combined effect of the proposed limits on the aromatic, olefinic, oxygen, benzene and sulfur contents and on T90, if assumed to apply to all exhaust emissions from gasoline vehicles in the future, are converted into approximate emission rates in Appendix 8. Table IV-14 shows the results. The 14 ton per day is about a 20 percent reduction from the baseline.

Table IV-14

Emission changes in 2000 Due to Phase-2 Specifications
(tons/day)

Benzene	-18.8
1,3-butadiene	- 1.6
Formaldehyde	+ 6.0
Acetaldehyde	+ 0.2
Total	-14.0

We estimate that, over the period 1996 to 2010, a total of about 35 potential cases per year would be avoided as a result of the Phase 2 gasoline specifications. Of the total reductions, about 14 cases per year are due to the benzene limit and the rest are due to the specifications on the aromatic, olefinic and oxygen contents and on T90. The derivation of these numbers is in Appendix 8. Table IV-15 gives an example for the year 2000.

Table IV-15

Cases Avoided @ 2000 Conditions

Phase 2 Limit:	0.80% Benzene (only)	Other[a] (only)	All[b]
	cases avoided/year		
Benzene Cases			
by benzene limit	17.9	0	16.8
by other limits	0	17.6	16.1
total	17.9	17.6	32.9
1,3-Butadiene Cases	0	8.6	8.6
Formaldehyde & Acetaldehyde cases	0	-0.8	-0.8
	17.9	25.4	40.7

[a] on aromatic, olefins, oxygen, sulfur, and T-90

[b] benzene plus others

V.

DISCUSSION OF THE PROPOSED REGULATIONS

This Chapter discusses the proposed standards for California Phase 2 reformulated gasoline. In some cases, we have repeated information presented in the Staff Report. In other areas, particularly for alternative gasoline specifications and test methods, we have presented more detail than is presented in the Staff Report.

A. ORGANIZATION OF THE REGULATIONS

In order to facilitate incorporation of new regulations pertaining to Phase 2 reformulated gasoline, the ARB recently made editorial changes to the numbering and organization of its fuels and associated regulations. These editorial changes were approved by the Office of Administrative Law on September 17, 1991. The new organization of revised Subchapter 5, along with the proposed amendments and additions associated with this rulemaking, are presented in Table V-1.

In this regulatory action, staff is proposing that the ARB's existing standards for gasoline be placed in a subarticle 1 within Article 1, and that a new subarticle 2 be added establishing the requirements for California gasoline. In addition, the ARB is proposing to modify several existing regulations for gasoline. These changes are discussed below. The complete text of the proposed regulation order is included as Appendix A of the Staff Report (Volume 1).

Table V-1

Organization of Subchapter 5, Standards for Motor Vehicle Fuels

Article 1. Standards for Gasoline

Subarticle 1. Standards for Gasoline Sold Prior to January 1, 1996

§ 2250. Degree of Unsaturation Sold Before January 1, 1996
§ 2251. Reid Vapor Pressure for Gasoline
§ 2251.5 Reid Vapor Pressure of Gasoline Sold After January 1, 1992, and Before January 1, 1996
§ 2252. Sulfur Content of Gasoline Represented as Unleaded Sold Before January 1, 1996
§ 2253.2. Lead in Gasoline Sold Before January 1, 1992
§ 2253.4. Lead in Gasoline
§ 2254. Manganese Additive Content
§ 2257. Required Additives in Gasoline
§ 2258. Oxygen Content of Gasoline in the Wintertime

Subarticle 2. Standards for Gasoline Sold Beginning January 1, 1996

§ 2260. Definitions
§ 2261. Applicability of Standards; Additional Standards
§ 2262.1. Standards for Reid Vapor Pressure
§ 2262.2. Standards for Sulfur Content
§ 2262.3. Standards for Benzene Content
§ 2262.4. Standards for Olefin Content
§ 2262.5. Standards for Oxygen Content
§ 2262.6. Standards for Distillation Temperatures
§ 2262.7. Standards for Aromatic Hydrocarbon Content
§ 2263. Sampling Procedures and Test Methods
§ 2264. Designated Alternative Limits
§ 2265. Certified Gasoline Formulations Resulting in Equivalent Emission Reductions Based on a Predictive Model [Reserved]
§ 2266. Certified Gasoline Formulations Resulting in Equivalent Emission Reductions Based on Motor Vehicle Emission Testing
§ 2267. Exemptions
§ 2268. Liability of Persons Who Commit Violations Involving Gasoine That Has Not Yet Been Sold or Suppplied to a Motor Vehicle
§ 2269. Submittal of Compliance Plans
§ 2270. Testing and Recordkeeping
§ 2271. Variances

Article 2. Standards for Diesel Fuel

§ 2280. Sulfur Content of Diesel Fuel Sold in the South Coast Air Basin or Ventura County Prior to October 1, 1993.
§ 2281. Sulfur Content of Diesel Fuel.
§ 2282. Aromatic Hydrocarbon Content of Diesel Fuel.

Article 4. Sampling and Testing Procedures

§ 2296. Gasoline Sampling Procedures for Reid Vapor Pressure
§ 2297. Test Method for the Determination of the Reid Vapor Pressure Equivalent Using an Automated Vapor Pressure Test Instrument

B. STANDARDS FOR CALIFORNIA PHASE 2 REFORMULATED GASOLINE AND OVERALL STRUCTURE OF THE REGULATIONS

The proposed California Phase 2 reformulated gasoline regulations will require that all gasoline sold or made available as a motor vehicle fuel in California (hereafter referred to as "California gasoline"), meet specified standards for sulfur content, benzene content, aromatic hydrocarbon content, olefin content, RVP, oxygen content, 90 percent distillation temperature (T90), and 50 percent distillation temperature (T50). These standards would be applicable beginning January 1, 1996.

There would be only one RVP standard, generally applicable to all gasoline whenever it is sold or supplied throughout the distribution system during the RVP season. The standards for the properties other than RVP would include at least two tiers--an absolute limit (often referred to as a "cap") that would apply to all gasoline whenever it is sold or supplied throughout the distribution system, and a more stringent standard that would apply to gasoline when it is initially sold or supplied from the facility at which the producer or importer produced or imported the gasoline.[1] As discussed below, the regulations provide for the certification of alternative gasoline formulations resulting in equivalent emissions reductions. Gasoline that is timely reported as a certified alternative formulation would be subject to the caps (and the RVP standard). However, this gasoline would not be subject to the more stringent standards applicable to gasoline when it is supplied from the production facility. Instead, the gasoline would have to meet the alternative specifications for the formulation as identified in the certification of the formulation.

In the case of the sulfur, benzene, and aromatic hydrocarbon limits, producers would have an additional option in complying with the standards applicable to their gasoline when it is first supplied from the production facility. They could choose either a flat limit or a more stringent limit that can be met on average through a "designated alternative limit" process. This averaging option is described below.

The proposed standards for Phase 2 reformulated gasoline are presented below in Table V-2. The rationale for the numerical values selected is explained elsewhere in this report.

---

[1] The provisions in the regulations applicable to producers and the gasoline they sell or supply from their production facilities also generally apply to persons who import California gasoline into the state ("importers") and the gasoline they sell or supply from their import facilities. To simply the discussion of the regulations in this report, references to "producers" apply to both producers and importers unless otherwise indicated.

Table V-2

Proposed Standards for California Phase 2 Reformulated Gasoline

Property	Units	"Cap" for All Gasoline	Flat limit for Producers	Limit for Producers Using Averaging
Sulfur	ppm by wt.	80	40	30
Benzene	vol. %	1.2	1.00	0.80
Aromatic	vol. %	30.0	25	20
Olefin	vol. %	10.0	5.0	N/A
RVP	psi	7.0 a/	N/A	N/A
Oxygen	wt. %	1.8(min) b/ 2.7(max)	1.8 - 2.2	N/A
T90	° F	330	300	N/A
T50	° F	220	210	N/A

---

a/ Applicable during summertime control periods only.
b/ Applicable during wintertime control periods only.

We believe that it is appropriate to have a set of standards for specified gasoline properties as the central feature of the regulations. Any gasoline regulations designed to to reduce emissions from motor vehicles must ultimately involve the identification of specifications, because that is the only way commercial gasoline in the field can be measured and compared. Even a "performance standard" expressed as a required emissions reduction must necessarily be implemented by comparing selected properties of a commercial gasoline against a matrix of specifications determined to yield the necessary emissions reduction. We believe that sufficient studies on the emissions effects of various characteristics of gasoline have now been conducted to justify the selection of a set of specifications which can result in maximum feasible emission reductions. At the same time, the provisions on alternative gasoline formulations will help enable refiners to achieve the anticipated emission reductions in the most cost-effective manner.

We also believe that it is important to identify caps, applicable throughout the distribution system, for the various gasoline properties being controlled. Caps enable enforcement personnel to determine compliance by sampling and testing gasoline in the field. The ability to detect violations through field testing can be a significant deterrent to intentional violations, and can encourage more vigorous quality control programs. Further, in enforcing a cap through field testing there is no need to require extensive recordkeeping or to conduct complicated audits. Caps also help avoid temporal or geographic "spikes" in various properties. The advantages of caps are sufficiently great that we are proposing an absolute limit for each of the regulated properties. Because RVP has been shown to have a major effect on emissions and we believe it it technologically feasible for refiners to meet a 7.0 psi standard without averaging, we propose a single 7.0 psi RVP standard that would generally apply to to all gasoline during the RVP control periods. For the other properties the caps have been set at levels which will permit a meaningful field enforcement program while allowing appropriate variations under the averaging and alternative gasoline formulation provisions.

Many refiners have urged that an averaging program would give them substantially more flexibility in their refinery operations. With averaging they would not have to structure their operations to meet the same flat standard for every gallon of gasoline; when equipment or supply constraints make it necessary to produce batches of gasoline exceeding the standard they could average those with batches below the standard. The refiners indicate that such flexibility is particularly necessary during scheduled maintenance or turnarounds, and would allow them to significantly reduce their costs. We are concerned that averaging makes effective enforcement more difficult and necessitates complex requirements on testing, recordkeeping and reporting. However, we also recognize the advantages of greater flexibility. Accordingly, we have evaluated the processing needs for each standard, and the relative benefit that averaging would provide. We recommend that averaging be permitted for compliance with the sulfur, benzene, and aromatic hydrocarbon standards. With regard to the other properties, we do not believe that the the potential processing benefits of averaging justify the adverse impact on enforcement.

It is important that the averaging provisions not result in overall greater emissions that would result from the flat limit. Producers who choose to meet the flat limit would not produce all gasoline at the maximum permitted levels. The average would be less than the permitted standard. Therefore we propose that producers choosing to comply with the producer standards for sulfur, benzene or aromatic hydrocarbons through averaging must meet a standard somewhat more stringent than the "flat" limit for producers to assure equivalent emissions reductions.

C. APPLICATION OF THE STANDARDS FOR PRODUCERS AND IMPORTERS

The standards other than the caps are imposed on the producer or importer. This is the party that has primary control over the specifications of the gasoline, and that can make most use of the options of complying through averaging or alternative formulations. The standards apply to gasoline when it is supplied by a producer or importer from its production or import facility. This provides a distinct and uniform point in the distribution process at which compliance can be evaluated and verified, before the gasoline is commingled with other gasoline. A provision is included under which the limits for gasoline supplied from a production or import facility do not apply to a party that did not produce or import the gasoline. In that case the party that previously produced or imported the gasoline was subject to the limits, when the gasoline was supplied from that party's facility.

Imposing prohibitions on the "producer" of the gasoline makes it important to identify just who is the producer of a given quantify of gasoline. "Produce" is generally defined as converting liquid compounds that are not gasoline into gasoline. When a person blends volumes of blendstocks which are not gasoline with volumes of gasoline acquired from another person, and the resulting blend is gasoline, the person conducting such blending has produced only the portion of the blend which was not previously gasoline. When a person blends gasoline with other volumes of gasoline, without the addition of blendstocks which are not gasoline, the person does not produce gasoline.

There are two exceptions to this general definition of "produce." First, a refiner who acquires gasoline from another party and agrees both to further process it at the refiner's refinery and to be treated as the producer will be deemed the producer. This is consistent with another provision that exempts the party initially supplying the gasoline under such circumstances from being treated as the producer.

Second, a person who blends oxygenates into gasoline that has already been supplied from the production or import facility, and does not alter the quality or quantity of the gasoline in any other way, will not be considered to have produced gasoline. We propose this approach because it avoids having to subject downstream oxygen blenders to all of the requirements applicable to gasoline producers. It also avoids the difficulties inherent in calculating the specifications of the proportion of a gasoline blend that was "produced" by a person who adds oxygenate. We do not believe it is necessary to assign a particular "producer" to that portion of the gasoline blend because the oxygen blender will not have caused an increase in any of the regulated properties other than oxygen content (e.g. there would be no increase in sulfur content, benzene content etc.).

One consequence of this approach to oxygenate blenders, however, is that while the downstream addition of oxygenate should dilute and thus reduce properties such as sulfur and benzene content, no producer can take credit for this dilution. In order to address the implications of downstream blending, EPA is proposing to allow refiners and importers to sell "reformulated gasoline blendstock for oxygenate blending" ("RBOB") as long it will meet the reformulated gasoline requirements after a specific type and quantity of oxygenate is added. The federal requirements in this area are quite complex. We have not yet identified a practical mechanism under which the producer limits could be enforced at the production facility level while accounting for the dilution effects of downstream oxygenate blending.

D. PROVISIONS UNIQUE TO THE RVP AND OXYGENATE STANDARDS

The RVP standard. Because the RVP regulation only applies during specified regulatory control periods, it contains various provisions not applicable to the other standards. The regulation is very closely patterned after the Phase 1 RVP regulation adopted after the September 1990 Board hearing. The regulatory control periods are identical to those in the Phase 1 regulation except that Ventura County will be included with the South Coast Air Basin rather than the South Central Coast Air Basin; this will treat Ventura County the way it had been in the original nine psi RVP regulation. Air quality data indicate that Ventura County has a similar climate and geography as the South Coast Air Basin and experiences a number of ozone exceedances in April.

The RVP regulation continues the requirements in the Phase 1 regulation that the RVP limits apply one month earlier for gasoline being transferred from a refinery or import facility than for gasoline in the downstream parts of the distribution system. This will help assure that by the time the limits apply to retailers, there has been sufficient replacement of their higher RVP gasoline with lower RVP gasoline. Again like the Phase 1 regulation, the RVP regulation includes provisions intended to clarify the applicability of the standard when gasoline is sold upstream in one control area or time period and dispensed into vehicles in a different area or time period. There will be no liability for otherwise covered upstream transactions if the seller demonstrates that reasonably prudent precautions have been taken to assure that the gasoline will only be delivered to a retail outlet when it is not subject to RVP limits and is not covered by the refiner or importer controls.

The oxygen content standards. The oxygen content caps and standards applicable to producers include limits on both maximum and minimum oxygen content. A primary objective of the minimum limit is to reduce CO emissions. Accordingly, the CO minimum absolute limit applicable throughout the distribution system applies only during the CO regulatory periods discussed in the accompanying staff report on the wintertime oxygenates program.

It is expected that methyl-tertiary-butyl-ether ("MTBE") and ethanol will be the primary oxygenates in the near term. Ethanol is typically not added to gasoline before it reaches the terminal. While gasoline supplied from a production or import facility would initially be subject to both the oxygen content caps and the producer limits, transactions before the final distribution facility would be exempt from the minimum oxygenate requirements if specified steps are taken to assure that the gasoline meets the oxygenate requirements before it is supplied from the distribution facility. This feature is discussed in more detail in the wintertime oxygenates staff report.

E. DESIGNATED ALTERNATIVE LIMITS

As indicated above, an averaging program provides refiners with additional flexibility in complying with the standards. However, the drawback with most averaging approaches is that compliance is entirely dependent on self-reporting and verifying the accuracy and completeness of reported data is very difficult. Therefore, staff is recommending the same sort of "designated alternative limit" approach as is contained in the diesel fuel aromatic hydrocarbon content regulation adopted by the Board in 1988. The two primary features of this approach are that producers notify the ARB of alternative limits being assigned to various batches of gasoline they produce, and that batches exceeding the basic standard be offset with batches below the basic standard. These features enable enforcement personnel to sample gasoline at the refinery in order to determine whether it meets the assigned limit. The designated alternative limit mechanism would be available as an option for complying with the benzene, sulfur, and aromatic hydrocarbon content standards applicable to gasoline being supplied from the production or import facility.

Since producers using the designated alternative limit option would be subject to a more stringent standard than those complying with the flat limit, all producers would have to elect which compliance option they will be subject to. The elections would apply for a minimum of one year and would effective in calendar year increments. The initial election would have to be made by September 1, 1995, and subsequent changes would have to be made by October 1 of the preceding year. Producers electing to use the averaging option for one property would not have to choose it for the others that could be averaged.

Assignment of designated alternative limits. Producers electing the averaging option could assign designated alternative limits to final blends being supplied from their production facility. If no alternative limit is assigned the blend would be subject to default limits of 0.80 vol. % benzene content, 30 ppm by wt. sulfur content, or 20 vol % aromatic hydrocarbon content. The designated alternative limit could not be lower than the property of the gasoline as shown by the testing that the producer is required to conduct.

The producer would have to notify the Executive Officer of the final blend's designated alternative limit and volume. We expect that ARB compliance staff will set up a 24-hour system for telephonic notification. The notification would have to be received before the start of physical transfer of the gasoline from the production facility, and in no case before the producer either completes physical transfer or commingles the blend. The ARB needs to be notified in sufficient time to have the opportunity to verify compliance by sampling some part of the blend before it has left the facility. At the same time, it would be unduly burdensome for refiners to have to hold a final blend for a substantial period before it is shipped out. We believe that the proposal strikes an appropriate balance between these two objectives. Notifications of designated alternative limit batches would be permitted after the specified time periods if the Executive Officer determines the delay was not caused by the intentional or negligent conduct of the producer or importer.

As in the diesel aromatics regulation, the timeliness of offsets would be calculated from the start of physical transfer of blends exceeding the basic standard and from the completion of physical transfer of blends below the basic standard. These events are reasonable and readily identifiable. The producer would be required to timely notify the Executive Officer when these events have occurred.

The regulations would expressly authorize the use of protocols between the Executive Officer and an individual producer to specify how the designated alternative limit requirements are applied to the producer's operations. The diesel aromatics regulation includes essentially identical provisions.

The specific offsetting requirements would depend on whether the applicable standard is (a) sulfur or aromatic hydrocarbon content, or (b) benzene content. For the sulfur and aromatic hydrocarbon standards, offsets would be calculated as they are in the existing diesel aromatics regulation.

A producer could supply a final blend with a designated alternative limit in excess of the basic standard from a production facility as long as the producer offsets the blend 90 days before or after by supplying sufficient quantities of gasoline with a designated alternative limit below the standard from the production facility.

The averaging approach for benzene would involve the establishment of credit account for each production facility. Credits would be deposited for blends with designated alternative limits less than 0.80 vol. percent, and would be withdrawn for blends with designated alternative limits above the basic standard. In order to avoid potentially lengthy periods of production of high-benzene gasoline, the quantity of credits that could be in an account at any time would be limited to 1.20 percent times the volume of gasoline produced by that producer during the last two calendar quarters. The 1.20 percent value equals the reduction in the average benzene content in California gasoline from its estimated current average value of 2.0 percent. If at any time the credit balance in an account is insufficient to allow the withdrawal of the amount of credits needed by a batch of gasoline with a designated alternative limit above the basic standard, that batch will not have been offset.

Producers would be prohibited from selling or supplying gasoline which has been reported pursuant to the designated alternative limit provisions if it does not meet the designated limit, or if the excess benzene, sulfur, or aromatic hydrocarbon content is not fully offset. The regulation would prohibit selling gasoline in a blend with a designated alternative limit above a basic standard if the total volume of the blend sold exceeds the volume reported. It would similarly prohibit selling vehicular diesel fuel in a blend with a designated alternative limit below a basic standard if the total volume of the blend sold is less than the volume reported. These provisions would protect against misreporting volumes of diesel fuel to which a designated alternative limit has been assigned.

Producers electing a designated alternative limit option would be subject to testing and recordkeeping requirements patterned closely after those in the diesel aromatics regulation. They would be required to sample and test each final blend of vehicular diesel fuel for the appropriate property, aromatic hydrocarbon content, and maintain specified records for two years records. Producers would be required to provide the records to the ARB within 20 days of a written request. We believe that these provisions are necessary to enable ARB staff to conduct compliance audits, particularly since the designated alternative limit and small refiner provisions make field testing potentially less effective. Producers would be authorized to enter into protocols with the Executive Officer to specify alternative sampling, recordkeeping, or small refiner reporting requirements. This would afford flexibility to tailor the requirements to special operational needs.

D. ALTERNATIVE GASOLINE SPECIFICATIONS-PREDICTIVE MODEL

The ARB staff is proposing to develop a predictive model for use by the refiners as an alternative to the basic fuel specifications. A predictive model is a set of equations based on the results of a number of motor vehicle emission tests which provide information about how different fuel specifications affect exhaust emissions. There have been several models developed within the last year based on limited emissions data. These data are being complied into a comprehensive database which will allow a thorough statistical evaluation of the effects of gasoline composition on emissions. The data from many of these studies have only recently been made available to the ARB. Therefore, our analysis is not yet complete.

It is our intention to develop a comprehensive model that can be used as an alternative method of complying with the proposed regulation. We expect that this model will include all of the identified specifications in the proposed regulation, and that no alternative specification will be allowed to exceed the absolute limit specified in Table V-2. We also expect to return to the Board no later than early next year to requrest adoption of the predictive model.

The following informtion presents our framework for development of the the predictive model.

1. Limitations on the Use of a Predictive Model

Even when carefully developed, a predictive model can be only of limited usefulness. First, the model should only be used within the range of the data; extrapolation in these circumstances would not be reliable. This means that the values of variables, such as aromatic hydrocarbons, should be within the range of variation used in the experiments, and that relationships between variables existing in the data used for estimation should continue to hold for fuels where reliable prediction is needed.

Second, as a related point, it is not possible to vary certain prescribed factors in a fuel without changing others as an unavoidable consequence. For example, all classes of compounds (aromatic hydrocarbons, olefins, etc.) must add to 100 percent, thus inducing a negative correlation. Although one can produce factorial designs in certain specified variables, others are changed as a consequence, and it may be difficult to determine finally which caused the observed change in emissions.

Third, although the vehicles used in the emission testing are intended to represent certain fleets of vehicles, they are not in any sense a random sample. Thus, any differences in the fuels that vary from vehicle to vehicle cannot be reliably extrapolated to the set of vehicles on the road.

In spite of these limitations, a statistically derived predictive model can be of significant benefit in developing cleaner fuels or less expensive fuels that achieve equivalent emissions benefits.

2. Motor Vehicle Emission Testing Database

The ARB is in the process of compiling a comprehensive database which will allow for a thorough statistical evaluation of the effects of gasoline composition on emissions. The following studies will form the basis of the statistical analysis:

- The Auto/Oil AQIRP-Phase I Studies
- Unocal Parametric Study
- Chevron Study on Aromatic Hydrocarbons and Driveability
- ARB Oxygenate Study
- American Petroleum Institute RVP/Oxygenate Study
- ARCO Clean Fuels Study
- General Motors/Western States Petroleum Association/ARB Study on RVP and Driveability Index
- General Motors/ARB Reformulated Gasoline Confirmation Tests
- EPA Emission Factor Data Base
- API Exhaust Benzene Study
- NIPER/ARB Benzene Study
- NIPER/CRC Study

3. General Approach

As a first step, the aforementioned data sets will be separately analyzed to identify important variables for inclusion in the models. All parameters for which we set specifications would be included in some fashion. Outliers are to be excluded only when there is an identifiable engineering reason for them, not based on statistical criteria alone. Vehicles will be coded as separate random effects to avoid false replication. The primary tool used to identify important effects in factorial experiments will be the normal probability plot of effects. Residuals will be examined to identify any need for transformation of the measurements (such as logarithms), as well as other problems with the underlying models. This entire procedure will be performed for each pollutant considered.

The second stage will be to pool data from all experiments. These will be treated as blocks for the purpose of analysis. Variables identified as potentially important in the first step will be the primary candidates for inclusion in second step models. Unless there is evidence of a need for third-order effects, quadratic response surface models will be developed, eliminating variables that do not seem to be predictively useful. Careful examination of residuals, as well as tests for transformation and added variables will be used to test the validity of the models.

Finally, the prediction error of the model will be codified. Suppose the final model for a pollutant is of the form:

$$Y = X\beta + \epsilon,$$

with residual mean square s^2 (X includes recoded quadratic variables as well as the original variables). Then the uncertainty in β is given by the covariance matrix:

$$s^2 * (X'X)^-$$

If xo corresponds to the reference fuel and x1 corresponds to the candidate fuel, then the predicted difference is:

$$(x1 - xo)\beta$$

with variance equal to:

$$s^2*(x1 - xo)'*(X'X)^{-1}*(x1 - xo).$$

The square root of this quantity is an appropriate standard error for the predicted difference.

4. Criteria for Equivalency

An assumption of this section is that separate predictive models are to be derived for each regulated emission and that a test fuel can be judged to be equivalent to a reference fuel based on predictive models under one of two procedures. The first is as follows:

1. The parameters of the test fuel must fall within the range of reliable prediction of the predictive models.
2. For each regulated emission, the predicted performance of the test fuel must be equal to or better than the predicted performance of the reference fuel.

The second is as follows:

1. The parameters of the candidate fuel must fall within the range of reliable prediction of the predictive models.
2. For each regulated emission, a one-sided upper 85% confidence interval for the difference between the predicted performance of the test fuel and the predicted performance of the reference fuel falls below a percentage (delta) of the predicted performance of the reference fuel. The confidence interval refers to the uncertainty resulting from the set of experiments used to develop the predictive model.

To be certified, a test fuel must result in exhaust emissions of carbon monoxide, oxides of nitrogen, non-methane organic gases on a mass basis, NMOG on an ozone-forming potential basis, and the potency-weighted sum of toxic pollutants that do not individually exceed the emissions of the corresponding pollutants when the reference fuel is used. Staff expects that the RVP will be fixed at 7.0 psi, and that olefins with a carbon number of five or less will be limited to one percent by volume. With these restrictions, the predictive model does not need to address evaporative emissions.

Upon development and approval by the Board of a revised predictive model, the test fuel would have to recertified. For re-approval, the test fuel would have to pass the same emission criterion discussed above for each pollutant measure. If the test fuel should not pass all the criteria, the alternative specifications could not be used following a two-year grace period.

G. ALTERNATIVE GASOLINE SPECIFICATIONS-EMISSION TESTING

The proposed regulations would allow a gasoline producer to apply for certification of an alternative gasoline formulation found through emission testing to result in emissins equivalent to gasoline meeting the Phase 2 reformulated gasoline flat limits. A certification by the Executive Officer would include the identification of an alternative set of specifications. A producer supplying a batch of gasoline from its production facility could notify the Executive Officer that the gasoline is an alternative gasoline formulation in essentially the same way as batches are reported under the designated alternative limit provisions. Gasoline so reported would have to meet the alternative set of specifications rather than the regulatory limits for gasoline being supplied from a production facility. This approach is intended to give producers more flexibility and to provide an opportunity to produce gasoline achieving the targeted emission reductions in the most cost-effective manner.

The central concept is the evaluation and certification of gasoline with an alternative specification, as long as the gasoline sold under the certification does not exceed the specification of the tested gasoline, or exceed the absolute limit specified in Table V-2. This concept permits a very careful scrutiny of the test gasoline, coupled with reasonable assurance that the commercial product should have similar emission characteristics when produced to the test fuels specifications.

The test fuel would be compared directly to the reference fuel which meets the Phase 2 gasoline basic limits, and the results would be statistically analyzed. The comparison would be made by testing a group of vehicles, in vehicle categories that reflect the on-road fleet mix, on both the test and the reference fuel. To be certified, a test fuel must result in exhaust emissions of carbon monoxide (CO), oxides of nitrogen (NOx), non-methane organic gases (NMOG) on a mass basis, NMOG on an ozone-forming potential basis and the potency-weighted sum of toxic pollutants that do not individually exceed the emissions of the corresponding pollutants when the reference fuel is used.

The proposed procedure would, by a statistical test, usually reject specifcations that could cause emissions of criteria or toxic air contaiminats to increase by more than a small tolerance. This tolerance is set at one percent of the emisions expected from the use of California Phase 2 reformulated gasoline. Although it would be desirable to eliminate the possibility of accepting specifications that could increase emissions, practical statistical testing always entails some chance of error.

The specific procedure to be used is entitled "California Test Procedures for Evaluating Alternative Specifications for Gasoline," and is presented in Appendix B of the Staff Report.

This section discusses the major elements of the proposed test procedure, the statistical test to be used, the practical effects of the statistical test, and the requirements made under the various elements of the procedure. Appendix 10 gives the derivations of the statistical parameters.

1. Scope of Requirements

The proposed test procedure prescribes:

-- what gasoline properties could have alternative specifications;

-- how alternative specifications would be set;

-- a fleet of at least 20 gasoline-capable vehicles, including low-emission vehicles, in which to test a test fuel representing the proposed alternative specifications;

-- vehicle categories, corresponding to different levels of emission control, from which the test fleet would be composed;

-- criteria by which test vehicles would be selected from the categories so as to be representative of the road population;

-- a test plan to be submitted by the applicant and requiring approval by the executive officer before testing could begin;

-- the pollutants to be measured (NMOG, reactivity-adjusted NMOG, CO, NOx, and a measure of overall toxic emissions);

-- the procedures for preparing test vehicles for emission measurements and for the emission measurements (Federal Test Procedure);

-- computations on the emission data;

-- the statistical criterion by which the emissions would be compared between the test fuel and Phase 2 gasoline;

-- how the approval of alternative specifications would be made, if the criterion is met; and

-- the procedure of re-approval, which would be required every five years, including a requirement for test data for vehicle categories not available at the time of the initial approval.

2. Synopsis of Emission Comparison

A test fuel is selected to represent the proposed specifications.

The difference in emissions between the test fuel and Phase 2 gasoline (test fuel emissions minus Phase 2 emissions, in grams/mile) is computed for tests in each test vehicle and then averaged over all vehicles within each of several vehicle categories in a test fleet. These average differences by category are combined into a mileage-weighted mean that serves as an estimate of the difference in average emissions between the test fuel and Phase-2 gasoline in the on-road vehicle fleet. A statistical upper bound for this mileage-weighted estimate is computed from the standard deviations of emission differences in the several vehicle categories. A mileage-weighted estimate of average emissions from Phase-2 gasoline among the on-road vehicle fleet is also computed, using the same weights.

For each pollutant, the statistical upper bound for the average difference in emissions is compared to one percent of the average emissions of that pollutant from Phase-2 gasoline. If the upper bound value is greater than the latter number, for any pollutant, the alternative specifications cannot be approved.

3. Practical Effect of the Statistical Comparison

The type of statistical upper bound computed by this procedure is called an "upper confidence limit" in the statistical literature. There is a high probability that an upper confidence limit for a statistical result exceeds the true value of the quantity being estimated. In this case, the probability is about 85 percent that the upper confidence limit computed from the test data will exceed the true average emission difference, among the on-road vehicles, between the test fuel and Phase 2 gasoline. Therefore, if the true emission difference were equal to, or greater than, the one percent criterion value, there would be only a 15 percent, or less, chance that the test fuel would pass the comparison. Thus, the statistical test tends to ensure (but cannot guarantee) that on-road emissions would not increase more than slightly (one percent) if gasoline meeting alternative specifications were to replace Phase 2 gasoline.

A gasoline that would cause an emission difference less than a one percent increase would have a chance greater than 15 percent of passing. A hypothetical case of interest is the gasoline that is exactly equivalent to Phase-2 gasoline in on-road emissions (zero emission difference). The chance of this gasoline passing the criterion for any single pollutant might or might not be significantly greater than 15 percent, depending on the size of statistical variability (random error) in the emission testing. The less that variability relative to one percent, the greater would be the chance of passing for the equivalent fuel.

The statistical variability depends on the design of the test program and the inherent variability of the emission measurements. In general, the greater the number of vehicles tested (a decision made by the applicant) and the more precise the measurements (partly controllable by the applicant), the less is the variability and--thus--the greater the chance of a "good" fuel passing.

4. Details of the Procedure

a. Test Fuel and Establishing Specifications

Among the properties with specifications listed in Table V-2, any but Reid vapor pressure (RVP) could have alternative specifications established by the test procedure. Also, specifications could be established for gasoline properties not regulated by ARB. The specifications for RVP could not be changed because the test protocol does not involve measurements of evaporative and running loss emissions. In addition, olefins with a carbon number of five or less would be limited to one percent. By limiting the RVP and the olefin content, emission testing could be solely based on exhaust emission testing.

Each new specification would be expressed in one of the following ways, as appropriate, for the particular property for controlling emissions.

-- property < [limit value]

-- property > [limit value]

-- [lower limit] < property < [upper limit]

The values of "limit value" would be exactly those measured in the test fuel that the applicant would use in the test vehicles described in subsection c. In the case of a property needing both lower and upper limits, the value in the test fuel would have to be intermediate. Staff would determine whether or not the gasoline properties proposed for specification and the forms of the specifications were appropriate to ensure that all gasoline made under the specifications would be at least as "clean" as the test gasoline.

b. Test Fuel

The applicant would measure, in vehicles described in sub-section 3, the emissions from using a test fuel representing the alternative specifications and the emissions from using Phase-2 gasoline. The test fuel would be fully described in a test plan (sub-section 4) and approved by the ARB staff as part of that plan. If the test fuel would pass the statistical criteria discussed in sub-section 6, the required demonstration concerning emissions would be accomplished for the alternative specifications.

c. Test Vehicle Fleet

The test vehicles would represent all categories of gasoline-capable vehicles, including low-emission vehicles, that make a significant contribution to on-road emissions. The categories aggregate vehicles built under the same emission standards and, therefore, built with similar emission controls. In the analysis of test data, statistics would be calculated within each category.

Table V-3 shows the vehicle categories that could need testing. If, at the time of testing, a category accounts for at least three percent of on-road NMOG emissions or at least five percent of miles travelled, testing would be required in the category.

At least five vehicles would be required per category tested, and the entire test fleet would have to include at least 20 vehicles. Within each category, the draft procedure requires reasonable mixes of engine displacement, manufacturer, model year, emission control system, and other variables, to guard against the creation of a test fleet that would give a biased estimate of the effects of the test fuel in the real on-road fleet.

Table V-3

Vehicle Categories for Testing

Model Year	Description
pre-1975	no catalyst
1975 to 1980	open-loop, oxidizing catalyst
1981 to 1985	early closed-loop, 3-way catalyst
1986 to 1990	current closed-loop, 3-way catalyst
1990+	not low-emission vehicle (LEV)
(1994+)	Transitional LEV
"	LEV
"	Ultra-LEV

d. Test Plan

Before testing could begin, the applicant would need the executive officer's approval of a test plan. This plan would propose the alternative specifications, describe the test fuel, describe the models of the vehicles proposed in each test category, and propose quality-control procedures for the emission tests. This requirement would help to avoid post-testing controversy over the adequacy of the specifications, the test fuel, the test fleet, or the quality and quantity of data.

e. Required Data

Once vehicles were selected and acquired for testing, they would have to be tested without repairs and regardless of emission characteristics. The only grounds for not testing a vehicle acquired per an approved test plan would be a hazard in testing or inability to perform the FTP on the vehicle.

In the testing, the applicant could run any number of tests per vehicle per fuel within an vehicle category. The number could differ among the vehicle categories and would be set for each category by the test plan. Any individual datum could be deleted as a statistical outlier according to the applicant's statistical test approved by the executive officer in the test plan. There is also a provision for deleting data when an "engineering problem"--i.e., a fault in the test procedure or the test equipment--is apparent in the documentation of a test.

Testing would be required only among vehicle categories that are on-road at the time of the tests. However, if at the time re-approval would be required (see subsection i) new vehicle categories have appeared, the existing set of data would have to be supplemented by tests on vehicles in those categories.

f. Emission Comparisons and Statistical Criterion

In each test vehicle, emissions would be measured for both the test fuel and Phase-2 gasoline. The pollutant measures developed from the data would be the mass rates (grams/mile) of (1) exhaust non-methane organic gasses (NMOG)--in terms of both grams NMOG per mile and grams ozone per mile--(2) carbon monoxide, (3) oxides of nitrogen, and (4) a weighted sum of benzene, 1,3-butadiene, acetaldehyde, and formaldehyde. The weights of these four toxic pollutants would be proportional to their unit risk numbers (cancer potencies). Testing would be conducted according to the Federal Test Procedure. For computing grams ozone per mile, emissions of NMOG species would be adjusted by Carter reactivity factors.

For each of these pollutant measures, the applicant would use the test data to estimate the average difference in emissions between the two fuels in the entire on-road fleet of gasoline vehicles. A statistical upper bound on the likely true value of that average emission difference also would be calculated for each pollutant. This upper bound would have to be less than a criterion value. Only if the test fuel passed the criterion for each of the five pollutant measures could the alternative specifications be approved.

The calculations to be performed on the test data are as follows.

- For each vehicle, the difference in average emissions per mile is calculated as the average emissions (per mile, over all tests) from the test fuel, minus the average emissions from Phase 2 gasoline.

- Within each vehicle category, the difference in emissions between the two fuels is estimated as the mean value among test vehicles of the above difference value. The standard deviation of the difference value among vehicles is also calculated for the category.

- The on-road vehicle fleet's average difference in emissions between the two fuels is estimated as a weighted average of the differences in emissions among the vehicle categories. The weights used in the averaging are the ARB's estimates of total miles travelled by on-road vehicles in the various categories.

- The standard error of the estimated average difference in emissions is calculated from the weights, the numbers of test vehicles in the categories, and the standard deviations within categories. The approximate degrees of freedom is also calculated from the same parameters.

- A statistical upper bound on the average difference in emissions for the on-road fleet is calculated from the estimated average difference, its standard error, and the one-sided student-t value for the 0.15 significance level and the calculated number of degrees of freedom. The upper confidence limits computed by this procedure are 85 percent one-sided upper confidence limits for a weighted average of normally distributed random variables. They are based on an approximate t-distribution. The associated degrees-of-freedom parameter is calculated by Welch's approximation. See Appendix 10 for details.

- The maximum allowable value for the upper bound is one percent of the weighted mean of the average emissions measured within vehicle categories on Phase-2 gasoline. Weighting is by the same weights as for the average difference estimate.

g. Potency Weights for Toxic Air Contaminant Emissions

In the calculations and emission comparison, the emission rates of the four toxic pollutants--benzene, 1,3-butadiene, acetalehyde, and formaldehyde --would be weighted in proportion to their unit risks (cancer potency values) and summed to yield a single result. The weights would be each pollutant's unit risk divided by the greatest among them, which is that of 1,3-butadiene. For that compound, benzene, and formaldehyde, the unit risk values employed here are the "best values" recommended by the Department of Health Services. For acetaldehyde, the values is that used for risk assessment by the California Air Pollution Control Officers' Association (CAAPCOA). Table V-4 shows the potency weights.

Table V-4

Potency Weights for Toxic Air Contaminant Emissions

Compound	Weight
1,3-butadiene	1.00
benzene	0.21
formaldehyde	0.17
acetaldehyde	0.016

h. Approval of Alternative Specifications

The proposed procedure would impose on the executive officer schedules for making determinations on the test plan and the applicant's submittal of the test data, calculations, and emission comparisons. If the test fuel were found to meet the emission criteria, the executive officer would approve the alternative specifications and provide notice to the public of the approval.

i. Periodic Re-approval

The initial approval would last five years. At that time and every subsequent five years, the upper confidence limit and the estimate of Phase-2 emissions would both be re-calculated using the then-current estimates of the mile travelled within each of the on-road vehicle categories. The emission data used in the new calculations would be the original data, any additional data volunteered by the applicant (produced under the control of the procedure), and any new data required for new vehicle categories. For re-approval, the test fuel would have to pass the same emission criterion discussed above for each pollutant measure.

If the test fuel should not pass all the criteria, the alternative specifications could not be used after two years from the loss of approval unless one of two things were to happen:

-- additional test data would change the calculational results to satisfy the criteria for all pollutant measures, or

-- the alternative specifications could be approved on the basis of emission models.

G. TEST METHODS AND SAMPLING

1. Goals for Method Development

In choosing a test method to complement a fuel specification, staff considers the cost of the equipment, cost of analysis, availability of the measurement technology, familiarity with the measurement technology, analysis time, turn-around time, degree of automation, ability to be used in the ARB's mobile laboratory, accuracy, and precision. The precision of a method must be cited. Typically, reproducibility, the interlaboratory precision of the test method, is cited.

2. Specified Methods

The following test methods would apply to determining compliance with the standards (other methods found by the Executive Officer to yield equivalent results could also be used):

RVP	ASTM D 323-58 or 13 CCR Section 2297
Sulfur Content	ASTM D 2622-87
Benzene Content	ASTM D 3606-87 ARB MLD 116 (if ethanol is present)
Olefin Content	ASTM D 1319-88
Oxygen Content	ASTM D 4815-88
T90 and T50	ASTM D 86-82
Aromatic Hydrocarbons	ARB MLD 116

The specified sampling method would generally be the ARB's current procedures on sampling for RVP. In the case of samples for properties other than RVP, T90 and T50, references in the RVP sampling method to the required use of a cooling bath would be deleted. The following subsections summarize the proposed analytical methods.

In this discussion, repeatability is the expected variance of test results of replicate measurements within a laboratory. Reproducibility is the expected variance of measurements between laboratories. Both are inverse to "precision" in that the greater is the value of repeatability or reproducibility, the less precise is the method.

3. Additional Development

Industry representatives have suggested that industry and staff work together to improve the accuracy and precision of the test methods. Staff believe that this is a good suggestion and intends to work cooperatively with industry to develop improvements to the test methods. As appropriate, we will recommend changes to the Board concerning test methods prior to the implementation date of the proposed regulations.

4. Proposed Test Method for RVP

a. ASTM D 323-58

ASTM D 323-58 measures the absolute vapor pressure of volatile crude oil and volatile nonviscous petroleum products, with the exception of liquefied petroleum gases. The test method uses a vapor pressure apparatus to contain the test specimen. The apparatus is connected to an air chamber and immersed in a constant-temperature bath. The apparatus is shaken periodically until equibibrium is reached. The pressure is then read.

b. 13 CCR Section 2297

This method measures the total pressure of volatile petroleum products with automated vapor pressure instruments that perform measurements on liquid specimens. The test method uses a thermostatically controlled test chamber. The test chamber is heated under vacuum to a new equilibrium temperature. The resulting rise in pressure in the chamber is measured using a pressure transducer sensor and indicator. The total pressure is converted to the Reid vapor pressure.

5. Proposed Test Method for Sulfur Content

ASTM 2622-87 measures the the total sulfur content in liquid petroleum products with x-ray spectromety. Optimum conditions will allow the direct determination of sulfur in essentially paraffinic samples at concentrations exceeding 0.0010 mass percent.

6. Proposed Test Method for Aromatic Hydrocarbons

ARB Method MLD 116 measures the benzene, other aromatics, and the total aromatic fraction in gasoline by gas chromatography. This method can also be used to analyze gasolines containing up to ten volume percent ethanol. In this method, a highly polar capillary column is used to separate the aromatic and non-aromatic components. A photoionization detector is used in series with a flame ionization detector to quantify the components.

7. Proposed Test Method for Olefin Content

ASTM 1319-88 provides information on the total volume percent of saturates, olefins, and aromatics in petroleum fractions. This test method covers the determination of hydrocarbon types over the concentration ranges from five to 99 volume percent aromatics, 0.3 to 55 volume percent olefins, and one to 95 volume percent saturates in petroleum fractions that distill below 600° F. The method uses a special glass adsorption column in which the hydrocarbons are separated into aromatics, olefins, and saturates by fluorescent indicator adsorption.

8. Proposed Test Method for Oxygen Content

The ASTM D 4815 method is a gas chromatography procedure cited for analysis of methyl tertiary-butyl ether (MTBE) and C-1 through C-5 alcohols. This method utilizes a GC/FID with dual capillary type columns and backflush. The capillary type column is more fragile and more expensive than a packed column but can provide better resolution.

9. Proposed Test Method for Distillation Temperatures

ASTM D 86-82 provides distillation characteristics of petroleum products. This method covers the distillation of motor gasolines and distillate fuel oils. In this test procedure, a sample of the petroleum fuel is distilled under prescribed conditions and thermometer readings and volumes of condensate are recorded periodically. The test can be performed using a specified gas burner and condenser and cooling bath set-up or using an automatic distillation apparatus.

10. Proposed Test Method for Benzene Conent

a. Current Method-ASTM D 3606

ASTM D 3606 is the industry standard method to determine benzene and toluene in gasoline. This method utilizes a gas chromatograph with a thermal conductivity detector (GC/TCD), dual packed column and backflush. An internal standard, methyl ethyl ketone (MEK), is added in a known amount to the gasoline sample. A fraction of the gasoline sample is then introduced into the gas chromatograph, which is equipped with two columns connected in series. The first column is packed with a non-polar phase such as methyl silicone. This column separates the hydrocarbon species in the gasoline according to their boiling points. After octane separates, the flow through the non-polar column is reversed, back-flushing the higher-boiling compounds before they elute. The octane and the lower-boiling components then pass through a column with a highly polar phase such as 1,2,3-tris(2 cyanoethoxy)-propane, which separates the aromatic and nonaromatic compounds. The eluted compounds are passed through a thermal conductivity detector, and the detector signal is recorded on a strip chart recorder. The peaks are measured, and the concentration of each component is calculated relative to that of the internal standard. The official repeatability of this test method (as published by ASTM) is 3% and the reproducibility is 28%.

As a potential test method for enforcing a limit on the benzene content in gasoline, ASTM D 3606 has three weaknesses. First, ethanol coelutes with benzene. This is the major weakness because many gasolines may contain ethanol. Second, the high reproducibility means that the measured value of the benzene content of gasoline could be up to 28% greater than the regulatory limit before a notice of violation could be issued. Third, this method does not use newer state-of-the-art technology such as automated sampling techniques which can improve precision and save time.

Eventually, a benzene test method should be part of an overall sampling and analysis procedure for all aspects of gasoline regulations. However, before that overall procedure is determined, there must be a method to be adopted as part of the regulation on the benzene content of gasoline. This method must allow detection of benzene in the presence of ethanol. For choosing a method for immediate adoption, time does not allow optimization with respect to all the considerations listed above. Therefore, the staff's goal is to complement the currently proposed limit on benzene with a workable and reasonable method. If advantageous, a revised method for benzene can be substituted later when test methods for other gasoline properties are developed.

b. Alternative Methods

i. ASTM D 4053

ASTM D4053 utilizes infrared absorption at 673 cm^{-1} for benzene quantitation. Unfortunately, toluene interferes with benzene but this can be overcome by successive addition, a technique of adding known amounts of benzene to the sample and extrapolating back to zero added amount to obtain the sample amount of benzene. This is labor intensive and requires large volumes of gasoline samples. The published repeatability is 8% and the reproducibility is 18%.

ii. Air Resoures Board Draft Standard Operating Procedure Number 116

The ARB FID/PID (Draft Standard Operating Procedure Number 116) method can be used to speciate all major aromatic components in gasoline including benzene. This method utilizes a GC with a FID/PID duel detector. The PID is not sensitive to aliphatic compounds so the PID response is free of interference and is used for quantitation of benzene. The FID is used as an internal standard to compensate for PID drift. The column is a capillary (megabore) type which is expensive, fragile but provides better resolution. The turn around time is longer than for the current ASTM D3606 but could possibly be shortened, especially if only benzene analysis is required. The repeatability is 2% and the reproducibility was correlated to the repeatability and determined to be 15 - 20%.

iii. ASTM D 4815

The ASTM D 4815 method is a gas chromatography procedure cited for analysis of methyl tertiary-butyl ether (MTBE) and C-1 through C-5 alcohols. This test method is not cited for benzene although a benzene determination can be made. This method utilizes a GC/FID with dual capillary type columns and backflush. The capillary type column is more fragile and more expensive than a packed column but can provide better resolution. There is not a reproducibility value for benzene using this test procedure nor does the ASTM D 4815 state that benzene is free of interference. An ASTM committee is currently generating a written procedure based on ASTM D 4815 which is designed to analyze benzene, toluene, and xylene as well as methyl benzene in the presence of ethanol. Oxygenates cannot be analyzed at the same time as the benzene is analyzed utilizing this method but oxygenates can be analyzed on the same equipment.

iii. Fourier Transform Infrared Spectroscopy (FTIR)

This technology can determine benzene, toluene and xylene, methyl tertiary-butyl ether (MTBE), methanol and ethanol. This is an infrared spectroscopy method that is coupled with multicomponent analysis software (partial least squares) to quantify components based on their particular absorbance patterns. The equipment is expensive. This method should be very repeatable, reproducible and have a very quick turn around time. Unfortunately, this method is not completely developed yet.

iv. ASTM D 3606

This is the current method which has already been introduced. This method is relatively inexpensive technology and familiar to industry. Many laboratories utilize ASTM D 3606 but substitute the TCD for a flame ionization detector (FID). A recommended modification is the addition of automated sampling. The auto sampling decreases turn around time and improves precision. The existing ASTM reproducibility value of 28% can be used as the error limit for compliance testing, without new interlaboratory testing of the modified method, since this change will not decrease the precision.

c. Recommendation

The most expeditious choice of benzene test methods is the ASTM D 3606 with modifications specified to include automated sampling. ASTM D 3606 is currently the industry standard method for determination of benzene and toluene in gasoline. The addition of an automated sampler decreases turn around time and improves precision. The modification should not increase the range of error, so no development of new precision data will be required. ASTM D 3606 is the best choice for benzene analysis of gasooline without ethanol at this time.

For gasoline with ethanol, the ARB SOP #116 is the recommended test procedure. This method can determine benzene content in the presence of ethanol and speciate aromatics. The precision is 2% and the corresponding reproducibility selected by ARB is 15 - 20%. A copy of this test method is included as Appendix 5.

In the future the benzene test method should be integrated into a test procedure for all or several of the Phase 2 gasoline specifications. ASTM D 4815 is promising for oxygenates and benzene provided that 1) there is no interference with the benzene peak and 2) a reproducibility value is determined for the benzene analysis. The new ASTM procedure based on ASTM D 4815 may also work well for Phase 2 gasoline specification. The ARB duel detector method for aromatics and benzene is also promising. As FTIR techniques are further developed, a test method may emerge that can evaluate all the Phase 2 gasoline specified components.

H. VARIANCES

The executive officer would be authorized to issue variances from the various standards in essentially the same manner as in various other ARB fuels regulations. We believe that a variance provision is needed to mitigate, in appropriate instances, extraordinary hardships that are beyond the reasonable control or regulated parties.

I. OTHER ELEMENTS OF THE REGULATIONS

The proposed regulations will authorize the executive officer to exempt gasoline being used for research purposes from the Phase 2 standards. The maximum volume allowed will be 5000 gallons per application. This provision is needed to allow continuing research efforts on gasoline and allow the production of test fuels for the emission testing option discussed in section E. This is similar to a provision contained in the RVP regulation adopted by the Board in 1990.

The regulations would provide that each retail sale of gasoline for use in a motor vehicle, and each dispensing of gasoline into a motor vehicle fuel tank, is also deemed a sale by any person who previously sold the fuel in violation of the substantive standards. This provision would help assure that Health and Safety Code Section 43016 "per vehicle" penalties will apply to persons who sell noncomplying diesel fuel to distributors, service stations or bulk purchaser-consumers. It is based on essentially identical language in several other ARB fuels regulations.

The proposed regulations require producers to provide, periodically, schedules for complying with the regulation. The first plan is due January 1993 with updates provided in January of 1994 and 1995. This provision allows ARB staff to closely follow the refiners' plans to comply with the regulation.

J. PROPOSED MODIFICATIONS TO EXISTING REGULATIONS

We are proposing to make several additional changes to existing regulations. The purpose of these changes is to update provisions to the latest standards, or to ensure that the regulations are consistent with the proposed new regulations. The following changes are proposed:

- <u>Add January 1, 1996, expiration clauses to the following regulations:</u>

  Section 2250 - Degree of Unsaturation for Gasolines
  Section 2251.5 - Reid Vapor Pressure of Gasoline Sold After January 1, 1992
  Section 2252 - Sulfur Content of Gasoline Represented as Unleaded

  These changes will ensure that the existing regulations will not conflict with the new regulations.

- <u>Modify the RVP limit in Section 2251.1 to be 7.80 psi instead of 7.8 psi.</u>

  This change will make the existing limit consistent with the test method requirement of reporting to the nearest 0.05 psi.

- <u>Include Ventura County with the South Coast Air Basin in Section 2251.5, and exclude Ventura County from the South Central Coast Air Basin in Section 2251.5.</u>

  When the 7.8 psi RVP regulation was adopted following the September 1990 hearing, this designation was inadvertently deleted. The proposed change will reinsert this provision in Section 2251.5.

- <u>Change the test method in Section 2252 to 2622-87</u>

  This change will ensure that the most recent and accurate test method is used to determine compliance with the sulfur content limit.

CHAPTER VI.

ECONOMIC IMPACTS OF THE PROPOSED REGULATIONS

A. BACKGROUND

The California refining industry includes a total of thirty individual refineries and altogether processed a total of approximately 1.90 million barrels of crude oil per operating day during 1990. Of the thirty refineries, seventeen facilities produce approximately ninety-eight percent of the gasoline sold in California.

Upon comparison of the various refinery process capacities and configurations, it is evident that all the refineries operating within California can be categorized into four distinct groups which include: topping, hydroskimming, conversion and deep conversion. The following is a brief description of the various refinery groups which are categorized above.

Topping refineries are limited to simple atmospheric and vacuum distillation of crude with products being comprised of naphtha and distillate feedstocks in addition to crude residuals and/or asphalt manufacturing. Typically, these refineries do not market automotive gasoline, but, sell gasoline grade products to larger refineries for further upgrading. However, a few refineries do produce small quantities of diesel fuel.

The second group of refineries which operate at a higher level of complexity within the state are hydroskimming refineries. These refineries possess process equipment which include atmospheric crude distillation in addition to naphtha hydrotreating and catalytic reforming. Catalytic reforming units are utilized to produce a high octane blending component for gasoline. Hydrotreating is used by refiners to remove sulfur from the reformer feed since sulfur has the effect of poisoning the reformer catalyst. These refineries produce small amounts of gasoline and diesel, but, also produce fuel oils and feedstocks for the larger refineries. Hydroskimming refineries commonly purchase some blending components on the spot market to supplement their gasoline and diesel production.

Conversion refineries have more process flexibility in producing more gasoline blending components for the gasoline pool. Process units typically include atmospheric distillation, vacuum distillation, hydrocracking, naphtha and distillate hydrotreating, catalytic reforming and alkylation. However, conversion refineries do not possess coking and some refineries in this class do not posses catalytic cracking capability to upgrade the heavier components of the crude to gasoline and distillates.

The refineries with the most capability to process the heavy components of the crude in order to increase production of high value products such as gasoline and diesel fuel are the deep conversion refineries. Typically, these refineries include the same processing units as the conversion refineries, but, in addition include coking and hydrocracking capacity as well. Within California, there are two deep conversion refineries which do not possess hydrocracking capacity, but, do possess coking.

Table VI-1 shows the contribution from each refinery group to the total gasoline production within the state.

Table VI-1

Characterization of 1991
California Refining Industry

Refinery Group	No. of Refineries	Total Ave. Daily Gaso. Production a/(MB/D)	Percent of Total
Topping	10	0.0	0.0%
Hydroskimming	3	10.2	1.1%
Conversion	5	148.3	15.7%
D. Conversion	12	783.3	83.2%
Total	30	941.8	100.0%

a/ Based on: 1) CEC Quarterly Oil Report, July 1991 (1st. quarter).
2) CEC PIIRA database from Jan. 1, 1991 - March 1, 1991.

Table VI-2 lists all of California refineries operating in each of the four groups in 1991. This grouping separates refineries according to their complexity and groups together refineries that have similar processes and capabilities for gasoline production. In fact, this methodology is common practice and has been has been employed by the Arthur D. Little consulting firm for the ARB in a previous cost study to determine fiscal impacts from the regulation limiting the aromatic hydrocarbon content of motor vehicle diesel fuel (Title 13, California Code of Regulations, section 2256).

B. DISCUSSION OF PROCESS OPTIONS TO MEET PHASE 2 GASOLINE SPECIFICATIONS

Each individual specification proposed by the staff for Phase 2 will in itself require a specific strategy for compliance and in some cases developing a strategy for meeting one specification could either help or lead to adverse effects on other specifications or on gasoline quality and volume. Defining the overall strategy for complying with Phase 2 regulations results in an extremely complex problem due to all the interrelationships which occur while trying to comply with all of the specifications and yet simultaneously maintaining the same production levels.

Processes that a refiner would consider for Phase 2 gasoline are shown in Table VI-3 along with their impact on the gasoline properties that are being regulated. As seen in the table, not all process units will be effective for controlling all the properties that are being regulated through Phase 2 regulations. Individual refineries will need to develop a

---

Table VI-2

1991 California Refining Groups

Group 1 - Topping:

Anchor Refining - McKittrick
Chemoil Refining - Signal Hill
Conoco - Santa Maria
Edgington Oil - Long Beach
San Joaquin Refining - Bakersfield
Witco Chemical - Oildale
Huntway Refining - Benecia
Huntway Refining - Wilmington
Lunday Thagard - South Gate
Ten By - Oxnard

Group 2 - Hydroskimming:

Kern Oil & Refining - Bakersfield
Paramount Petroleum - Paramount
Sunland Refining - Bakersfield

Group 3 - Conversion:

Chevron - Richmond
Fletcher - Carson
Golden West Refining - Santa Fe Springs
Pacific Refining - Hercules
Texaco - Bakersfield

Table VI-2

1991 California Refining Groups

Cont'd

Group 4 - Deep Conversion:

ARCO - Carson
Chevron - El Segundo
Exxon - Benecia
Mobil Oil (BP) - Torrance
Powerine - Santa Fe Springs
Shell - Martinez
*Shell - Wilmington
*Ultramar - Wilmington
Texaco - Wilmington
Tosco - Martinez
Unocal - San Francisco
Unocal - Los Angeles

*- These refineries possess no hydrocracking capability.

Source: 1. Oil and Gas Journal, March 18, 1991, pages 88 through 89.
2. Arthur D. Little report for the ARB entitled, "Cost of Reducing Aromatics and Sulfur Levels in Motor Vehicle Fuels", August 1988.

particular investment strategy to match their capabilities in order to precisely refine the gasoline pool blendstocks to meet Phase 2 regulations. The following is a discussion of probable strategies that refiners would follow to meet the requirements of Phase 2 gasoline.

1. Aromatics and Benzene

Aromatic blendstocks have historically been added to the gasoline pool due to their high octane values. The main source of aromatic hydrocarbons in gasoline derives from the catalytic reformer unit, in addition to small amounts which come from straight run gasoline and the fluid catalytic cracking unit.

Some limits specified for other gasoline properties would help a refiner in meeting the aromatic hydrocarbon content limit. The addition of oxygenates required to meet the oxygenates limit would dilute the aromatic hydrocarbon content of the gasoline pool. EPA has estimated that the addition of 11 percent MTBE would reduce aromatic hydrocarbon levels by about 6 percent. The T90 reduction to 300°F, as required by staff's proposal, would cut out of the gasoline pool a significant part of the C8+ aromatic hydrocarbons which would further reduce the total aromatic hydrocarbon in the gasoline. In addition to the above, refiners would basically pursue two options to reduce aromatics. One option will be to operate the catalytic reformer unit at a less severe condition thereby decreasing the level of aromatic hydrocarbon formed in the reformate blendstock product. The second option is to process high aromatic hydrocarbon blendstocks in order to remove aromatic hydrocarbons through

TABLE VI-3

INVESTMENT PROCESS OPTIONS AND IMPACT ON REGULATED PROPERTIES OF CURRENT GASOLINE POOL

	OCTANE	RVP	OLE	ARO	BEN	SULFUR	T50	T90
BLENDSTOCK PROCESSING:								
Alkylation	+	-	-	-	-	-	+	+
Isomerization	+	+	-	-	-	-	-	-
Dimersol	+	+	-	-	-	-	-	-
Reformer	+	-	-	+	+	+	+	+
Aromatic Saturation	-	+	NC	-	-	-	NC	NC
Benzene, Toluene, Xylene Extraction	-	+	NC	-	-	-	-	-
MTBE	+	+	-	-	-	-	-	-
FCC Gasoline Hydrotreating	-	NC	-	-	-	-	NC	NC
a/ INTERMEDIATE FEEDSTOCK PROCESSING:								
FCC Gas Splitter	NC	-	NC	NC	NC	-	-	-
Reformate Splitter	NC	-	NC	-	-	NC	+	+
Cat Gas Depentanizer	+	-	-	NC	NC	NC		
Dehexanizer	NC	NC	NC	-	-	NC		

a/ These units operate in conjunction with other process units to achieve impacts on limiting qualities. The effect properties shown in the table are the most likely impacts these process equipment will have as part of the refiner's over strategy to comply with Phase 2 regulations.

separation or decrease aromatic hydrocarbons through saturation. Refiners may utilize a reformate splitter, or a fractionator, to separate the heavier aromatic hydrocarbons and the benzene portion of the reformate, thus, reducing the portion of the reformate with the highest concentration of aromatics. The heavier stream could then be charged to a aromatic saturation plant where cyclohexane and other non-aromatic products could be produced, or be sent to a hydrocracking unit for reduction to smaller molecules. However, in the latter approach there is a disincentive since this stream contains the high octane components and processing by hydrocracking would essentially destroy the octane benefit of the reformate. Another option for refiners in reducing aromatic hydrocarbons while reducing the need for reformate is to add new processes such as isomerization, dimersol, or additional alkylation units to produce blendstocks high in octane and low in an aromatic content. Addition of these blendstocks would replace high aromatic blendstocks and would dilute the overall aromatic hydrocarbon level of the gasoline pool.

Benzene predominantly originates in the reformer, but, small amounts come from straight run gasoline from the crude distillation tower. Since benzene is an aromatic compound, methods for reducing aromatic hydrocarbons will also in general reduce benzene. Of the strategies that exist to specifically reduce benzene levels, benzene extraction and benzene saturation are two of the most technologically viable approaches. Benzene is marketed as a petrochemical feedstock for use in plastics production. However, benzene extraction for sales to the petrochemical market will most likely not be feasible due to the lack of demand on the West Coast and prohibitive transportation expense due to toxicity and special handling requirements.

2. RVP, T50 and T90

The proposed limits for RVP and distillation properties would require refiners to maintain tighter control over the distillation range of the specific blendstocks which enter into the gasoline pool. From a processing perspective, refiners would have to utilize various fractionators in order to separate the heavy and light fractions out of the various blendstocks in order to reduce the overall volatility of gasoline, or, have precise control over the distillation characteristics of the products produced in the various process units.

RVP- To reduce RVP, the first likely option for refiners will be to exclude or reduce the butanes in the gasoline pool. Refiner's which currently add butane to the gasoline pool to adjust for RVP and for high octane value would likely have to discontinue this practice. It is possible that butane exclusion from the gasoline pool would not be sufficient to reduce RVP to the 7.0 psi level. This would require refiners to also extract butanes that exist in the gasoline blendstocks and sell them on the open market. However, since a limited market exists for butane, sales levels would be dictated by market forces. Another option exists for refineries with enough butane production capacity is to use butanes in a butane to iso-butylene conversion unit for feed to a MTBE unit, for MTBE production.

Refiners will need to devise additional process options in the case that removing butanes from gasoline would not be enough to meet the 7.0 psi RVP requirement. Toward this end, the most likely step will be to target all light blending components such as light FCC gasoline and light straight run gasoline. These blendstocks may need to be fractionated to remove lighter components such as C5s to subsequently lower RVP. The light ends produced through this fractionation could be sent to other process units such as alkylation, or possibily incorporated into the plant fuel system.

T50- The midrange of gasoline distillation will be affected by all blending components which have midrange temperatures higher than the proposed limit. These components may include: heavy or full range reformate, heavy straight run naphtha, heavy or full range FCC gasoline and heavy or full range alkylate. Oxygenate addition, especially MTBE addition, would probably result in reductions of T50. If insufficient T50 reductions are achieved through oxygenate addition, the fractionation of blendstocks would be required. The final gasoline blend specification would most likely involve blending of the necessary stocks with sufficiently low midrange temperatures to meet the T50 limit.

T90- This specification targets the heavier components of the gasoline pool and would require refiners to further fractionate blendstocks to remove the back end of the distillation range. These heavier components will most likely end up in the naphtha products such as jet fuel or as feed to the FCC unit. The T90 reductions would significantly reduce aromatic hydrocarbons in the gasoline pool because a portion of the aromatic hydrocarbons are in the T90+ distillation range. But, it would increase the aromatic hydrocarbon content in the jet fuel distillates if T90+ products are incorporated into the jet fuel pool. Another impact of T90 reductions would be a shift in the gasoline composition toward lighter gasoline blending components. This in turn would decrease the refiners ability to meet the RVP standard.

3. Oxygenates

In the near term, refiners would have to buy oxygenates from the open market in order to meet the wintertime oxygenate requirement because they would not have the option of building oxygenate plants in time. Likely oxygenates to be purchased include MTBE and ethanol. MTBE due to its high oxygen content, high octane and superior blending characteristics and ethanol because of availability and economics. The long term compliance plan for refiners to meet the 2 percent oxygen content requirement of phase 2 gasoline would likely involve either the building of MTBE plants to the extent that the feedstocks are available, and the economics make it attractive, or the purchasing of oxygenates from the open market. Availability of isobutylene feedstock for MTBE production in a refinery would depend on the size and the type of the FCC unit in operation. The addition of oxygenates would help refiners meet the aromatics limit because oxygenates would replace the need for high octane high aromatics reformate in the gasoline pool and because of the dilution effects. However, if the oxygenate of choice is ethanol it could have adverse effects on RVP, but a combination of MTBE and ethanol could help refiners in meeting the T50 limit.

4. Sulfur

The blendstock in gasoline which contributes the most to gasoline sulfur levels is FCC gasoline and coker gasoline to a lesser extent. FCC gasoline has high sulfur levels because it is produced from processing the heavier components of the crude oil which have higher sulfur levels and are typically added to the pool for its high octane value and relatively low aromatic hydrocarbon content. The strategies that refiners would follow to reduce the sulfur content in FCC gasoline would be to either fractionate the FCC gasoline product, or to severely hydrotreat the feed to the FCC unit. Some refiners currently hydrotreat the feed to the FCC to remove sulfur, but, the level of desulfurization is not adequate to meet the 30 ppm average sulfur limit being proposed. Refiners would need to either increase the severity of hydrotreating, or add an expansion to their hydrotreating capacity to meet the 30 ppm limit. This approach would increase the refiner's need for hydrogen, a necessary ingredient in hydrotreating, and could involve additional capital investment for increasing the existing hydrotreating capacity. The option to treat the FCC gasoline would require fractionation and construction of a high severity hydrotreater to treat the heavier component of the FCC gasoline. If coker gasoline is a part of the gasoline pool it would also need to be hydrotreated at the same levels. A severe hyrdotreating process is capable of reducing the sulfur to a very low level, below 10 ppm. The option of hydrotreating part of the FCC product could be less expensive since refiners will add less capacity to hydrotreat part of the FCC feed instead of severely hydrotreating all FCC gasoline, or all the FCC feed. Hydrotreating of the FCC gasoline would have a small adverse impact on octane value and would increase the need for high octane blending components such as, alkylate, isomerate, or oxygenates to maintain octane.

5. Olefins

Gasoline olefins derive principally from the midrange of FCC gasoline. FCC gasoline has an olefin content which typically ranges from 25-45 volume percent and constitutes approximately 30 to 45 percent of the gasoline pool for conversion and deep conversion refineries. Depending on the levels of olefin content in the FCC gasoline and the percent of FCC gasoline in the gasoline pool, some refiners might be able to meet the olefin standard by changing the operating conditions of the FCC unit with a small penalty or octane values. For others, the olefin reduction strategy could depend on the strategy to reduce sulfur content. To reduce sulfur, desulfurizing of FCC gasoline or a portion of it would be required. This would be achieved by hydrotreating a portion, or all, of the FCC gasoline and hydrotreatment could automatically result in olefin saturation. Such an approach would result in a loss of octane number because of the saturation of high octane olefinic compounds to low-octane parafinic compounds and would increase the need for high octane gasoline blendstocks.

C. COSTS OF COMPLIANCE

1. Capital Cost Requirements

Phase 2 gasoline regulations would force refiners to increase their flexibility to produce various blendstocks with specific chemical properties. The challenge facing refiners in the future will be to produce a gasoline with much stricter specifications while simultaneously trying to maintain control on gasoline production volume and on octane quality. Moreover, refiners will need to do this at a cost which would not be prohibitive to the refiner and result in a loss of competitive advantage in the marketplace.

In order to comply with the proposed Phase 2 gasoline specifications, each individual refiner will have to develop an investment strategy based on the specific processing and operating capability of their facilities. To evaluate the economic impacts to the refining industry, staff is in the process of developing five economic models of California refineries with different complexity which would represent the spectrum of the California refining industry. Because the results of this study are not yet available, staff has developed the cost analysis presented in this report based on cost data provided by six refiners. Staff are also expecting to receive additional cost data from the Western States Petroleum Association (WSPA) and other individual refiners and staff will be evaluating that data prior to the November 21, 1991 Board hearing. Three of the refiners which submitted data are large complex refineries and the remaining can be classified as small refineries.

Table VI-4 shows the capital and operating costs as provided by the refiners. The capital costs include investment costs for the specific process units which will be necessary for Phase 2 gasoline, in addition to off-site costs such as labor, permitting, support equipment (such as pumps, piping, etc.), land cost (if applicable) and other directly related costs. The operating costs are also included in Table VI-4. For those refineries which did not submit an estimate of operating costs, staff assumed that operating costs equaled 50 percent of the total capital investment cost. The 50 percent factor was a conservative estimate since data received by refiners indicate that operating costs typically range from about 25 to 40 percent.

Using the data shown in Table VI-4 and the refinery's gasoline production rates, staff estimated that the capital investment cost ranges from $13 to $21 per barrel-day of gasoline produced. This capital investment cost was then applied to about 900,000 barrels per day of gasoline produced in California to estimate a total capital investment cost from four to seven billion dollars for the California refining industry.

Table VI-6

Estimated Gasoline Production Cost Increase for Six California Refineries

Cost per gallon
(cent/gallon)

Refinery	Staff's Estimates N=10	Staff's Estimates N=15	Refiner's Estimate
A	12	11	30
B	16	15	18
C	12	11	16
D	14	13	N/A
E	N/E	N/E	15
F[b]	4	3	N/A

N/A - Not Available, N/E - Not Estimated.

[a] The staff assumed 50 percent of capital cost to be operating expenses.

[b] This is the cost for meeting the olefin and sulfur limits only.

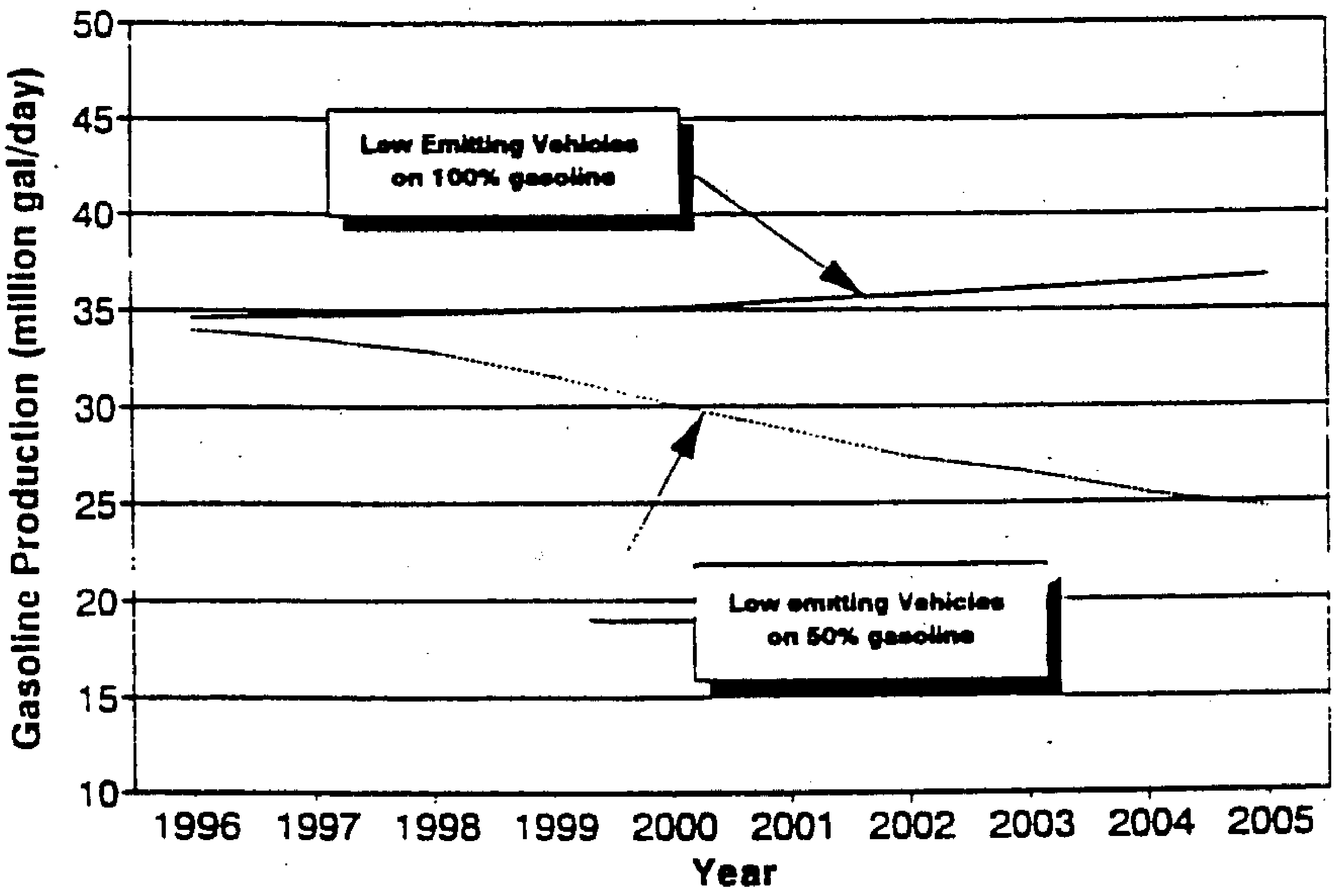
2. Impact of LEV Penetration on Gasoline Price

The staff's evaluation of the cost per gallon assumes that Phase 2 gasoline would be clean enough so that all low emission vehicles could meet the regulatory requirements by using Phase 2 gasoline. The staff has also evaluated a second scenario with the assumption that 50 percent of the low emission vehicles could operate on Phase 2 gasoline and 50 percent of the low emitting vehicles on other clean fuels. Since such an assumption would reduce gasoline consumption in the future when significant volumes of low emitting vehicles penetrate the automobile market, the staff calculated the impact of decreased gasoline consumption to gasoline price on a cents per mile basis. In this scenario, staff used the assumptions on low emitting vehicle penetration and fuel requirements from Table 6-6 of appendix 6 and calculated fuel need for the years 1996 to 2005.

The result of staff's analysis is shown in figure VI-1 and in Table VI-7 and indicates that by the year 2005 the gasoline demand would be reduced by 30 percent. To calculate the cost on a per gallon basis, staff assumed that: (a) 50 percent of the 14 cents/gallon price increase could be attributed to operating cost and (b) in the future when gasoline production is decreased, operating costs would also be proportionately reduced. Figure VI-2 shows the result of this analysis and indicates that by the year 2005, the price of gasoline would be increased from 14 cents per gallon to about 18 cents per gallon. The staff believes that the most likely scenario is probably somewhere between these two extremes.

Figure VI-1

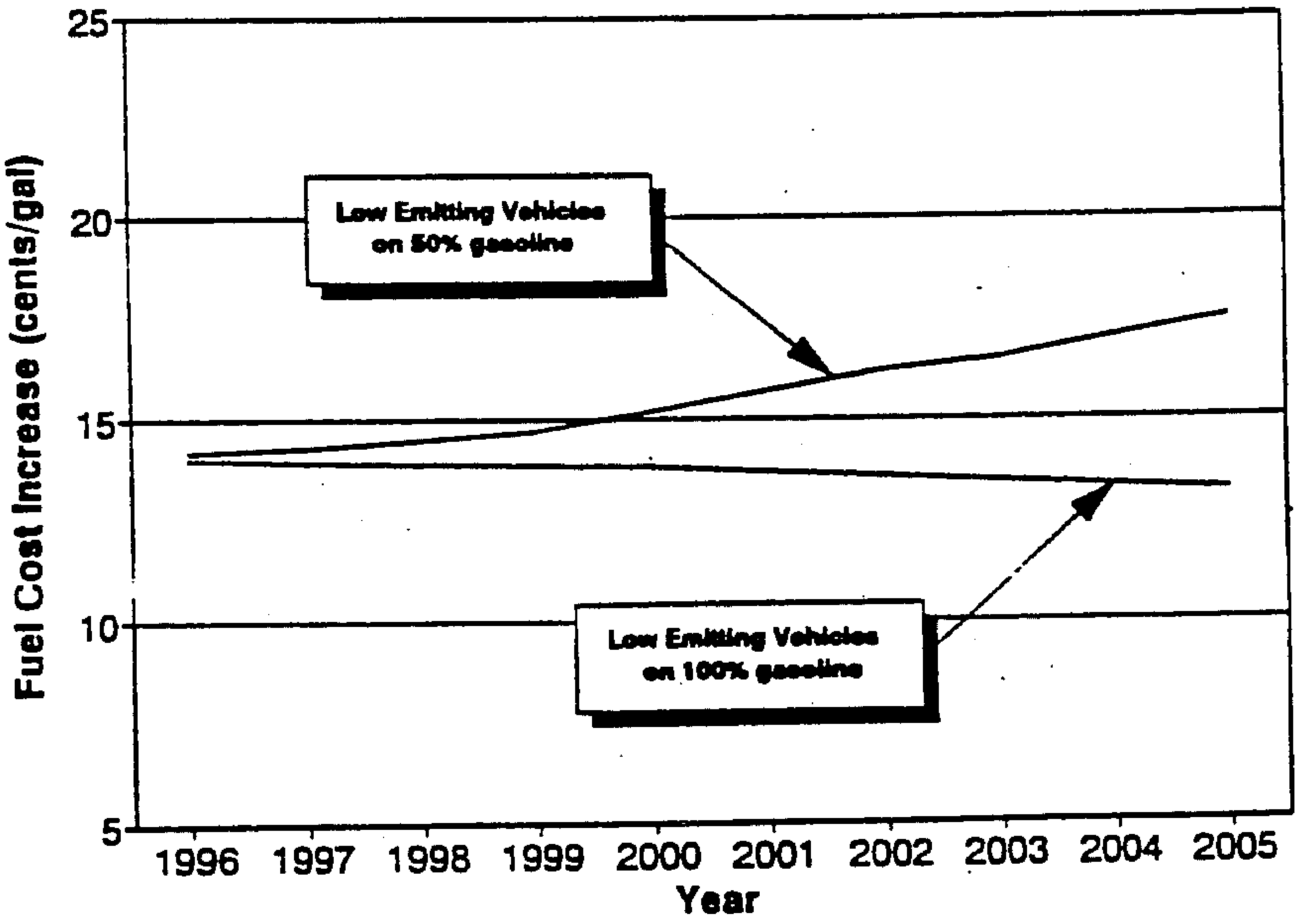
Projected Total California
Gasoline Production Trends



Sources: ARB Ozone Planning Inventory, 1996-2010
Low Emission Vehicle/Clean Fuels Staff Report, August 1990.

Figure VI-2

Average Fuel Cost Increase Due to
Low Emitting Vehicles in the Fleet



Sources: ARB Ozone Planning Inventory, 1996-2010
ARB Technical Support Document, Proposed Regulations for California Phase 2 Reformulated Gasoline, October 4, 1990.

To assess the increased price per gallon, staff adjusted the annualized capital cost to reflect the changing operating cost associated with the decrease in gasoline production.

Table VI-7

Projected Gasoline Consumption 1996-2010

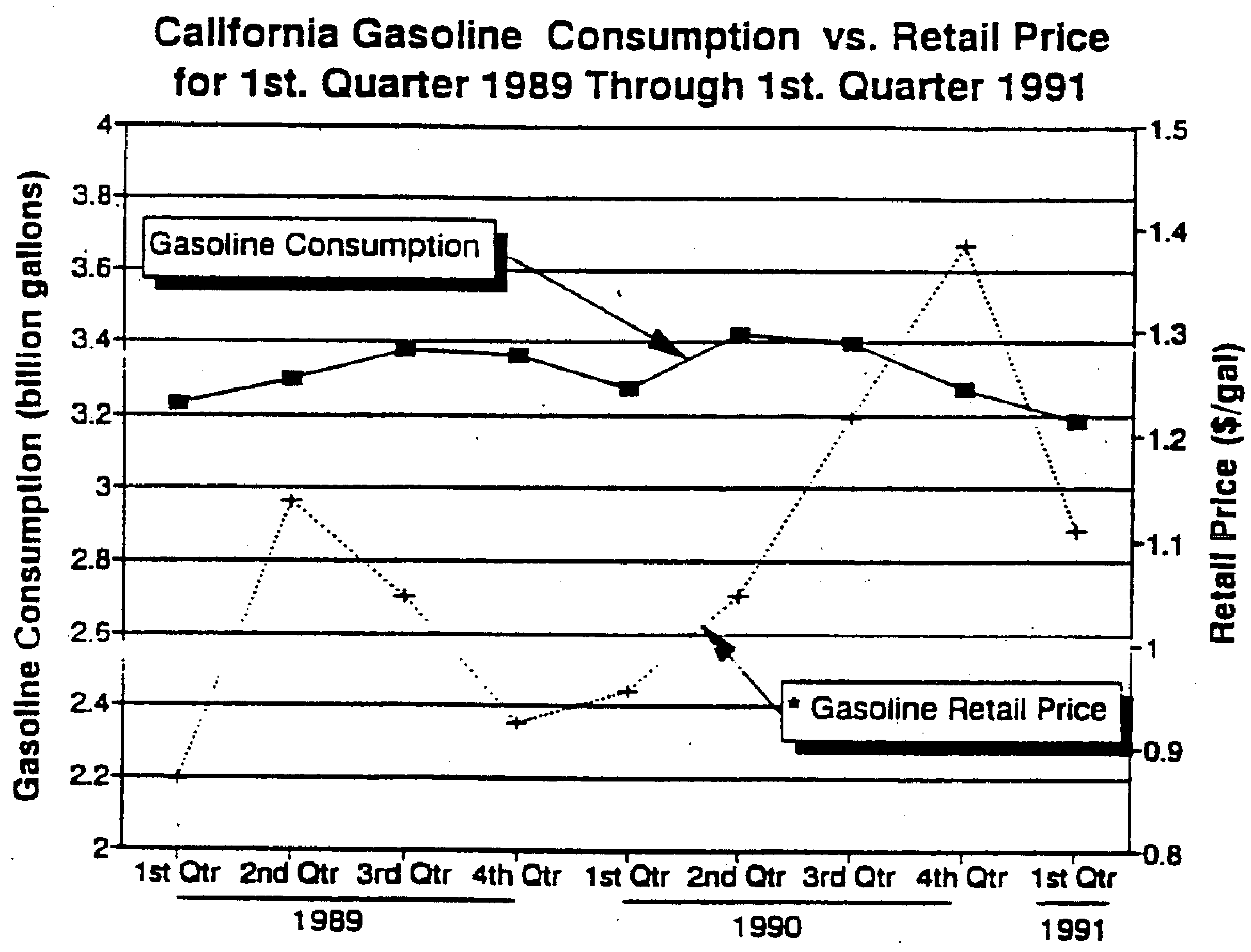
Year	Projected Gaso. Demand (gallons/day)	a/Fraction of Gaso. Displaced by LEVs	Projected Gaso. Demand(w/LEVs) (gallons/day)
1996	34,608,080	0.040	33,223,757
1997	34,725,400	0.071	32,259,897
1998	34,842,720	0.121	30,626,751
1999	34,960,040	0.194	28,177,792
2000	35,077,360	0.288	24,975,080
2001	35,401,753	0.38	21,949,087
2002	35,726,146	0.459	19,327,845
2003	36,050,539	0.53	16,943,753
2004	36,374,932	0.60	14,549,973
2005	36,699,325	0.657	12,587,868
2006	37,023,718	0.70	11,107,115
2007	37,348,111	0.73	10,083,990
2008	37,672,504	0.76	9,041,401
2009	37,996,897	0.80	7,599,379
2010	38,321,290	0.826	6,667,904

a/ ARB 1990 Technical Support Document entitled, "Proposed Regulations for Low-Emission Vehicles and Clean Fuels". These factors account for light and medium duty vehicles

3. Effect of Increased Fuel Price on Demand

The staff has also reviewed historical data in order to evaluate the sensitivity of gasoline consumption to gasoline prices. Figure VI-3 depicts the interrelationship between gasoline price and consumption for the years 1989 to present. As Figure VI-3 shows, significant changes in gasoline prices for the years 1989 and 1990 did not change gasoline consumption with the exception of normal seasonal variations. In fact, during the Valdez oil spill, which is exemplified by the period between the first quarter of 1989 to the second quarter of 1989, prices increased by 25 cents per gallon. But, consumption increased by two percent. The period on the graph between he second quarter of 1990 and the fourth quarter of 1990 corresponds to Iraq's invasion of Kuwait. During this period, gasoline prices rose by 32 cents per gallon, yet, consumption again remained stable with the exception of an expected decrease over the winter months. It appears from these data that gasoline consumption is not that sensitive to fluctuations in gasoline prices in the range of 15 to 20 cents per gallon.

Figure VI-3



*Prices are for self serve unleaded regular

Sources: 1. Quarterly Oil Report, California Energy Commission, May and July, 1991.

2. Interoffice memo dated August 28, 1991, from the Board of Equalization, Office of Research and Statistics, to ARB.

D. COST-EFFECTIVENESS

1. Criteria Pollutants

Staff performed a number of cost-effectiveness analyses by using the estimated cost of production of about 12 cents to 16 cents per gallon and the emission reductions shown in Tables VI-5 and VI-8, respectively. Two cost-effectiveness analysis scenarios were analyzed by staff: 1) Scenario A in which 80 percent of the costs were attributed to reductions in VOC, NOx, 1/7 CO, and SO2 and 20 percent were attributed to reductions in toxic air contaminants, and 2) Scenario B in which 50 percent of the costs were attributed to criteria pollutants and 50 percent to toxic emission reductions.

a. Cost

The costs for the 1996 cost of compliance were calculated by the staff by multiplying the cost of the regulation (12 to 16 cents per gallon) by the total projected gasoline volume in 1996 ($34x10^6$ gal/day). Following this methodology, the staff estimated a cost of compliance of about $4.08 M to about $5.4 M per day. This cost was then multiplied by a Cost Adjustment Factor (CAF) of 80 percent for Scenario A, or, by 50 percent for Scenario B to estimate the cost attributed to reduction of criteria pollutant emissions. The 80/20 split in costs is derived from that previous surveys that have indicated a two to three cent per gallon cost increase for meeting the proposed benzene limit alone. Therefore, about 20 percent of staff's estimated 12 to 16 cent per gallon increase can be attributed to reductions in toxic air contaminants. The 50/50 split in costs is similar to methods used for cost analyses in the past for other regulations adopted by the Board. Based on this methodology, the staff estimated the cost attributed to reductions in criteria pollutants to range from $3.26 M to $4.32 M for Scenario A and $2.03 M to $2.60 M for Scenario B per operating day.

The same methodology was used to determine the costs and emissions reductions for years 1996 to 2005. In this calculation, average yearly cost over the ten year period (1996 through 2005) was determined by utilizing an average gasoline consumption of $35x10^6$ gal/day resulting from the ARB ozone planning inventory. The average cost was then multiplied by 50 or 80 percent to determine cost-effectiveness for the two cost distribution scenarios.

b. Emission Reductions

The staff also estimated emission reductions for 1996 which are shown together with emission reductions for years 1996 to 2005 in Table VI-8. Note that the totals in Table VI-8 include the discounted 1/7 carbon monoxide value as previously discussed.

Table VI-8

Emission Reduction Trend for 1996-2005

Pollutant	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
VOC	104	96.8	89.5	82.3	75	68.6	62.2	55.8	49.4	43
NOx	54	50.9	47.8	44.6	41.5	38.4	35.2	32.2	29.1	26
CO	1305	1212	1120	1027	934	855	775	696	616	537
SO2	36	36.3	36.5	36.8	37	37.2	37.4	37.6	37.8	38
Offroad	14	14.3	14.5	14.8	15	15.2	15.4	15.6	15.8	16
Stationary Sources	16	16.3	16.5	16.8	17	17	17	17	17	17
a/Totals	410.4	387.6	355	341.8	318.9	298.5	278	257.6	237.2	217

a/ Totals incorporate (1/7) CO discounted value in sum.

Average emission reductions for 1996 to 2005 were calculated as the arithmetic average of the reductions shown as the totals in Table VI-8 above.

c. Cost-Effectiveness Calculations

Based on the estimated cost of compliance and the emission reductions for 1996 and for the period 1996-2005, the staff estimated the cost effectiveness by:

$$\text{C/E (\$/ton)} = \frac{\text{Cost of Compliance (\$/day) (CAF)}}{\text{Emissions Reductions (tons/day)}}$$

The results of staff's analysis are shown in Table VI-9.

Table VI-9

Cost-Effectiveness for California Phase 2 Reformulated Gasoline

	Cost-Effectiveness ($/Ton)	
Costs of Compliance	1996 Emissions Benefits	Emissions Benefits Averaged 1996-2005
Scenario A a/		
12 cents/gal	8,000	10,800
16 cents/gal	10,600	14,400
Scenario B b/		
12 cents/gal	5,000	6,800
16 cents/gal	6,600	9,000

---

a/ Based on 80 percent of costs attributed for VOC, NOx, 1/7CO, & S02 reductions and 20 percent of costs for reductions in toxic air contaminants.

b/ Based on 50 percent of costs attributed for VOC, NOx, 1/7CO, & S02 reductions and 50 percent of costs for reductions in toxic air contaminants.

Table VI-9 shows an average range of cost-effectiveness of the proposed Phase 2 gasoline specifications from about three to seven dollars per pound of pollutant reduced depending upon the cost of compliance and the distribution of costs among toxics and other pollutant benefits. In the staff's cost-effectiveness analysis, cost was factored into total aggregate pollutant reductions including carbon monoxide. However, staff discounted carbon monoxide emissions benefits by 6/7 according to the Board's guidance document entitled, "California Clean Air Act Cost-Effectiveness Guidance", published in September 1990. Emissions reductions used are averages for each year and integrated from the year 1996 to the year 2005.

d. Cost-effectiveness to the consumer

The cost-effectiveness calculations performed above does not include the fuel economy penalty which was estimated by some refiners to be about 2-4 cents per gallon. The staff has recalculated the cost-effectiveness to the consumer, using the same methodology described above, based on the resultant increase in the range of gasoline costs including fuel penalty (14 to 20 cents per gallon). The results of this analysis are shown in Table VI-10.

Table VI-10

Cost Effectiveness
Considering Consumer Cost
($/Ton)

Cost Basis	1996	Over 10 year average (1996 - 2005)
Scenario A a/		
14 cents/gallon	9,500	12,800
20 cents/gallon	13,500	18,200
Scenario B b/		
14 cents/gallon	5,900	8,000
20 cents/gallon	8,400	11,400

---

a/ Based on 80 percent of costs attributed for VOC, NOx, 1/7CO, & SO2 reductions and 20 percent of costs for reductions in toxic air contaminants.

b/ Based on 50 percent of costs attributed for VOC, NOx, 1/7CO, & SO2 reductions and 50 percent of costs for reductions in toxic air contaminants.

As Table VI-10 shows, cost effectiveness for these scenarios ranges from about four to nine dollars per pound of pollutants reduced depending on the cost distribution scenario which is being evaluated. Again, as stated in the previous discussion, the carbon monoxide emissions benefits were discounted by 6/7.

e. Cost to the Consumer

The increased cost for gasoline which consumers will pay at the pump is a result of two factors. The increased cost of production at the refinery level and the fuel economy penalty which is associated with the lower heating value of reformulated gasoline. The production cost increase is summarized in Table VI-5 and is estimated to be 12 to 16 cents per gallon.

Some refiners have estimated fuel economy penalty for their reformulated gasoline to be about 2 cents to 4 cents per gallon. Given fuel economy penalty, the resultant increase in the cost to the consumer is expected to range from 14 to 20 cents per gallon.

To add perspective to the costs of reformulated gasoline to the consumer, staff has calculated costs of vehicle operation when reformulated gasoline is used and compared it with current costs. These results are shown in Table VI-11. Cost of vehicle operation includes operating and ownership costs. Operating costs are those costs which arise from vehicle usage and include: gasoline and oil, maintenance and tire wear. Ownership costs are those costs which a person would incur even if the vehicle is not used and include: registration fees, insurance coverage, license fees, depreciation, taxes and finance charges.

To calculate annual operating costs, staff utilized information from the American Automobile Association's pamphlet, "Your Driving Costs". In this report, composite costs of operating a vehicle were calculated for various rates of annual mileage accumulation. Table VI-11 shows the national average range of costs for four different vehicle types and the composite operating costs.

Table VI-11
Annual Operating Costs

Vehicle	Miles Per Year		
	10,000	15,000	20,000
Ford Escort (4-cyl;114 CID)	33.0	20.0	25.1
Ford Taurus L (6 cyl; 182 CID)	41.0	34.2	30.4
Chevrolet Caprice (8-cyl; 305 CID)	44.0	36.8	32.6
Composite	39.3	33.0	29.4

Average annual mileage rate was determined by factoring total vehicle miles traveled with the total number of vehicles on the road by the following calculation:

Average VMT = Total VMT/Total ANV

where:

Total VMT = Total Vehicle Miles Traveled
Total ANV = Total Annual Number of Vehicles Operating

The values used in the equation above were obtained from the California Department of Transportation's report, "California Motor Vehicle Stock, Travel and Fuel Forecast" and resulted in an average VMT estimated to be about 12,000 miles per vehicle. By linear interpolation of the data shown in Table VI-11 for 12,000 mile per year operation, the composite operation cost was then determined to be 37.2 cents per mile. This approximation is reasonable since most of the operating costs are ownership costs which are directly related to the number of miles driven per year. Annual vehicle operation cost was determined by multiplying the operation cost per mile with the average VMT (12,000 mi/yr).

Fuel cost was determined by apportioning the fuel-weighted fraction of the operating cost and adjusting that portion with the increased price of gasoline associated with Phase 2 gasoline. For the base case, annual fuel cost was determined by multiplying the fuel weighted portion times the average VMT. From the American Automobile Association's pamphlet, the average fuel portion of the operating cost was 5.4 cents per mile, which includes oil costs. To determine the fuel cost only, staff subtracted the cost of oil used from the total fuel cost. The cost of oil used was estimated by:

$$\text{Annual Oil Change Cost (\$/mi)} = \frac{\text{(3 oil changes/yr)(25\$/oil change)}}{\text{12,000 mi/yr}}$$
$$= 0.0063 \text{ (\$/mi)}$$

Therefore, the fuel cost is 0.047 $/mile, which is multiplied by 12,000 miles per year to calculate an average annual fuel cost of $572 per year. To calculate future operating costs resulting from Phase 2 regulations, staff adjusted the base fuel cost portion of the total operating cost ($0.0477 per mile) to include the added cost of Phase 2 gasoline. This resulted in an adjusted fuel cost portion of $0.054 per mile (for a 14 cent/gallon increase basis) and $0.056 per mile (for a 20 cent/gallon increase). The resultant change increased the cost of operating a vehicle to 37.8 cents per mile (for a 14 cent increase) and 38.0 cent per mile (for a 20 cent increase). These results are shown in Table VI-12. Once the adjusted cost of vehicle operation was determined, staff calculated the annual vehicle operation cost by multiplying the adjusted operating cost by 12,000 miles.

In summary, the overall effect of reformulated gasoline use to the average consumer would increase the cost of operation of a vehicle by 1.6 percent to 2.1 percent on a cost per mile basis.

Table VI-12

Impact of Phase 2 Reformulated Gasoline
Regulations on the Cost of Operating a Vehicle a/

	Current Costs	Costs After Regulation @ $0.14	@ $0.20
Average Vehicle Operation Cost (cents/mile)	37.2	37.8	38.0
Fuel Cost (cents/mile)	4.8	5.4	5.6
Typical Fill-up Cost	$11.4	$12.8	$13.4
Annual Fuel Cost	$572	$643	$673
Total Annual Cost	$4464	$4536	$4560

Source: American Automobile Association pamphlet entitled, "Your Driving Costs", 1990.

a/ Based on 12,000 mi/yr operation and $1.14/gal fuel price. The 12,000 mile average is derived from total miles traveled and total vehicle population from California Dept. of Transportation's report entitled, "California Motor Vehicle Stock, Travel and Fuel Forecast", dated November 1989. The $1.14 per gal fuel price is average retail price of unleaded regular from 1st. quarter 1990 through 1st. quarter 1991 from the CEC Quarterly Oil Report, July 1991.

2. Toxic Air Contaminants

The cost-effectiveness of the Phase 2 gasoline specifications is expressed, for toxic air contaminants, in terms of cost per potential cancer case avoided. As explained in a previous chapter, the Phase 2 gasoline specifications are expected to result in a total of 35 potential lifetime cancer cases avoided per year over the 15-year period form 1996-2010. Under Scenario A, 20 percent of the total costs to the consumer of meeting Phase 2 gasoline specifications are attributed to toxic air contaminant reductions, resulting in a cost of 11 to 16 million dollars per cancer case avoided. Under Scenario B, 50 percent of the total costs to the consumer for meeting Phase 2 gasoline specifications are attributed to toxic air contaminants, resulting in a cost of 28 to 40 million dollars per cancer case avoided. All of these values are within the range of cost-effectiveness values for other air toxic air contaminant measures already adopted by the Board. For example, the recently adopted low emission vehicle/clean fuels program had a cost per cancer case avoided of 5 to 50 million dollars.

E. COMPARISON TO OTHER MEASURES

Table VI-13 shows a comparison of the cost-effectiveness of the Phase 2 reformulated gasoline as a control measure to other measures that have been adopted in recent years.

Table VI-13

Comparison of Cost-Effectiveness of the Proposed Phase 2 Gasoline Specifications with Cost-effectiveness of Other Control Measures

Source	Pollutant(s)	Capital Cost (million $)	Cost-Effectiveness ($/Ton of Pollutant Reduced)
Aromatics Content of Diesel Fuels	NOx, PM10	720	14,000
Low Emission Vehicles/Clean Fuels	VOC,NOx,CO	N/A	10,000-32,000
Light Duty Diesel Exhaust Standards	PM10	N/A	5,400-21,400
Light-Duty Gasoline Vehicle Standards	NOx	N/A	1,300
Heavy Duty Diesel Exhaust Standards	PM10	N/A	6,400
SCAQMD Rule 1135 Power Plants	NOx	532	24,000-30,000
SCAQMD Rule 1146 Industrial Boilers & Heaters	NOx	N/A	20,000
Phase 2 Gasoline	VOC, NOx CO, SO2	4,000-7,000	2,000-18,000

Source: ARB/SSD

As shown in Table VI-13 above, the cost-effectiveness of the proposed regulation is within the range of other control measures adopted by the Board or the districts.

F. ANALYSIS OF COSTS USING LINEAR PROGRAMMING MODELS

For determination of the fiscal impacts stemming from Phase 2 regulations on the refining industry, staff intends to conduct an in-depth study through the use of linear programming (LP) refinery models. This approach will provide specific economic data for specific refineries operating within California. Results from modeled refineries will provide valuable information when evaluating the rest of the refineries with similar operating characteristics. However, since at the present time the LP models are not yet sufficiently developed to produce an accurate assessment of costs, staff utilized data submitted from refiners, in addition to other sources of data, to estimate the fiscal impact on the refining industry. The presented cost analysis indicates a preliminary cost estimate and we wxpect that a more refined cost-analysis will be completed once the refinery LP models have been fully developed. The staff believed that the LP analysis would result in optimizing costs for the refineries and therefore could be a lower estimate than the costs used in the cost effectiveness presented in this report. A more detailed discussion of the LP analysis is given below.

1. Refinery Cost Analysis Through LP Refinery Modeling

A linear program is a mathematical technique which is commonly used to find optimum solutions to problems which consist of many unknowns. More specifically, linear programs are a series of equations that are developed to characterize the unknowns and interrelationships of a well defined problem. Linear programs can be arranged to produce a determinant matrix of coefficients which can then be solved to produce an "optimal" answer to the set of equations defining the problem. An LP refinery model is simply an application of the linear programming technique to the refining industry. Refining operations inherently lend themselves to solutions through the LP technique and have proven to be accurate and reliable. Moreover, the current state of the art in computer technology provides the capability to encorporate more sophisticated and efficient algorithms in order to solve more complex problems.

To determine the cost impact affecting refiners from staff's proposed regulations, ARB staff contracted the services of the Bechtel Corporation to develop a series of linear programming refinery models which would simulate actual refinery operations. For this study, specific California refineries were modeled from each of the four groups discussed in the background. Two refineries were modeled in the deep conversion group. The specific refineries from each group include:

- Topping - Chemoil Refining Corp. (Signal Hill)
- Hydroskimming - Kern Oil & Refining Co. (Bakersfield)
- Conversion - Fletcher Oil & Refining Co. (Carson)
- Deep Conversion - Tosco Corp. (Martinez)
- Deep Conversion - Texaco Refining & Marketing (Wilmington)

2. LP Study Methodology

In assessing the art of Phase 2 regulations, staff needs to estimated the fiscal impacts affecting the public resulting from increased production costs at the refinery level. In staff's LP analysis, increased production costs were determined through a comparative analysis in which net operating margin for California refineries was compared at two points in time. The base case for this study incorporates current refinery process configurations and production costs of Phase 1 reformulated gasoline. Projected future case includes the capital investments and production costs required for production of Phase 2 reformulated gasoline. The change in net operating margin between the two cases will be determined, in addition to total motor gasoline volume, in order to calculate the corresponding increased cost in cents/gallon. The higher costs of production mainly result from capital costs and associated increased operating costs from needed process units necessary for the production of reformulated gasoline. Capital and operating costs will be determined for the modeled refineries, and those costs will be extrapolated to other refineries within California with similar processing capabilities to evaluate the overall impact of staff's proposals on industry.

For our study, Bechtel utilized their proprietary LP refinery modeling system software called the Process Industry Modeling System (PIMS). PIMS is developed and marketed by the Bechtel Corporation for use in simulating various process industries, and is widely used by the California refining industry to perform investment analysis and plant process optimization. The unique "modular" design feature of the PIMS software allows the user the flexibility to model virtually any refinery process and makes PIMS well suited for a cost study of this nature. Actual operations data is input into the PIMS model and when the LP is solved, PIMS creates and solves a determinant matrix and maximizes an objective cost function which in this case represents the net operating margin of a refinery. In order to maximize net operating margin, PIMS minimizes operating costs, feedstock purchases, utility consumption, etc. and maximizes production of high value products.

a. Study Basis:

As previously discussed, staff performed a comparative cost analysis in which the profitability of a refinery could be compared for two different points in time. To assess the full impact of Phase 2 regulations, the LP model needed to reflect operating conditions facing refiners for two different regulatory scenarios. The first regulatory scenario that the staff evaluate will consist of the base case in which refiners are mandated to comply with Phase 1 reformulated gasoline specifications. These regulations consist of a 7.8 psi RVP maximum (during the RVP season April through October), prohibition of use of tetra-ethyl lead (TEL) starting in 1992, the use of deposit control additive, and a prohibition on sales of commercial leaded gasoline starting in 1994. Will have from a modeling perspective, staff will utilize a scenario in which refiners to comply with the 7.8 psi RVP, in addition to no sales on leaded gasoline.

This previous scenario will compare with the future projection in which refiners would be facing phase 2 regulation specifications in the year 1996. When projecting forward, staff assumed that production of reformulated gasolines for 1996 would be at the same levels as today. Future crude prices were obtained from the 1989 Fuels Report released by the California Energy Commission (CEC).

b. Extrapolation of Costs to other refineries:

The methodology which will be followed for extrapolating costs to other members within each refinery group will be similar to the approach used in a previous analysis done by the Arthur D. Little consulting firm in the study to reduce aromatic hydrocarbon content of motor vehicle fuels.

3. LP Development

a. Data Base for LP development:

The accuracy of the LP model is directly related to the robustness of the data base being used for the development of the refinery model. Obviously, the more information which can be added to the model, the more accurate the representation of the actual refining process will be. For staff's LP modeling effort, data were obtained directly from refiners which cooperated with ARB's refinery LP development. Additional specific operating data were obtained for typical operating periods in 1990 and 1991 through the refinery survey shown in attachment 1 and private consultations for follow-up information.

b. LP Validation

Staff's goal for the validation of refinery LPs is to reasonably simulate actual refinery operations in three areas: material balance, final product quality, and capacity utilization. Staff attempt to obtain the necessary data to fully validate the performance of the models based on the criteria stated above. However, in some cases, the specific data needed was not available or simply did not exist. In those situations, substitute generic data will be used as an estimate. Some of these data were provided by Bechtel and are representative of typical data seen in practice.

To ensure that the LP models would reasonably reflect reality, Bechtel validated all the LP models under ARB guidance. Since not enough time or data was available for rigorous refinment of the model, LP validation primarily focused on maintaining representative material balance. The LP results of finished product qualities were also compared to data obtained from ARB's Voluntary Reporting Program for a further indication of model performance. Model results were also compared to actual regarding processing unit capacity utilization. This comparison was appropriate when Bechtel modeled the specific refinery configuration identically. In some cases, Bechtel utilized library submodels in lieu of actual processing unit representation in order to simplify the LP structure.

Bechtel validated the LP models to the extent possible given the strict time constraints present and limitations with data utilized for the study. Overall, the LP models depicted real refining material balance sufficiently accurate for the cost determinations of this study.

c. Status of LP Refinery Models:

Currently, five refinery models have been develped by the Bechtel Corporation for use in ARB's LP cost analysis. Of the five models, the models representing the topping and hydroskimming refineries, Chemoil and Kern models, respectively, incorporate relatively simple process submodels due to the level of complexity of these refineries. However, the models representing the conversion and deep conversion refineries (Fletcher, Tosco and Texaco) involve increasingly more sophisticated LP techniques and more need for property data.

Reconciliation of the base Chemoil and Kern models proved to be a relatively straight forward task. Reasonable duplication of material balance was achieved for these two refineries. However, refinements still need to be made to more accurately reflect actuacl product slate.

The Chemoil model will not include investment models since these refineries typically do not produce finished gasoline for competition in the open market. Investment submodels have been added to the Kern model, but, since refinements in data inputs need to be made, those investment options have not been evaluated.

The current status of the Fletcher refinery LP model provides for a realistic representation of actual operations. Material balance produced by the model closely reproduces the data sumbmitted by the refinery and comparison of process unit capacities also closely match reality. Moreover, the finished gasoline grade properties are accurately represented when comparing with refiner's data and results from ARB's Voluntary Gasoline Properties Reporting Program.

The Fletcher model includes various investment option submodels to evaluate Phase 2 regulatory impacts. However, at the time of this report a full assessment of the performance of the investment models could not be determined. At this point it is apparent that inconsistances in property data may exist.

The Tosco model has proven to be the most complex of the five refinery models. The basis for ARB's Tosco model development stems from Tosco's own proprietary PIMS refinery model. To a large extent, data for ARB's model is derived from Tosco's model. The current status of the ARB's Tosco model is it reasonably represents the actual material balance with actual 1990 operations data. Gasoline final properties are also in reasonable agreement. However, at theis time a detailed analysis of specific fuel property disparities has not been performed.

Several sensativity case runs of the model indicate that the LP's respond appropriately to different problems. However, the investment option case runs seen to show deficiencies in property data associated with the new investment submodels.

The Texaco model has proven to be troublesome, in part due to the atypical process configuration of the refinery. However, Bechtel has successfully modeled the Texaco refinery with all appropriate intermediate streams and process flow given the data supplied by the refiner. This refinery LP still needs to be fully evaluated to assess the overall performance. Initially, it is evident that property data and process submodel refineries need to be made to better represent material balance.

Staff intends to complete the LP analysis prior to the November Board hearing. To this end, additional refinements to most of the models needs to be accomplished. In addition, update of capital cost of investment units and further changes to various properties still needs to be done. It is staff's goal to finalize the development and validation of the models in order to accomplish a detailed study of costs for the entire refinery industry in time for the November Board hearing.

G. COST ESTIMATES FOR BENZENE LIMIT IMPLEMENTED ALONE

The staff received data from 19 California refineries in 1988 on their capital and operating costs for meeting limits of 1.2, 1.0, 0.80, and 0.60 percent by volume benzene in their typical gasolines. The respondents accounted for 90 percent of the gasoline used in California in 1987. The aggregate responses (in 1988 dollars) are in Appendix 3, and the estimation of costs from the responses is in Appendix 6. The data apply specifically to meeting a limit on the benzene in each respondent's typical or average gasoline. Thus, the data are best suited for estimating the cost of meeting the basic limit (0.80 percent by volume). However, the staff has also used the data to estimate the cost of meeting the absolute limit on benzene (1.20 percent by volume).

The cost data in the survey responses apply if the benzene limit were the only new specification for gasoline. In such a case, reducing the benzene content wold involve adding new equipment to the "tail-end_ of existing gasoline production processes. However, meeting the entire set of Phase 2 specifications would greatly alter the existing process and, via the aromatic limit, reduce the the benzene content even without a benzene limit. Therefore, the costs shown in this section should not be viewed as the exact component for meeting the benzene limit within the overall cost for the Phase 2 specifications. However, the costs do represent an upper bound on the benzene limit's component of the total cost.

1. Cost to Refiners

A refiner's net cost for meeting a regulation is the sum of (1) increased operational expenses (for labor, fuel, utilities, purchased stocks, etc.), (2) the cost of debt incurred, or capital expended, for new equipment, and (3) reductions in income tax from the expenses. The refiner's cost is equal to the reduction in annual profit if there were no increase in revenues (i.e., no price increase for gasoline).

Table VI-14 shows estimates of the total initial capital investment needed for all refineries in the state, the total increased operating expenses, and the average refiner's cost expressed in cents per gallon for several values of a basic benzene limit. Details of the calculation are in Appendix 6. For the proposed basic limit (0.80 percent by volume), the average cost among all gasoline is 1.6 cents (in 1991 $) per gallon. Among the refiners who responded to the survey, the cost ranges from 0.35 to 5.5 cents per gallon. In addition, there would be a cost to comply with the absolute limit of 1.20 percent by volume. The staff has assumed a need for redundant equipment capable of meeting the absolute limit when the primary equipment (used to meet the basic limit) would be out of service for maintenance. The amortized capital for redundant equipment for 1.20 percent by volume benzene is 0.42 cents per gallon.

Table VI-14

Refiners' Cost[a] of Reducing Benzene in Gasoline

Basic Limit (vol. %)	Capital Cost (million $)	Operating Cost (mill. $/yr)	Average Cost[b] (cents/gal.)	
			avg.	range
1.20	740	170	1.1	(.20 - 2.0)
1.00	860	230	1.3	(.20 - 4.9)
0.80[c]	1,100 (740)*	280 --	1.6 (.42)*	(.35 - 5.5)
0.60	1,410	370	2.2	(.72 - 6.5)

[a] after tax; among all refineries supplying California; 1991 $

[b] average over all gallons; range among refineries

[c] corresponding to the proposed regulation

* added cost of meeting absolute limit (1.20 percent by volume).

The numbers in the table apply if gasoline will be the sole fuel for low-emission vehicles (LEVs). If other fuels displace gasoline in LEVs, the refiners costs would be lower because there would be less demand for gasoline to meet the limits, but the cost per gallon would increase.* In the case of gasoline used in half of all LEVs, the estimated average cost per gallon to meet the basic limit (0.80 percent by volume) is 2.6 cents per gallon over the period 1996 to 2010 (to compare with 1.6 cents in the table). (The cost of meeting the absolute limit remains 0.42 cents per gallon.) The estimation of cost when gasoline is not used in all LEVs is described in Appendix 6.

The survey responses do not suggest that reducing benzene in gasoline would cost more per gallon for a small refiner than for a large one. However, the data do not address potential difficulty in financing capital expenses. The need to meet the recently adopted limits on the aromatic and sulfur contents of diesel fuel could affect the ability of small refiners to raise capital. Also, the staff did not receive survey responses from blenders. One importer provided estimates of the costs for meeting the basic limit by removing benzene from the gasoline it receives. The costs are equivalent to 9 to 13 cents per gallon. These estimates are higher than the refiners' estimates because of the smaller scale of the importer's operations and the need to provide basic refining infrastructure as well as equipment to remove the benzene.

2. Potential Cost to Consumers

The effect of the refiners' extra costs on the price of gasoline (the consumer's cost) is difficult to predict. One possible value of price increase that is of particular interest is the price corresponding to the increased revenue needed to exactly offset the refiners' added costs, called the "revenue requirement". If a refiner's revenue requirement is attained, its net profit of operation would not be affected by the regulation. The revenue requirement is higher than the cost because a profitable business must pay income taxes--with funds that come from revenue.

---

* This results from an assumption that the capital investment in 1996 would be the same whether or not gasoline demand would decrease in the future because of LEVs.

Table VI-15 shows the price increases corresponding to the average, high, and low revenue requirements among the refiners who responded to the survey. Since the range among the refiners is large, a price increase corresponding to the average revenue requirement would increase profits for some refiners and decrease them for others.

Figure VI-4 is a graph of the average revenue requirement per gallon. It shows that the incremental requirement increases sharply for benzene limit less than 0.80 percent. At 0.80 percent by volume (the proposed value), the price increase is 2.76 cents per gallon with an additional 0.70 cents for meeting the absolute limit.

Table VI-15

Price Increases that Would Meet Aggregate Refiners' Revenue Requirements

Basic limit (vol.%)	Revenue required[a] (mill.$/yr.)	Price increase[b], cents/gal	
		average[c]	range[d]
1.20	288	1.77	0.33 - 3.38
1.00	364	2.24	0.34 - 8.16
0.80	450 (114)*	2.76 (.70)*	0.58 - 9.19 ---
0.60	589	3.61	1.21 - 11.0

[a] to leave aggregate refiners' profits unaffected; million $/year

[b] to raise the revenue

[c] total revenue required / total gallons

[d] range among refiner's revenue requirements

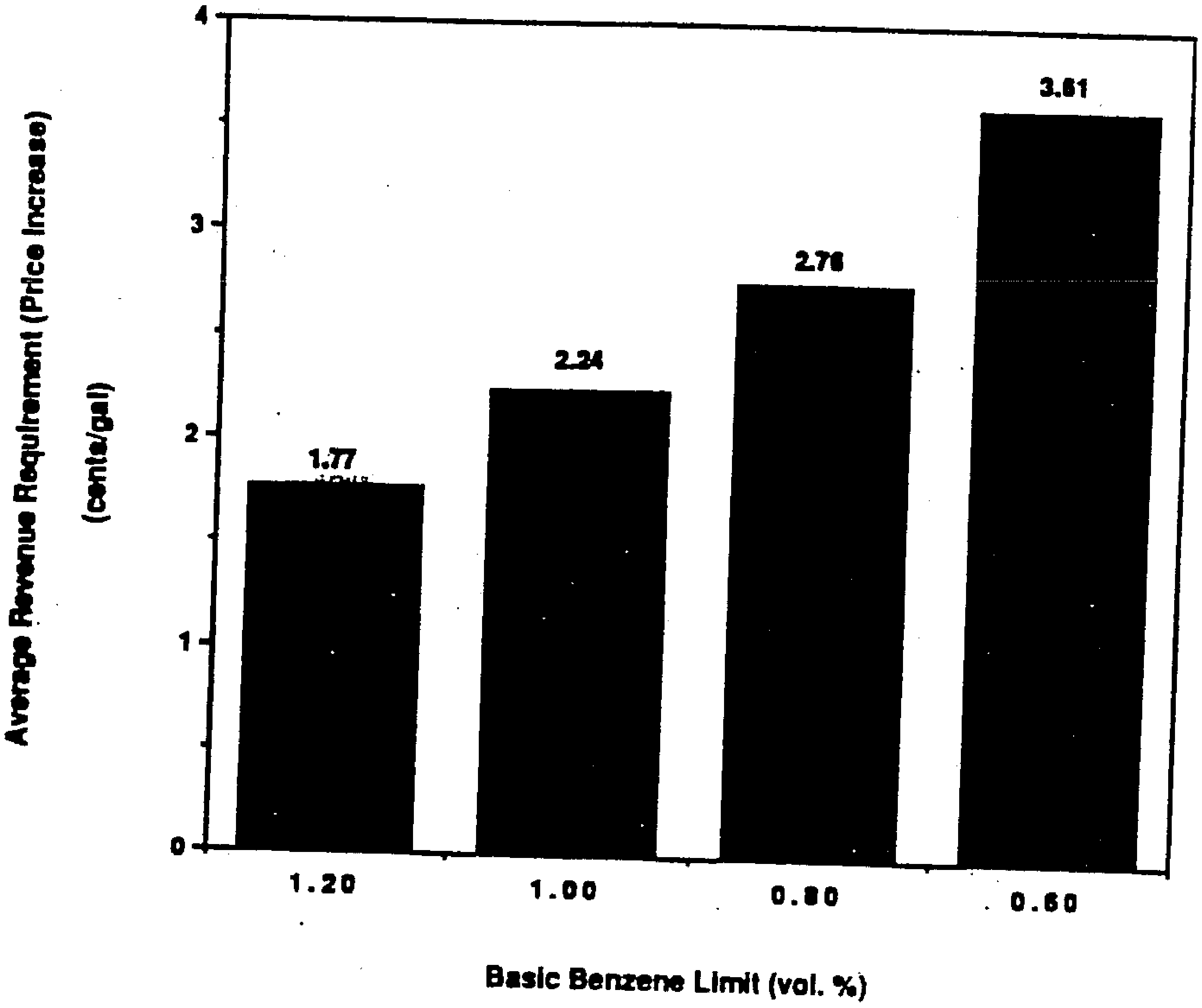
* added revenue to meet absolute limit at 1.2 percent by volume.

The revenue requirements in the table apply if gasoline will be the only fuel used in LEVs. If gasoline would be used in in only half of the LEVs, the revenue required per gallon would be 3.23 cents per gallon for meeting the basic limit at 0.80 percent by volume (to be compared to 2.76 cents in the table).

For computing cost-effectiveness of the proposed regulation, the staff uses the price increase corresponding to the average revenue requirement.

Figure VI-4

Average Revenue Required per Gallon



3. Supply vs. Price vs. Cost

Although a refiner would like to increase its price enough to offset the extra costs of producing complying gasoline, any actual price increase would be limited by the economic forces of the market. If the regulation would not reduce supply, the market would sharply limit any increase in price. If the gasoline supplied by existing sources should decrease, the excess demand would force the price high enough to induce someone to produce or import more gasoline.

The survey responses indicate virtually no technical problem among refiners in maintaining their gasoline production at a benzene limit of 0.80 volume percent. However, it is conceivable that individual refiners would decide to curtail production for financial reasons. For example, refiners with high revenue requirements might be prompted to curtail production rather than absorb added costs not offset by the actual price increase. Also, refiners with unusually high debts relative to assets, which include most small refiners, might curtail production because of high costs of further borrowing for capital expenses. Refiners able to increase gasoline production profitably would be expected to offset the curtailment.

One segment of existing supply that could be in question is gasoline imports, especially from foreign sources, which do not now provide low-benzene gasoline. However, in light of the impending reformulation required by the federal Clean Air Act for much of the nation's gasoline, it is possible that foreign refiners will lower their benzene contents to preserve their U.S. markets.

Companies responsible for about half of the gross imports to California (the state is a net exporter) provided cost data higher than the average among survey respondents. If any of the existing suppliers should curtail production, thus prompting a price increase, a limit on the increase should be the price needed to induce Gulf Coast refiners to produce complying gasoline and ship it to California. According to the staff's analysis (in Appendix 6), an increase in price in California of four to eight cents per gallon would suffice.

A more extensive discussion of gasoline marketing economics and of the financial positions of small refiners is in Appendix 6.

4. Cost per Cancer Case Avoided

Table VI-16 shows the quotient of revenue required and cancer cases avoided as calculated in Appendix 1. Depending on the base year and the scenario, the cost per case avoided ranges from $22 million to $40 million.

The numbers in Table VI-16 include only the revenue required to meet the basic limit on benzene, not the added revenue required to meet the absolute limit of 1.20 percent by volume. Table VI-17 shows the total revenue requirement for the 1.20 percent by volume absolute limit plus the 0.80 v% basic limit per potential case avoided by the basic limit. They range from about $29 million to $45 million per case.

Table VI-16

Cost per Potential Case Avoided by Basic Limit (million $)

Base year	Basic benzene limit 1.20%	1.00%	0.80 *	0.60%
1994	22.2	22.6	23.2	26.1
2000				
If all LEVs use gasoline	24.1	24.4	25.1	28.1
If 1/2 of LEVs use gasoline	21.5	21.5	22.4	24.8
2010				
If all LEVs use gasoline	34.2	34.5	35.5	39.8
If 1/2 of LEVs use gasoline	34.2	34.5	35.6	39.8

* proposed value

Table VI-17

Total Cost per Case Avoided of the Basic Limit at 0.80 v% Plus the Absolute Limit (1.20 v%) (million $)

base year:	1994	2000	2010
If all LEVs use gasoline	29.1	31.5	44.5
If 1/2 of LEVs use gasoline	29.1	28.8	44.5

Alternatively, the cost per case avoided can be computed as the 15-year revenue requirement of the basic limit divided by the integrated measure of the 15-year effect as described in Chapter V, section B. The results for the proposed limit at 0.80 v% are $27.7 million per case if gasoline is the only LEV fuel and $25.4 million per case if gasoline is only half of LEV fuel. The respective total costs, including the cost of the absolute limit, are $34.7 million and $32.7 million per case avoided. As shown in Table VI-18, these costs compare favorably with the costs for other toxic measures adopted by ARB.

Table VI-18

Cost per Potential Cancer Case Reduced

Measure	Cost (million dollars/case avoided)
Benzene (service station)	10 - 76[a]
Chromium (cooling towers)	2 - 25
Chromium (plating)	0.1 - 1
Ethylene Oxide (sterilizers)	2 - 3
LEV/Clean Fuels	5 - 50

[a] Ranges reflect ranges of unit risk.

H. ECONOMIC EFFECTS ON SMALL REFINERS AND IMPORTERS

Over the last decade, the refining industry in California has been consolidating as small refineries either shut down or are bought by larger companies. At present, there are only two independent small refineries (refineries owned by companies without other significant assets.

The staff assessed the financial conditions of the small refiners (owners of gasoline-producing refineries with crude oil capacities less than 55,000 barrels per day) in California for which data are available. On average, the small refiners would have lower costs per gallon for meeting the 0.80 volume percent limit on gasoline. However, because of higher-than-average debts relative to assets and lower returns on investment in comparison to the large refiners, the small refiners would generally find it more expensive to raise funds for the new capital expenses. This could be most troublesome for the independent (not owned by a larger company) refiners, who lack the assets of parent companies. A detailed financial analysis of small refiners is in Appendix 6.

Some gasoline imported into California is imported by small marketers. Such a company may be unable to purchase gasoline with benzene less than 0.80 volume percent benzene. An alternative would be to process its purchased gasoline to meet the limit. Two companies who import gasoline to California provided information on processing costs. Their cost estimates were higher per gallon than the cost reported by California refiners. If importers' costs could not be sufficiently recovered by a price increase, they could choose to leave the gasoline business rather than install process equipment.

A number of small refiners that currently do not produce automotive gasoline would not be affected by the proposed Phase 2 regulation. Staff met with representatives of the small refineries that market gasoline in California to discuss the options available to them to comply with the requirements of the Phase 2 gasoline specifications. The options available to small refiners are limited; they must either install capital equipment to produce gasoline of the specified quality or to withdraw from the California gasoline market and target alternative markets.

The staff has requested cost information from the small refineries and has already received some cost data which have been included in the staff cost-effectiveness analysis. A preliminary analysis of the data provided by several small refiners indicates that the major obstacles that small refiners would be facing is their ability to raise the necessary capital and the uncertainty on their ability to pass the cost of compliance to the consumer in today's competitive fuel market. It also appears from this preliminary evaluation that their ability to meet the proposed standards vary from refinery-to-refinery. Some refiners might require large capital investments to meet the proposed sulfur standards but some others might require large capital to meet the aromatics hydrocarbons or the olefins standard. The staff expects to complete its evaluation of the impacts to the small refiners and if changes are warranted will propose them at the Board hearing.

I. ECONOMIC EFFECTS ON SMALL BUSINESSES

Government Code Section 11342 et seq. requires the ARB to discuss adverse effects on small businesses that would have to comply with a proposed regulation. The effects that must be discussed are the effects that are direct results of the need to comply.

The Code explicitly excludes all refiners from the definition of "small business". Also, the definition includes only businesses that are independently owned and, if in retail trade, that gross less than $2,000,000 per year. Thus, with respect to the proposed Phase 2 reformulated gasoline specifications, the Code requires a discussion of adverse effects of compliance for only some gasoline retailers and jobbers. (A jobber is a business that buys gasoline at wholesale and delivers and sells it to another party, usually a retailer or a user.)

If the wholesale price of gasoline would rise as refiners comply with the proposed Phase 2 reformulated gasoline specifications, retailers and jobbers would have to pay more for every unit of complying gasoline that they re-sell. Since they could legally sell only complying gasoline, this higher price of acquisition could be construed as an adverse effect upon them--but only if their profits would decrease. The profits could decrease either because retail prices might not increase as much as would wholesale prices or because the public's demand for gasoline might slacken at a higher retail price.

The magnitude of a reduction in profit would be difficult to estimate reliably for any particular wholesale price increase since large swings in price commonly occur without obvious major detriment to retailers. Therefore, the staff does not foresee any significant adverse effect upon small businesses as defined.

VII.

ANALYSIS OF ALTERNATIVES

This chapter presents various methods to reduce emissions, the extent to which some of these methods are being pursued, and some of the technical problems associated with these methods. It explains why the Phase 2 gasoline regulation is favored as an additional method for reducing emissions.

Listed here are the other methods to reduce emissions examined by the staff:

1. Adopt tighter standards for vehicular emissions.
2. Require the use of fuels other than gasoline.
3. Adopt an emission standard for toxic air pollutants.
4. Adopt more control measures for stationary sources.

The rest of this section discusses each of the above methods to reduce emissions and explains why staff believes that the Phase 2 gasoline regulation would be preferable.

1. Tighter Emission Standards for Hydrocarbons

With the adoption of the low-emission vehicle standards, to take effect in 1994, the Board has already prompted the eventual use of on-road vehicles with much lower hydrocarbon (HC), NOx, and CO emissions than have ever been produced to date. Adopting even lower vehicle emission standards and/or an earlier implementation date (neither of which appear technically reasonable) would not reduce emissions from vehicles produced before the low-emission vehicle standards go into effect. These vehicles account for most of the emissions for the decade following the implementation of the low-emission vehicle standards because it takes approximately a decade to replace the older vehicles with vehicles meeting the low-emission vehicle standards.

As control measures for other mobile sources (off-road vehicles, utility equipment, and mobile equipment) are implemented, emissions of both criteria and toxic pollutants will decrease further. However, the development of such measures will be stretched over several years because they must be developed individually for many engine classes, and the implementation will take additional years. In contrast, a change to gasoline would be immediately effective in reducing emissions from other-mobile sources. Thus, ambient concentrations and risk in the near term can be significantly affected only by changes to gasoline composition.

2. Require the use of Fuels Other Than Gasoline

Existing gasoline vehicles are constrained to the use of gasoline. Future vehicles could use alternative fuels, all of which should produce less emissions than does gasoline. However, even if the Board were to specify the fuels to be used by future vehicles, such a specification could not be wisely done on the basis of only emissions. Accordingly, the Board has adopted a "fuel-neutral" policy regarding alternative fuels.

The ARB's "clean-fuel" regulation will make alternative fuels available if they become certification fuels for low-emission vehicles. However, even if all low-emission vehicles used alternative fuels exclusively, the resulting emissions reduction would not be significant until well after 2000.

3. Vehicular Emission Standard for Toxic Air Contaminants

Emission standards for toxic air contaminants from new vehicles would take at least a decade to reach full effect. Furthermore, there appears to be no vehicular control specifically applicable to toxic emissions; rather, vehicular controls that reduce HC emissions are also effective in reducing toxic air contaminant emissions. As discussed in 1, the latest adopted HC emission standards are technology-forcing and it does not appear to be technically feasible to adopt even lower emission standards at this time.

4. Stationary Source Control Measures

The ARB does not have direct authority to adopt regulations to control emissions from stationary sources. Local air pollution districts have this authority.

The California Clean Air Act requires districts to submit a plan designed to achieve a 5 percent reduction in emissions until the ambient air quality standards are met. Stationary sources account for about half of the emissions in the state and mobile sources account for the remainder. Clearly, it will be necessary to control both stationary source and mobile source emissions to achieve the ambient air quality standards throughout the state. The Phase 2 gasoline regulation provides a cost-effective, efficient means of significantly reducing emissions from mobile sources.

REFERENCES

1. Thrash, L.A., "Annual Refining Survey," Oil & Gas Journal,March 18, 1991, pp. 84-105.

2. "Countercurrents: The 'Painless' Tax Hike," Lundberg Letter, Vol XVII, Number 23, December 10, 1990.

3. "The Other Price Panic: Middle East Crisis and No. 2 Fuel", Lundberg Letter, Vol XVII, Number 17, September 11, 1990.

4. "Five Famous Weeks: Gasoline Price Tremors Continue," Lundberg Letter, Vol XVII, Number 16, August 30, 1990.

5. "The Invasion of Kuwait: What Prices Did and Did Not Do," Lundberg Letter, Vol XVII, Number 15, August 24, 1990.

6. "What's With the Crude Oil Spread? Wholesale Gasoline's Serpentine Path," Lundberg Letter, Vol XVII, Number 11, June 15, 1990.

7. "Radical Refinery Output Change: Mid-Unleaded's Variable Future, Lundberg Letter, Vol XVII, Number 5, March 26, 1990.

8. Luenberger, D.G., Introduction to Linear and Nonlinear Programming, Menlo Park, CA.: Addison-Wesley Publishing Company, 1973.

9. Leffler, W.L., Petroleum Refining for the Non-Technical Person, Tulsa, OK: PennWell Publishing Company, 1979.

10. Gary, J.H., Handwerk, G.E., Petroleum Refining Technology and Economics, 1975.

11. AAA, "Your Driving Costs," Heathrow, Fl, 1990.

12. Board of Equalization, Gasoline Gallonage Reports, Sacramento, CA, 1991.

13. California Energy Commission, Quarterly Oil Report, P300-91-019, Sacramento, CA, July 1991.

14. California Energy Commission, Quarterly Oil Report, P300-91-005, Sacramento, CA, May 1991.

15. Caltrans, California Motor Vehicle Stock, Travel and Fuel Forecast, Sacramento, CA, November 1989.

16. ARCO Products Company, EC-X Reformulated Gasoline Test Program Emissions Data, Clean Fuels Report 91-06, Anaheim, CA, 1991.

17. California Energy Commission, Fuels Report, P300-89-018, Sacramento, CA, December 1989.

18. Caltrans, Travel and Related Factors in California, Annual Summary, Sacramento, CA, 1988.

19. Arthur D. Little, Inc., Cost of Reducing Aromatics and Sulfur Levels in Motor Vehicle Fuels, Vol. II, Final Report, Prepared for California Air Resources Board, Contract No. A6-199-32, Sacramento, CA, August 1988.

20. Rieb, C., "Constant Crude Composition to Several Crude Units," PIMS User's Conference 1990, Confidential Information, Sponsored by Bechtel Corp., La Jolla, CA, October 24, 25, and 26, 1990.

21. Truesdale, P., "Refinery Wide Optimization - Combining LP and Advanced Control Technology in Real Time Application," PIMS User's Conference 1990, Confidential Information, Sponsored by Bechtel Corp., La Jolla, CA, October 24, 25, and 26, 1990.

22. Webster, M., "Capital Cost Investment Modeling," PIMS User's Conference 1990, Confidential Information, Sponsored by Bechtel Corp., La Jolla, CA, October 24, 25, and 26, 1990.

23. Gallagher,C., "Shadow Prices and Other Nasty Stuff," PIMS User's Conference 1990, Confidential Information, Sponsored by Bechtel Corp., La Jolla, CA, October 24, 25, and 26, 1990.

24. California Air Resources Board, Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, Sacramento, CA, August 1990.

25. California Air Resources Board, Emission Inventory 1987, Sacramento, CA, August 1990.

26. Marshall, W.F., Schoonveld, G.A., "Vapor Space Flammability of Automobile Tanks Containing Low RVP Gasolines," SAE 902096, 1990.

27. California Air Resources Board, Derivation of the EMFAC7E Emission and Correction Factors for On-Road Motor Vehicles, Sacramento, CA, July 1990.

28. LeRoy, C.F., and others, "Refiner Conducts Full Scale VGO Hydrotreating Study," Oil & Gas Journal, pp. 49-59, May 27, 1991.

29. Sardar, H., Li, A., Gendler, J.L.,"Thermal Hydrodealkylation Adapted to Heavy Aromatics Feeds," Oil & Gas Journal, pp. 91-99, March 20, 1989.

30. Davis, B.C., "Supplying High-Octane Gasoline Will Further Challenge U.S. Refiners," Oil & Gas Journal, pp. 35-40, May 15, 1989.

31. Carolyn, A. Y., Donald, A. K., Keith, R. A., Terry, A. R., "FCC LPG Olefinicity and Branching Enhanced by Octane catalysts", Oil & Gas Journal, pp. 56-63, May 29, 1989.

32. D'Souza, G. J., and others, "Add Flexibility to FCC's", Hydrocarbon Processing, September 1979.

33. Hatch, L.F., Matar, S., "From Hydrocarbons to Petrochemicals", Hydrcarbon Processing, August 1978.

34. Finelt, S., "Better C3 Distillation Presssure", Hydrocarbon Processing, February 1979.

35. Cox, Frank, W., Physical Properties of Gasoline/AlcoholBlends, Bartlesville Energy Technology Center, Oklahoma, September 1979.

36. Piel, Willliam J., "Ethers Will Play Key Role in 'Clean' Gasoline Blends," Oil & Gas Journal, December 4, 1989, pp. 40-45.

37. Gething, J.A., Welstand, J.S., and Horn, J.C., "Are the Reductions in Vehicle Carbon Monoxide Exhaust Emissions Proportional to the Fuel Oxygen Content?," SAE 890216, 1989.

38. Yaccarino, Philip A., "The Effect of Oxygenated Fuel, Altitude and Temperature on CO Emissions," SAE 892063, 1989.

39. Piel, William, "Technical Benefits of MTBE and Other Fuel Ethers," National Conference on Octane & Oxygenates, San Francisco, March, 1989.

40. Renewable Fuels Association, "Environmental Profile of Ethanol Blended Gasolines," Prepared for the California Air Resources Board, June 1991.

41. Werner-Selph, Mary Ann and Harvey, Craig A., "Assessment of Unregulated Emissions from Gasoline Oxygenated Blends," Environmental Protection Agency, Ann Arbor, MI, 1991.

42. Wollaston, G., Haflin, J., Ford, D., D'Souza, J., "FCC Model Valuable Operating Tool," Oil & Gas Journal, September 22, 1975, pp. 87-94.

43. Hatch, Lewis F., and Matar, Sami, "From Hydrocarbons to Petrochemicals," Hydrocarbon Processing, August 1978, pp. 153-161.

44. Murcia, A.A., Soudek, M., Quinn, G.P., D'Souza, G.J., "Add Flexibility to FCC's," Hydrocarbon Processing, September 1979, pp. 131-142.

45. American Petroleum Institute, Alcohols and Ethers: A Technical Assessment of Their Application as Fuels and Fuel Components, API Publication 4261, July 1988.

46. Unzelman, George H., "Future Role of Ethers in U.S. Gasoline," Presented at the NPRA Annual Meeting, San Francisco, March 1989.

47. Furey, Robert L., and King, Jack B., "Evaporative and Exhaust Emissions from Cars Fueled with Gasoline Containing Ethanol or Methyl tert-Butyl Ether," SAE 800261, 1980.

48. Boekhaus, K.L., DeJovine, J.M., McHugh, K.J., Paulsen, D.A., Rapp, L.A., Segal, J.S., Sullivan, B.K., Townsend, D.J., "Reformulated Gasoline for California: EC-Premium Emission Control Gasoline and Beyond," SAE 911628, 1991.

49. Hoshi, H., Nakada, M., Kato, M., Okada, M., Kayanuma, N., "Influence of Gasoline Composition on Emission and Driveability," Toyota Motor Corp., undated.

50. Methyl Tertiary Butyl Ether, Presented by WOGA, February 29, 1988.

51. Marshall, William F., Study to Determine the Fate of Benzene Precursors in Gasoline, Prepared for California Air Resources Board, IIT Research Institute, National Institute for Petroleum and Energy Research, December 1988.

52. Lax, David, Effects of Fuel RVP and Fuel Blends on Emissions at Non-FTP Temperatures, Health and Environmental Sciences Department, American Petroleum Institute, July 1991.

53. Wei, S.J., Informal Discussion for California Energy Commission Staff on Manufacturing Gasoline, Chevron Research and Technology Company, Richmond, CA, January 1990.

54. Croes, Bart, ARB Staff Proposal for Hydrocarbon Reactivity Adjustment Factors, CA Air Resources Board Research Division, Clean Fuel/Low Emission Vehicle Workshop, February 1990.

55. Saidaminov, Saidakmal S., "The Effects of Fuel Structure on the Autoignition of Fuel-Air Mixtures," SAE 800046, 1980.

56. Dorn, P., Mourao, A.m., Herbstman, S., "The Properties and Performance of Modern Automotive Fuels," SAE 861178, 1987.

57. Witherspoon, C. and Nevis, P., California Clean Air Act Cost-Effectiveness Guidance, Air Resources Board Office of Air Quality Planning & Liaison, September 1990.

58. Schoonveld, Gary A., and Marshall, William F., "The Total Effect of a Reformulated Gasoline on Vehicle Emissions by Technology (1973 to 1989), SAE 910380, 1991.

59. California Air Resources Board, Mobile Source Divison and Stationary Source Division, Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Staff Report, August 1990.

60. California Air Resources Board, Mobile Source Division, Research Division, Stationary Source Division, and Technical Support Division, Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Technical Support Document, August 1990.

61. Renewable Fuels Association, Environmental Profile of Ethanol Blended Gasolines, Prepared for the CA Air Resources Board, June 1991.

62. Sztenderowicz, Mark L., and Horn, Jerry C., Effect of Clean Air Act "Formula" Gasolines on Vehicle Emissions, December 1990.

63. Marshall, William F., and Gurney, M. Daniel, "Effect of Gasoline Composition on Emissions of Aromatic Hydrocarbons," National Institute for Petroleum and Energy Research, Bartlesville, Oklahoma, 892076.

64. McClement, D., Klausmeier, R., DeFries, T., Kishan, S., Quantification of Evaporative Running Loss Emissions from Gasoline-Powered Passenger Cars in California, Draft Final Report, Prepared for CA Air Resources Board, September 1991.

65. California Air Resources Board, Area Designations for State Ambient Air Quality Standards, July 1991.

66. South Coast Air Quality Management District, Proposed Amendments to Rule 1135 - Emissions of Oxides of Nitrogen from Electrical Generating Systems, June 1991.

67. Beck, D., Krueger, M., and Monroe, D., "The Impact of Sulfur on Three-Way Catalysts: Storage and Removal," SAE 910844, 1991.

68. Monroe, D., Krueger, M., Upton, D., The Effect of Sulfur on Three-Way Catalysts, General Motors Research Laboratories, August 1990.

69. Finelt, Stanley, "Better C3 Distillation Pressure," Hydrocarbon Processing, February 1979, pp. 95-98.

70. Keyworth, D., Reid, T., Kreider, K., Yatsu, C., "FCC LPG Olefinicity and Branching Enhanced by Octane Catalysts," Oil & Gas Journal, May 29, 1989, pp. 56-63.

71. McClung, Ronald G., "Reformer Operation Improved by Feed Sulfur Removal," Oil & Gas Journal, October 8, 1990, pp. 98-99.

72. OGJ Special, "Tough Air-Quality Goals Spur Quest for Transportation Fuel Changes," Oil & Gas Journal, June 18, 1990, pp. 33-57.

73. Viljanen, J., Kokko, J., and Lundberg, M., "Effects of MTBE on Gasoline Engine Cold Weather Operation," SAE 890052, 1989.

74. Christie, E., Crowle, T., Proctor, D., and Johnston, R., "The Importance of Fuel Properties in Correlating Carbon Balance and Volumetric Fuel Consumption," SAE 872159, 1987.

75. Gething, J.A., The Effect of Gasoline Aromatics on Emissions of Nitrogen Oxides in Vehicle Exhaust, Chevron Research and Technology Company, Richmond, CA, April 19, 1990.

76. Tomita, M., Okada, M., Katayama, H., Nakada, M., "Effect of Gasoline Quality on Throttle Response of Engines During Warm-Up," SAE 900163, 1990.

77. Abramo, L., Baxter, C.E., Costello, P.J., Kouhl, F.A., "Effect of Volatility Changes on Vehicle Cold-Start Driveability," SAE 892088, 1989.

78. SCAQMD, Global Warming and Stratospheric Ozone Depletion: Informational Report for Policy Development, El Monte, CA August 1989.

79. California Energy Commission, Global Climate Change: Potential Impacts and Policy Recommendations, P500-91-007, Sacramento, CA, March 1991.

80. Lockhart R., Bossong K., and others, Driving Up the Heat: A Buyer's Guide to 1991 Model Cars, Vans, and Light Duty Trucks and Their Impacts on Fuel Efficiency and Global Warming, Public Citizen Critical Mass Energy Project, Washington D.C., April 2, 1991.

81. "Auto/Oil Air Quality Improvement Research Program", Technical Bulletine- 1-5, 1990-1991.

82. Jessup, Peter, et al "Unocal Reformulated Fuels Technology- A Truly Innovative Approach" Presentation to ARB, 1991.

TABLE OF CONTENTS FOR APPENDICES

Appendix 1. ESTIMATION OF EMISSIONS, RISK, AND CANCER INCIDENCE FOR BENZENE

Appendix 2. EMISSION ESTIMATES RESULTING FROM TRANSPORTATION OF OXYGENATES

Appendix 3. ARB SURVEY OF REFINERS ON GASOLINE COMPOSITION AND COSTS OF REDUCING BENZENE IN GASOLINE

Appendix 4. ESTIMATION OF AVERAGE AMBIENT CONCENTRATIONS OF BENZENE 1986

Appendix 5. TEST METHOD SOP 116

Appendix 6. ESTIMATION OF COST, PRICE AND FINANCIAL EFFECTS FOR THE BENZENE LIMIT

Appendix 7. UPDATED EMISSION INVENTORIES, CONCENTRATION AND RISK ESTIMATES

Appendix 8. CALCULATIONS CONCERNING TOXIC POLLUTANTS

Appendix 9. PROCESSES FOR REDUCING BENZENE IN GASOLINE

Appendix 10. DERIVATION OF STATISTICAL PARAMETERS

Appendix 11. UNOCAL REGRESSION EQUATION

Appendix 12. AUTO/OIL REGRESSION EQUATIONS

Appendix 13. BASIS FOR CALCULATING EVAPORATIVE EMISSION REDUCTIONS FROM ON-ROAD GASOLINE-POWERED MOTOR VEHICLES

Appendix 1

ESTIMATION OF EMISSIONS, RISK, AND CANCER INCIDENCE FOR BENZENE

CONTENT

Page

I. ON-ROAD BENZENE EMISSIONS 1-3

  A. BENZENE FRACTIONS 1-3

  B. ON-ROAD BENZENE EMISSIONS 1-12

II. OFF-ROAD, STATIONARY SOURCE, AND TOTAL EMISSIONS 1-17

III. RISK AND INCIDENCE OF CANCER 1-20

IV. EFFECT OF REDUCED BENZENE IN GASOLINE 1-25

REFERENCES

I. ON-ROAD BENZENE EMISSIONS

Benzene emissions are calculated by multiplying hydrocarbon emissions (HC) by benzene fractions of HC ($\%B_{HC}$) computed for various types of on-road vehicles. For gasoline vehicles, the benzene fractions depend upon the benzene content of the gasoline and the catalyst technology.

To estimate the average benzene content of gasoline in 1986, the staff has considered data for 1984 collected by a survey of refiners in 1986 [1], data for 1987 collected by a survey shown in Appendix 3, and ARB measurements on gasolines sampled from in-use vehicles in 1987 [2]. For 1994, we have used refiners' estimates of gasoline composition in 1995 from the latter survey.* For 2000 and 2010, we have assumed that the pool will have the same contents as in 1994. Our estimates for gasoline compositions are:

	1986		1994	2000, 2010
	leaded	unleaded		
vol.% benzene ($\%B_g$)	1.56	1.73	1.99 *	1.99
vol.% aromatic ($\%A_g$)	30.4	34.1	34.4 *	34.4

Hydrocarbon emissions have been computed using EMFAC-7EP and BURDEN-7C, which are ARB's current models for emission factors and vehicle activity. They include running losses and temperature-adjusted evaporative emissions.

A. BENZENE FRACTIONS

1. Evaporation

The staff estimates the benzene fraction of evaporative emissions with:

$$\%B_{HC} = 1.2 * \%B_g$$

This relationship is derived from data reported from a study by NIPER [3] and the assumption that the amount of evaporative benzene is proportional to the benzene content of gasoline. ARB has compiled data showing the validity of this form of relationship for benzene in gasoline equilibrium vapors at a fixed temperature. The relationship

---

* Refiners estimated compositions for leaded and unleaded grades. Leaded gasoline has since been prohibited. We assume that gasoline will reflect the pool average of the estimates for the two grades.

is applied to all evaporative emissions, including running losses.

The NIPER study was designed to determine evaporative benzene emissions as a function of the benzene content of the gasoline in the fuel tank when the emissions were measured. Unexpectedly, it was found that the results of any particular test depended upon the benzene content of the gasolines used in preceding tests as well as that of the gasoline then in the tank; so the desired determination could not be made as planned. However, it was shown that the data fit the model:

$$\%B_{HC,j} = .76 * \%B_{g,j} + .42 * \%B_{g,j-1}$$

where j denotes a test result and the corresponding test gasoline, and .76 and .42 are regression coefficients. Since there were typically 19 tests per car with a random sequence of fuels, it is reasonable to average both sides of this expression over all tests:

$$\begin{aligned} \text{avg. } \%B_{HC} &= .76 * (\text{avg. } \%B_g) + .42 * (\text{avg. } \%B_g) \\ &= 1.18 * (\text{avg. } \%B_g) \end{aligned}$$

which is the model. As a check, the quotient of average wt.% over 93 tests among five cars in the NIPER study to average benzene content among the test fuels is 1.20.

We assume that in 1986, leaded gasoline was used in all non-catalyst vehicles and unleaded was used in catalyst vehicles. In 1994 and later, all gasoline vehicles will use the same fuel. The evaporative benzene fractions estimated with the model for the benzene contents of gasoline listed above are:

	1986		1994 to
	leaded	unleaded	2010
$\%B_{HC}$ (evap. HC)	1.87	2.08	2.39

2. Non-catalyst Exhaust

The staff used this relationship, explained in reference 1:

$$\%B_{HC} = 2.57 + .943 \times \%B_g$$

At the gasoline compositions shown above (leaded, in 1986), the values of benzene in exhaust are:

1986 (unleaded)-- 4.04 wt.% 1994 to 2010 -- 4.45 wt.%

(These values have been applied to off-road vehicles as well as to non-catalyst on-road vehicles.)

3. Oxidation Catalyst Exhaust

The staff used this relationship, explained in reference 1:

$$\%B_{HC} = 2.32 + .719 \times \%B_g$$

The modeled benzene fractions of exhaust are:

1986 (unleaded)-- 3.56 wt.%   1994 to 2010 -- 3.75 wt.%

This vehicle category is used for the light-duty vehicular inventory only in 1986. For the later years, we regard the entire light-duty fleet as having three-way catalysts. However, the value 3.75 wt.% is used for medium and heavy-duty trucks for 1994 and later.

4. Diesel

The benzene fractions, explained in reference 1, are 1.1 wt.% for heavy-duty trucks and 2.3 wt.% for all other diesel vehicles, including off-road sources.

5. Three-way Catalyst (LDV) Exhaust

The model is:

$$\%B_{HC} = .07 + 0.74 * \%B_g + .11 * \%A_g \qquad \text{or (equivalently)}$$

$$\%B_{HC} = .07 + 0.85 * \%B_g + .11 * \%A'_g$$

where %A' is the total aromatic content less benzene (%A - %B). This model is derived from data taken with fuel-injected vehicles with single-bed catalysts (FISB). FISB is now the dominant new-car technology and is expected to remain so in the forseeable future. This model is applied to all light-duty vehicles in 1986 to 2010 even though in 1986 many carbureted vehicles were on the road.

(Note that $\%A_g$ includes $\%B_g$. Thus, among any group of gasolines, at least some correlation of the two variables must exist. Also, since the refinery processes that create benzene also create other aromatic materials, even the non-benzene aromatic content correlates with $\%B_g$. This correlation of $\%B_g$ and $\%A_g$ means that misleading results could be obtained if the model were obtained by multiple regression of B_{HC} against the two gasoline variables measured for in-use fuels. In this work, the coefficients for $\%B_g$ and $\%A'_g$ are determined independently.)

a. Derivation of the Coefficient for $\%B_g$

It would be most rigorous to include only data from FISB cars without air injection because air injection has become uncommon in new cars. However, since the number of such cars providing data is small, the staff has added data from FISB cars with air injection. According to data in reference 4, confounding the air injection variable into the analysis does not add greater uncertainty to the result for $\%B_{HC}$ vs. $\%B_g$ than already exists because of variations within fuel-injection type (throttle-body vs. port injection) and within single-bed type (monolith vs. beaded).

Three published studies provide information on the sensitivity of $\%B_{HC}$ in exhaust from three-way catalyst vehicles to $\%B_g$. The API study [4] measured the slope of $\%B_{HC}$ versus $\%B_g$ in 41 cars, of which 17 were FISB's without air injection. Two studies by NIPER [3,5] involved five three-way catalyst cars each. However, only two cars in each study were FISB's without air injection. To increase the number of cars providing data, we have included the data from test vehicles that were FISB with air injection. This admits a total of 22 cars in the API study, two cars in the NIPER/CRC study [3], and four cars in the NIPER/ARB study [5].

In the NIPER/ARB study, two cars were FISB, two were FISB plus air injection, and one (#604) had a double-bed catalyst and air injection. It would be appropriate to delete #604 from the analysis. However, the analysis was a multi-variable regression applied to data from all the cars on nine fuels. The influence of any single vehicle cannot be removed from the results without a complete re-analysis. However, in a plot of the benzene sensitivity versus test fuel, car 604 behaves similarly to the 5-car mean; so, keeping #604 in the analysis does not affect the results much.

In the NIPER/ARB work, both the $\%B_{HC}$ in exhaust and the log of $\%B_{HC}$ were regressed against fuel variables. The models yielded similar standard errors of regression. The coefficient for $\%B_g$ was 1.18 in the linear model. When the log model is plotted on a linear scale against $\%B_g$ and the least-squares-fit straight-line approximation is made for the curve, the slope is 1.02. We take the mean of the two linearized slopes, 1.1 wt.% per vol.%, as the result of the study applicable to FISB's.

Tables 1-1 and 1-2 show the applicable data from the API and NIPER/CRC studies. Table 1-3 summarizes the various results.

Table 1-1. Data for FISB Cars in the API Study [4]

Vehicle	Slope[a]	HC (gm/mi)[b]	Vehicle	Slope[a]	HC (gm/mi)[b]
5	1.126.	.12	22	-.330[c]	
7 *	.659	.205	23	.357	.178
8 *	.549	.375	24	.714	.189
10	.934	.128	27	.496	.115
12	.797	.148	28	.330	.447
14	1.264	.205	29	.879	.23
16	2.198 [c]		30	.879	.203
17	.577	.15	31 *	.769	.51
18 *	.385	.43	35	.577	.167
19	.934	.14	37	.549	.41
20 *	.055	.13	44	.330	.19
			mean:	.658	.234
			std. dev.:	.297	.125

[a] change in $\%B_{HC}$ per unit change in $\%B_g$; avg. of two values

[b] mean of four measurements by FTP

[c] extreme value deleted

* air-injected

Table 1-2. Data for FISB Cars in NIPER/CRC Study [3]

Vehicle	Low-aromatic gasoline	High-aromatic gasoline	
	response[a]		mean
401	.84	1.09	.97
501	.80	.84	.82
mean	.82	.97	.89

[a] change in $\%B_{HC}$/ change in $\%B_g$

Table 1-3. **Summary of Results on Response to Benzene Content**
(FISB cars)

Study	No. cars	No. fuels	Response[a]
API [4]	20	2	.66
NIPER/CRC [3]	2	10	.89
NIPER/ARB [5]	5	9	1.1

[a] change in $\%B_{HC}$ / change in $\%B_g$

One way to arrive at an overall statistic from these results would be to weight each result by the number of cars involved, yielding 0.76. However, the number of cars is not the only measure of importance of a study. Another measure is the number of fuels. If the three results are weighted by both the number of cars and the number of fuels, the result is 0.89. Another method would be to take the simple mean of the three results: 0.88. Since these results do not differ by much, we adopt 0.85 as a reasonable central value for the sensitivity for FISB's.

b. Derivation of the Coefficient for $\%A'_g$

Three published studies supply data on the dependence of benzene in exhaust on the non-benzene aromatic content of gasoline. In [3] at each of five doping levels for $\%B_g$, the mean reponse of $\%B_{HC}$ was .17 per $\%A'$. In [5], the regression yielded .087. The ARB staff has treated the data in the "Auto/Oil" Phase-1 study as a 2^4 factorial experiment (an approximation that reproduces closely the published results [6] for HC emissions). The value from the resulting model, calculated for olefinic content = 9.0%, 90% distillation point = 320 degrees, MTBE = 0 is .11 $\%B_{HC}$ per $\%A'_g$. Table 1-4 summarizes the results.

We select the Auto/Oil-derived value, .11, for the model because it is central and it corresponds to a weighted mean of the three values that has a low weight on the NIPER/CRC value. This seems appropriate because of the few cars used from that study.

Table 1-4. **Summary of Results on Response to Non-Benzene Aromatic Content** (FISB cars)

Study	Number of cars	No. arom. contents	Response[a]
NIPER/CRC [3]	2	2	.17
NIPER/ARB [5]	5	9	.087
Auto/Oil (ARB analysis)	10	2[b]	.11

[a] change in $\%B_{HC}$ / change $\%A'_g$

[b] 16 fuels were used at two nominal aromatic contents

c. Derivation of Constant Term

The model derived thus far is:

$$\%B_{HC} = \text{constant} + .85 * \%B_g + .11 * \%A'_g$$
$$= \text{constant} + .74 * \%B_g + .11 * \%A_g$$

In 1987, the ARB [2] measured the benzene and aromatic contents of as-received gasolines in 88 cars with fuel-injection and single-bed catalysts (FISB). The mean gasoline variables were 1.91 (std. dev. .42) for $\%B_g$ and 33.7 (std. dev. 5.4) for $\%A_g$. The mean observed $\%B_{HC}$ was 5.19 (std. dev. 1.37) *. Applying the model to these mean data yields the value .07 for "constant".

d. Predicted Benzene Fractions

The model applied to the estimated gasoline compositions (page 3) yields for $\%B_{HC}$:

1986 (unleaded)-- 5.10 wt.% **1994 to 2010 — 5.33 wt.%**

---

* The mean excludes 1 car for which the observed benzene fraction, 14%, exceeded the mean by more than two standard deviations.

6. 3-Way Plus Oxidation Catalyst Exhaust

In 1986, a considerable number of cars had oxidation catalysts in series with 3-way catalysts. An estimate of the sensitivity in such cars of $\%B_{HC}$ to $\%B_g$ is not needed because in 1994 and later years, few of these cars will be on the road. However, a value of $\%B_{HC}$ is needed for 1986.

In the CRC/NIPER study [3], the ratio of the average value of $\%B_{HC}$ over all fuels among three cars with dual-bed catalysts to the average $\%B_{HC}$ among two FISBs was .77. In the API study [4], the analogous ratio for each of two fuels, among 17 dual-bed cars and 24 FISBs, was .55. In comparison, the ratio of the values of $\%B_{HC}$ estimated above for oxidation catalyst cars and 3-way catalyst cars is 3.56/5.10 = .69. Since this latter ratio falls between the experimental values for dual-bed catalyst cars, we have used the estimate for the oxidation catalyst exhaust, 3.56%, for the dual-bed catalyst exhaust in 1986.

7. Overall Catalyst (LDV) Exhaust

From estimates of the proportions of various catalyst types in new vehicles [7] and ARB's standard estimates of vehicle use by age-of-model, we estimate that in 1986, oxidation and dual-bed catalyst-equipped cars accounted for 34% and 25%, respectively, of all miles travelled by catalyst-equipped vehicles. Therefore, the estimate for the average benzene fraction of exhaust HC over all catalyst vehicles in 1986 is:

$$(.34 + .25) \times 3.56\% + .41 \times 5.10\% = 4.19 \text{ wt.}\%$$

In 1994 and later, all LDV's are regarded as FISB's with average benzene fraction 5.33 wt.%.

Table 1-5 summarizes the values of $\%B_{HC}$ by vehicle type and time. It also shows the values for 1994 and later that correspond to reduced benzene contents in gasoline. In estimating the latter values, we have assumed that A'_g(the non-benzene aromatic content of gasoline) would be invariant.

Table 1-5. **Benzene Fractions (%) of THC Emissions**

Benzene content:	Baseline[a]	1.20 v.%	0.80 v.%
		1986	
Exhaust[b]			
non-cat.	4.04	--	--
catalyst, LDV	5.10	--	--
HDT[c]	3.56	--	--
Evaporative[d]			
non-cat.[e]	1.87	--	--
catalyst	2.08	--	--
		1994 to 2010	
Exhaust[b]			
non-cat.	4.45	3.70	3.32
catalyst	5.33	4.65	4.31
HDT[c]	3.75	3.18	2.90
Evaporative[d]			
all	2.40	1.44	.96
Diesel			
heavy-duty	1.1		
light-duty	2.3		

[a] 1986: leaded--1.56% unleaded--1.73%
1994 to 2010: 1.99%

[b] gasoline vehicles

[c] heavy-duty trucks with oxidation catalysts

[d] including running loss

[e] leaded gasoline

B. ON-ROAD BENZENE EMISSIONS

The benzene fractions of hydrocarbon (HC) emissions are applied to HC emissions estimated using Burden-7C with Emfac-7E for the years 1986* and 1994 and Emfac-7EP for 2000 and 2010. For 2000 and 2010, two cases have been used. In one, we assume that gasoline will not be displaced by any alternative fuels in low-emission vehicles (LEVs). In the other we assume that half of all LEV fuel in any year will be gasoline. In either case, we assume that gasoline remains at 2.0% benzene, pool average. Tables 1-6 through 1-9 show the calculation of emissions.

All inventories after 1986 include the effects of all adopted measures in the ARB's "Motor Vehicle Plan" that affect the control of HC emissions and the effect of the RVP limit in the "Phase-1" gasoline regulation. In 2010, all non-catalyst vehicles are Mexican-registered vehicles assumed to operate in San Diego and Imperial Counties.

---

* 1986 is the base year for extrapolating ambient benzene concentrations to the future. However, Burden-7C / Emfac-7E is not available for 1986. The entries under "1986" are actually the 1987 inventory used as a surrogate for 1986.

Table 1-6. Estimation of On-Road Benzene Emissions in State, 1986*
(tons/day)

	TOG emissions[a]	THC/TOG	Benzene fraction	Benzene emissions[b]
GASOLINE VEHICLES				
Exhaust				
non-cat.	553	.943	.0404	21.1
cat., L&MDV	613	.944	.0510	29.5
cat., HDT [c]	1	.944	.0356	0.03
Evaporative[d]				
non-cat.	230	1.00	.0187	4.31
cat., L&MDV	333	1.00	.0208	6.91
cat., HDT	0	1.00	.0208	0
Total	1,730			61.8
DIESEL VEHICLES				
heavy-duty	83	.831	.011	0.76
light-duty	6	.831	.023	0.11
total	89			0.87
Grand total	1,819			62.7

* See footnote, preceeding page.

[a] total organic gasses; from Emfac-7E/Burden-7C

[b] TOG x THC/TOG x benzene fraction

[c] heavy-duty trucks with oxidation catalysts

[d] including running losses

Table 1-7. Estimation of On-Road Benzene Emissions in State, 1994 (tons/day)

	TOG emissions[a]	THC/TOG	Benzene fraction	Benzene emissions[b]
GASOLINE VEHICLES				
Exhaust				
non-cat.	136	.943	.0446	5.72
cat., L&MDV	504	.944	.0533	25.3
(T,U) LEV	0	.944	.0533	0
cat., HDT [c]	11.5	.944	.0375	0.41
Evaporative[d]				
non-cat.	44.5	1.00	.0239	1.06
cat., L&MDV	146	1.00	.0239	3.48
(T,U) LEV	0	1.00	.0239	0.11
cat., HDT	4.5	1.00	.0239	0
Total	846			36.1
DIESEL VEHICLES				
heavy-duty	72	.831	.011	.66
light-duty	3	.831	.023	.06
total	75			.72
Grand total	921			36.8

[a] from Emfac-7E/Burden-7C

[b] TOG x THC/TOG x benzene fraction

[c] heavy-duty trucks with oxidation catalysts

[d] including running losses; corrected for Phase-1 RVP limit for 1994

Table 1-8. Estimation of On-Road Benzene Emissions in State, 2000 (tons/day)

	TOG emiss. (a)	THC/ TOG	All LEVs use gasol.		1/2 LEVs use gasol.	
			benzene fraction	benzene[b] emiss.	benzene fraction	benzene[b] emiss.
GASOLINE VEHICLES						
Exhaust						
non-cat.	53	.943	.0445	2.22	.0445	2.22
cat., non-LEV	407	.944	.0533	20.5	.0533	20.5
LEV[c]	17	.944	.0533	0.86	.0267	0.43
cat., HDT [d]	17	.944	.0375	0.60	.0375	0.60
Evaporative[e]						
non-cat.	25.5	1.00	.0239	0.61	.0239	0.61
cat. non-LEV	121	1.00	.0239	2.88	.0239	2.88
LEV	8.5	1.00	.0239	0.20	.120	0.10
cat., HDT	6.0	1.0	.0239	0.14	.0239	0.14
Total	655			28.0		27.5
DIESEL VEHICLES						
heavy-duty	77.2	.831	.011	0.71	.011	0.71
light-duty	.8	.831	.023	0.02	.023	0.02
Total	78.0			0.73		0.73
Grand total	733			28.7		28.2

[a] total organic gasses; from Emfac-7Ep/Burden-7C

[b] TOG x THC/TOG x benzene fraction

[c] TLEVs, LEVs, and ULEVs

[d] heavy-duty trucks

[e] including running loss

Table 1-9. Estimation of On-Road Benzene Emissions in State, 2010
(tons/day)

	TOG emiss. (a)	THC/ TOG	All LEVs use gasol.		1/2 LEVs use gasol.	
			benzene fraction	benzene[b] emiss.	benzene fraction	benzene[b] emiss.
GASOLINE VEHICLES						
Exhaust						
non-cat.*	32	.943	.0445	1.34	.0445	1.34
cat., non-LEV	69	.944	.0533	3.47	.0533	3.47
LEV[c]	112	.944	.0533	5.64	.0267	2.82
cat., HDT [d]	16	.944	.0375	0.57	.0375	0.57
Evaporative[e]						
non-cat.*	8	1.0	.0239	0.19	.0239	0.19
cat. non-LEV	11.5	1.0	.0239	0.27	.0239	0.27
LEV	35.5	1.0	.0239	0.85	.0120	0.43
cat., HDT	8	1.0	.0239	0.19	.0239	0.19
Total	292			12.5		9.28
DIESEL VEHICLES						
heavy-duty	93	.831	.011	0.85	.011	0.85
light-duty	0	.831	.023	0	.023	0
Total	93			0.85		0.85
Grand total	385			13.4		10.1

[a] total organic gasses; from Emfac-7Ep/Burden-7C

[b] TOG x THC/TOG x benzene fraction

* Mexican-registered

[c] TLEVs, LEVs, and ULEVs

[d] heavy-duty trucks

[e] including running loss

II. OTHER MOBILE SOURCES, STATIONARY SOURCES, AND TOTAL EMISSIONS

Benzene emissions from "other mobile sources" (off-road mobile, utility equipment, and mobile equipment emission categories) and stationary sources have been estimated from values of reactive organic gases (ROG) in the ARB's Emission Data System (EDS) and values of benzene fractions taken from reference 8. Since inventories are not available for 1986, the inventories for 1985 are used as surrogates. The error caused by the surrogation is probably less than the errors in the inventory.

For the other mobile sources that use gasoline and for stationary engines, we have used the benzene fractions ($\%B_{HC}$) for on-road non-catalyst exhaust.

For gasoline marketing and storage/transfer, we have used for 1986 the benzene emission estimates in the EDS. For other years, we have used EDS estimates times the ratio of the applicable benzene content of gasoline to 1.7 % (which is the estimate of the benzene content in 1986).

Tables 1-10 shows the other mobile and stationary source benzene emissions in the state, and Table 1-11 shows total benzene emissions.

Table 1-10. **Benzene Emissions from Other Mobile & Stationary Sources**
(tons/day)

Source Category	1986	1994	2000	2010
OTHER MOBILE				
Gasoline				
off-road	3.86	5.38	5.61	6.48
mobile equipment	1.24	1.62	1.68	1.87
utility equipment	2.55	3.75	4.09	4.70
Total (gasoline)	7.65	10.8	11.4	13.1
Other	1.50	1.61	1.64	1.78
Total, other mobile	9.15	12.4	13.0	14.9
STATIONARY SOURCES				
Gasoline-related				
combustion	0.05	0.06	0.07	0.07
marketing	0.97	1.14	0.98	1.01
storage, transfer[a]	0.02	0.02	0.02	0.02
Total (gasoline)	1.04	1.22	1.07	1.10
Other	4.23	4.25	4.16	4.53
Total, stationary	5.27	5.47	5.23	5.63

[a] except in refineries

Table 1-11 Total Baseline Emissions of Benzene, State
(tons per day)

	1986	1994	2000		2010	
			A	B	A	B
Gasoline-related						
on-road vehicles	61.8	36.1	28.0	27.5	12.5	9.28
other mobile	7.65	10.8	11.4	11.4	13.1	13.1
stat. source	1.04	1.22	1.07	1.07	1.10	1.10
total	70.5	48.1	40.5	40.0	26.7	23.5
Diesel & Other Veh.						
on-road	0.87	0.72	0.73	0.73	0.85	0.85
other mobile	1.50	1.61	1.64	1.64	1.78	1.78
Stationary Sources[a]	4.23	4.25	4.16	4.16	4.53	4.53
Grand Total	77.1	54.7	47.0	46.5	33.8	30.6

A = if all LEVs use gasoline

B = if 1/2 of LEV's use gasoline

[a] not gasoline-related

III. RISK AND INCIDENCE OF CANCER

The population-weighted mean ambient benzene concentration in 1986 was estimated from monitoring data at 2.7 ppb for the state and 3.6 ppb for the SoCAB. (See Appendix 4.) The concentration was projected to future years by:

$$\text{conc. in future year} = \frac{(\text{Conc. in 1986}) \times (\text{benzene emissions in future year})}{\text{benzene emissions in 1986}}$$

The estimates of mean benzene concentration (ppb) in the state, if gasoline is the only LEV fuel are:

1986	1994	2000	2010
2.71	1.92	1.65	1.19

The estimated mean concentrations if half of LEV fuel is gasoline:

1986	1994	2000	2010
2.71	1.92	1.63	1.08

The average individual lifetime risk is computed as 93 cases in 70 years per million people per ppb * times the population-weighted average concentration of benzene. Table 1-12 shows the risks for the baseline case (benzene at 2.0 v.% in gasoline).

The potential number cancer cases over 70 years are calculated by multiplying the average individual risk for a particular year by the total population predicted by the Department of Finance for that year. The predicted populations are (in millions; based on the 1990 census):

1986	1995	2000	2010
27.05	32.75	36.26	41.00

---

* In previous work on benzene, the ARB has used a range of value for unit risk, 22 to 170 per million, as originally recommended by the Department of Health Services (DHS). DHS now recommends using 93 per million as the best value of unit risk. To compute estimates of risk or cancer incidence on the basis of unit risk at 22 or 170 per million, multiply numbers in this report by 22/93 or 170/93.

Table 1-13 shows the potential cancer incidence corresponding to the risk in Table 1-12.

Table 1-12. **Baseline Values of Average Individual Risk***

	1986	1994	2000	2010
if all LEVs use gasoline	252	179	153	111
if 1/2 of LEVs use gasoline	n/a	n/a	152	100

* average individual's chance per million over a lifetime, or cases per million people over 70 years of exposure to the benzene concentration estimated for the indicated year

Table 1-13. **Baseline Values of Potential Cancer Incidence***

	1986	1994	2000	2010
if all LEVs use gasoline	6,818	5,852	5,565	4,583
if 1/2 of LEVs use gasoline	n/a	n/a	5,503	4,099

* cases among a constant population over 70 years of exposure to the benzene concentration predicted for the indicated year

Tables 1-14 to 16 show the risks and potential cases of cancer in Tables 1-12 and 13 allocated among source categories in proportion to their benzene emissions in Tables 1-6 through 11.

Table 1-14. Benzene: Potential Risk and Incidence of Cancer in State, 1986 and 1994

	1986		1994	
	individ. risk[a,d]	incidence[b]	individ. risk[a,d]	incidence[b]
		Gasoline		
Exhaust				
non-cat	68.9	1,862	18.7	613
cat., L&MDV	96.5	2,609	82.8	2,712
LEV	N/A	N/A	N/A	N/A
cat., HDT	0.11	3.0	1.33	43.6
Evaporative[c]	36.7	992	15.2	498
Other Mobile	25.0	676	35.2	1,152
Stat. Source				
combustion	0.17	4.7	0.21	6.9
marketing	3.16	85.6	3.73	122
stor./transf.	0.06	1.6	0.07	2.2
	------	-------	------	-------
Total (gasoline)	230.6	6,234	157.2	5,150
		Diesel and Other		
On-road	2.85	77.2	2.34	76.6
Other mobile	4.90	132.5	5.25	172
		Stat. Source (non-gasoline)		
	13.83	374.1	13.9	455
	------	-------	------	------
Total	252.2	6,818	178.7	5,852

---

[a] average lifetime risk expressed per million

[b] risk * population; cases over 70 years among 27.05 million people in 1986 and 32.75 million people in 1994

[c] includes running loss

[d] total risk from Table 1-12 allocated by source in proportion to benzene emissions by source in Tables 1-6 and 1-10

Table 1-15. **Benzene: Potential Risk and Incidence of Cancer in State, 2000**

	if all LEVs use gasoline		if 1/2 of LEVs use gasoline	
	individ. risk[a,d]	incidence[b]	individ. risk[a,d]	incidence[b]
		Gasoline		
Exhaust				
non-cat	7.27	264	7.27	264
cat., L&MDV	66.9	2,426	66.9	2,426
LEV	2.80	101	1.40	50.5
cat., HDT	1.97	71.3	1.97	71.3
Evaporative[c]	12.5	464	11.9	430
Other Mobile	37.2	1,349	37.2	1,349
Stat. Source				
combustion	0.22	8.0	0.22	8.0
marketing	3.22	117	3.22	117
stor./transf.	0.07	2.6	0.07	2.6
Total	132.2	4,793	130.2	4,719
		Diesel and Other		
On-road	2.36	85.4	2.36	85.4
Other mobile	5.36	194	5.36	194
		Stat. Source (non-gasoline)		
	13.6	493	13.6	493
Total	153.4	5,565	151.5	5,491

---

[a] average lifetime risk expressed per million

[b] risk * population; cases over 70 years among 36.26 million people

[c] includes running loss

[d] total risk from Table 1-12 allocated by source in proportion to benzene emissions by source in Tables 1-8 and 1-10

Table 1-16. **Benzene: Potential Risk and Incidence of Cancer in State, 2010**

	if all LEVs use gasoline		if 1/2 of LEVs use gasoline	
	individ. risk[a,d]	incidence[b]	individ. risk[a,d]	incidence[b]
		Gasoline		
Exhaust				
non-cat.*	4.39	180	4.39	180
cat., L&MDV	11.4	465	11.4	465
LEV	18.4	755	9.2	378
cat., HDT	1.85	75.9	1.85	75.9
Evaporative[c]	4.92	202	2.15	88.0
Other Mobile	42.7	1,749	42.7	1,749
Stat. Source				
combustion	0.24	10	0.24	10
marketing	3.30	135	3.30	135
stor./transf.	0.06	2.4	0.06	2.4
Total	87.3	3,574	75.3	3,083
		Diesel and Other		
On-road	2.78	114	2.78	114
Other mobile	5.80	237	5.80	237
		Stat. Source (non-gasoline)		
	14.8	608	14.8	608
Total	111	4,533	98.7	4,042

[a] average lifetime risk expressed per million   * Mexican-registered

[b] risk * population; cases over 70 years among 41.00 million people

[c] includes running loss

[d] total risk from Table 1-12 allocated by source in proportion to benzene emissions by source in Tables 1-9 and 1-10

IV. EFFECT OF REDUCED BENZENE IN GASOLINE

For each category of gasoline vehicle *, the values of cancer incidence in 1994, 2000, and 2010 were multiplied by the ratio of the benzene fraction of HC ($\%B_{HC}$) at a reduced benzene content of gasoline ($\%B_g$) to the benzene fraction at the baseline benzene content ($\%B_g = 1.99$ v%). The value of $\%B_{HC}$ in emissions from gasoline marketing is assumed to be proportional to $\%B_g$.

Tables 1-17 to 1-19 show the calculation of reduced cancer incidence if gasoline is the only LEV fuel. Tables 1-20 and 1-21 show the calculation if half of LEVs use gasoline. Values for benzene limits not shown can be had by linear interpolation or extrapolation. All values shown correspond to cancer incidence among a fixed population (that of the indicated year) over 70 years. This provides the estimate of the effect of a benzene limit if, in the absence of a regulation, gasoline would not change from 2.0 v% benzene over an indefinite period. For the calculation of the effect of a benzene limit over the period 1996 to 2010, see Table 6-10 in Appendix 6.

---

* except non-catalyst in 2010, which are Mexican-registered vehicles assumed to use Mexican gasoline at 2% benzene, always.

Table 1-17 Estimation of Cases Avoided by Reduced Benzene in Gasoline 1994

	Cases @ Baseline[a]	1.20 v.%		0.80 v.%		Cases Reduced[d]	
		ratio[b]	cases[c]	ratio[b]	cases[c]	@ 1.20%	@ .80%
<u>Exhaust</u>							
non-cat	613	.831	509	.746	457	104	156
cat., L&MDV	2,712	.872	2,366	.809	2,192	346	520
LEV	0	.872	0	.809	0	0	0
cat., HDT	43.6	.848	36.9	.773	33.7	6.7	9.9
Evaporative[e]	498	.600	299	.400	199	199	299
Other Mobile[f]	1,152	.831	957	.745	858	195	294
<u>Stat. Sources</u>[f]							
combustion	6.9	.831	5.7	.745	5.14	1.2	1.8
marketing	122	.600	73.2	.400	48.8	48.8	73.2
stor./transf.	2.2	.600	1.3	.400	.88	0.9	1.3
	------		------		------	------	------
Total[f]	5,150		4,248		3,795	902	1,356

[a] 1.99% benzene in gasoline

[b] $\%B_{HC} / \%B_{HC}$ @ baseline

[c] cases at baseline x ratio

[d] vs. baseline

[e] includes running loss

[f] gasoline-related, only

Table 1-18. Estimation of Cases Avoided by Reduced Benzene in Gasoline 2000, gasoline as LEV fuel

	Cases @ Baseline[a]	1.20 v.%		0.80 v.%		Cases Reduced[d]	
		ratio[b]	cases[c]	ratio[b]	cases[c]	@ 1.20%	@ .80%
Exhaust							
non-cat	264	.831	219	.746	197	45	67
cat., L&MDV	2,426	.872	2117	.809	1,962	309	464
LEV	101	.872	88.1	.809	81.7	13	19.3
cat., HDT	71.3	.848	60.5	.773	55.1	10.8	16.2
Evaporative[e]	454	.600	272	.400	182	182	272
Other Mobile[f]	1,349	.831	1,121	.746	1,005	228	344
Stat. Sources[f]							
combustion	8.0	.831	6.7	.746	6.0	1.3	2.0
marketing	117	.600	70.2	.400	46.8	46.8	70.2
stor./transf.	2.6	.600	1.6	.400	1.1	1.0	1.6
Total[f]	4,793		3,956		3,537	837	1,256

[a] 1.99% benzene in gasoline

[b] $\%B_{HC}$/ $\%B_{HC}$ @ baseline

[c] cases at baseline x ratio

[d] vs. baseline

[e] includes running loss

[f] gasoline-related, only

Table 1-19. Estimation of Cases Avoided by Reduced Benzene in Gasoline 2010, gasoline as LEV fuel

	Cases @ Baseline[a]	1.20 v.%		0.80 v.%		Cases Reduced[d]	
		ratio[b]	cases[c]	ratio[b]	cases[c]	@ 1.20%	@ .80%
<u>Exhaust</u>							
non-cat.*	180	1.00	180	1.00	180	0	0
cat., L&MDV	465	.872	406	.809	376	59	89
LEV	755	.872	659	.809	611	96	144
cat., HDT	75.9	.848	64.4	.773	58.7	11.5	17.2
<u>Evaporative</u>[e]							
non-cat *	25.6	1	25.6	1.00	25.6	0	0
other	176	.600	106	.400	70.8	70	106
Other Mobile[f]	1,749	.831	1,453	.745	1,303	296	446
<u>Stat. Sources</u>[f]							
combustion	10	.831	8.3	.745	7.5	1.7	2.6
marketing	135	.600	81.0	.400	54.0	54	81.0
stor./transf.	2.4	.600	1.4	.400	1.0	1.0	1.4
Total[f]	3,574		2,984		2,687	590	887

* Mexican-registered

[a] 1.99% benzene in gasoline

[b] $\%B_{HC}$/ $\%B_{HC}$ @ baseline

[c] cases at baseline x ratio

[d] vs. baseline

[e] includes running loss

[f] gasoline-related, only

Table 1-20. Estimation of Cases Avoided by Reduced Benzene in Gasoline
2000, gasoline 1/2 of LEV fuel

	Cases @ Baseline[a]	1.20 v.%		0.80 v.%		Cases Reduced[d]	
		ratio[b]	cases[c]	ratio[b]	cases[c]	@ 1.20%	@ .80%
Exhaust							
non-cat	264	.831	219	.746	197	45	67
cat., L&MDV	2,426	.872	2,117	.809	1,962	309	464
LEV	50.5	.872	44	.809	40.9	6.5	9.6
cat., HDT	71.3	.848	60.5	.773	55.1	10.8	16.2
Evaporative[e]	442	.600	265	.400	177	178	265
Other Mobile[f]	1,349	.831	1,121	.745	1,005	228	344
Stat. Sources[f]							
combustion	8.0	.831	6.7	.745	6.0	1.3	2.0
marketing	117	.600	70.2	.400	46.8	47	70.2
stor./transf.	2.6	.600	1.6	.400	1.1	1.0	1.6
	------		------		------	------	------
Total[f]	4,731		3,905		3,491	826.6	1,240

[a] 1.99% benzene in gasoline

[b] $\%B_{HC}$/ $\%B_{HC}$ @ baseline

[c] cases at baseline x ratio

[d] vs. baseline

[e] includes running loss

[f] gasoline-related, only

Table 1-21. Estimation of Cases Avoided by Reduced Benzene in Gasoline 2010, gasoline 1/2 of LEV fuel

	Cases @ Baseline[a]	1.20 v.%		0.80 v.%		Cases Reduced[d]	
		ratio[b]	cases[c]	ratio[b]	cases[c]	@ 1.20%	@ .80%
Exhaust							
non-cat.*	180	1.00	180	1.00	180	0	0
cat., L&MDV	465	.872	406	.809	376	59	89
LEV	378	.872	330	.809	306	49	72.2
cat., HDT	75.9	.848	64.4	.773	58.7	11.5	17.2
Evaporative[e]							
non-cat*	25.6	1	25.6	1.00	25.6	0	0
other	119	.600	71.4	.400	47.6	47.6	71.4
Other Mobile[f]	1,749	.831	1,453	.745	1,303	296	446
Stat. Sources[f]							
combustion	10.0	.831	8.3	.745	7.5	1.7	2.6
marketing	135	.600	81.0	.400	54.0	54.0	81.0
stor./transf.	2.4	.600	1.4	.400	1.0	1.0	1.4
Total[f]	3,140		2,620		2,360	519.8	781

* Mexican-registered

[a] 1.99% benzene in gasoline

[b] $\%B_{HC}$/ $\%B_{HC}$ @ baseline

[c] cases at baseline x ratio

[d] vs. baseline

[e] includes running loss

[f] gasoline-related, only

References

1. Air Resources Board, Stationary Source Division; Technical Support Document to Proposed Benzene Control Plan, May 1986.

2. Air Resources Board, Mobile Source Division; memo from Leo Zafonte to Mary Hostak, "LD#9 Gasoline Aromatic Analysis," July 20, 1989.

3. Seizinger, D.E. et al; "Vehicular Evaporative and Exhaust Emissions as Influenced by Benzene Content of Gasoline" SAE Technical Paper Series, 860531, International Congress and Exposition, February 24-28, 1986.

4. American Petroleum Institute; Exhaust Benzene Emissions from Late Model Vehicles, API No. 841-44770, October 1988.

5. Marshall, W. F., Study to Determine the Fate of Benzene Precursors in Gasoline: NIPER; (ARB Agreement No. A5-128-32), December 1988.

6. Auto/Oil Air Quality Improvement Research Program; "Technical Bulletin #1, December 1990.

7. Energy and Environmental Analysis; Forecast of Emission Control Technology and Strategy for Light-Duty Vehicles, ARB Contract A2-065-32, task 2, March 1984.

8. Memo from R. Bradley, Technical Support Division, to W. Loscutoff, Stationary Source Division, March 28, 1986.

Appendix 2

EMISSION ESTIMATES RESULTING FROM TRANSPORTATION OF OXYGENATES

Emission Estimates Resulting from Transportation of Oxygenates

Emissions resulting from increases in use of transportation systems for the importation of oxygenates were calculated by following the steps below.

1. First, all oxygenate was assumed to be MTBE transported via ship from the Gulf Coast.
2. Second, all oxygenate was assumed to be ethanol arriving from the mid-west (Illinois) via rail.
3. Third, the emissions were calculated for the following cases: 95% MTBE/5% ethanol, 75% MTBE/25% ethanol and 50% MTBE/50% ethanol.

100% MTBE via Ship

$$\frac{\text{lbs emissions}}{\text{yr}} = \frac{\text{gals fuel}}{\text{trips}} \times \frac{\text{lbs emissions}}{\text{gal fuel}} \times \frac{\text{trips}}{\text{yr}}$$

$$\frac{\text{trips}}{\text{yr}} = \frac{\text{gal MTBE}}{\text{yr}} \times \frac{\text{trip}}{\text{gal MTBE}}$$

$$\frac{\text{gal MTBE}}{\text{yr}} = \frac{\text{gal gas}}{\text{yr}} \times .113 \text{ (2\% oxygenate)}$$

The amount of gasoline produced in California in one year was taken from a report by DeWitt & Company Inc. The estimate was 362,372,000 barrels of gasoline per year. The amount of MTBE required for that amount of gasoline was calculated to be 40,000,000 barrels per year for 2% oxygenate content. An average tanker carries 200,000 - 250,000 barrels of MTBE per shipment requiring 160 - 200 trips per year. The tanker used for this estimate, the OMI Willamette, burns 80 tons of fuel per day. A one way trip was estimated at 14 days to Los Angeles and 15 days to San Francisco. Therefore, the fuel consumed per trip was 1120 tons for the 14 day trip and 1200 tons for the 15 day trip. Fuel oil is roughly 6.5 barrels to the ton. Since there are 42 gallons to the ton, fuel consumption is 305,760 gallons per 14 day trip and 327,600 gallons per 15 day trip. Criteria pollutant emissions per 1000 gallons of fuel consumed were taken from <u>Inventory of Emissions From Marine Operations Within the California Coastal Waters</u>.

The low end of the emission range was calculated using:

$$160\ \frac{\text{trips}}{\text{yr}} \times 305{,}760\ \frac{\text{gals fuel}}{\text{trip}}$$

The high end of the emission range was calculated using:

$$200\ \frac{\text{trips}}{\text{yr}} \times 327{,}600\ \frac{\text{gals fuel}}{\text{trip}}$$

Emissions Resulting from Transportation of MTBE (tons/day)

Pollutant	HC	CO	NOx	SOx	Part.
low	0.005	0.5	4.3	21	1.5
high	0.01	0.6	5.7	28	2.1

100% Ethanol via Rail

The amount of ethanol required to oxygenate gasoline in California was related to the amount of MTBE required as follows:

1 gal ethanol = 1.95 gal MTBE

$$\text{Given:}\quad 401\ \frac{\text{gross ton miles}}{\text{gallon fuel}}$$

A locomotive would have to pull the weight of the ethanol plus the weight of the car. Car weight was estimated to be equivalent to the product weight. Length of the trip was estimated at 2000 miles.

861,538 gal ethanol weighs 2836 tons

(2836 x 2) tons x 2000 miles = 11,344,000 ton miles

and requires 28,289 gallons of fuel per year

Criteria pollutants per 1000 gallons of fuel were taken from the CARB Locomotive Emission Study.

Emissions Resulting from Transportation of Ethanol (tons/day)

Pollutant	HC	CO	NOx	SOx	Part.
	0.001	0.003	0.02	0.001	0.0003

Emissions Resulting from Transportation of 2% Oxygenates (tons/day)

Pollutant	HC	CO	NOx	SOx	Part.
100% MTBE	0.005	0.5	4.3	21	1.5
95% MTBE 5% EtOH	0.005	0.4	4	20	1.5
75% MTBE 25% EtOH	0.004	0.35	3.2	16	1.2
50% MTBE 50% EtOH	0. 003	0.24	2.2	11	0.8
100% MTBE	0.001	0.003	0.02	0.001	0.0003

Finally, the emissions resulting from transportation of oxygenates within the staff report for Phase 2 gasoline regulations were based on 25% MTBE imported by ship, 25% ethanol imported by rail, 25% oxygenates imported by pipeline and 25% oxygenates supplied within California. The figures in Table VI-1 were derived by estimating 25% of the emission contribution from MTBE transportation and 25% of ethanol transportation. Pipeline transportation was assumed to have a negligible impact on additional emissions.

Appendix 3

ARB SURVEY OF REFINERS ON GASOLINE COMPOSITION AND COSTS OF REDUCING BENZENE IN GASOLINE

Summary of All Responses

	1987	1995				
		benz. limit: none	1.2%	1.0%	0.8%	0.6%
Calif. gasoline, 1000 bbl/day (BPD)	801	955	954	954	958	958
MTBE, 10^3 BPD	2.1	15.4	25.7	28.9	30.6	34.8
NOx, tpy[a]	-	0	136	186	214	279
Capital cost, 1988$ / BPD						
average [b]	-	0	656	769	980	1,250
range[c]	-	-	54 to 3,720	84 to 4,000	128 to 4,380	170 to 5,060
Operating cost, 1988$ / bbl						
average[b]	-	-	.402	.534	.643	.853
range[c]	-	-	-.05 to 1.28	-.07 to 2.66	-.01 to 2.66	.12 to 2.74

[a] new emissions in tons/year, estimated at 0.03 lb/million BTU

[b] total cost / California gasoline volume

[c] among refineries

Summary of Responses from Five Small Refineries

	1987	1995				
benz. limit:		none	1.2%	1.0%	0.8%	0.6%
Calif. gasoline, 1000 bbl/day (BPD)	66	70	70	70	70	70
MTBE, 10^3 BPD	.004	.26	.49	.53	.56	.61
NOx, tpy[a]	-	0	4.3	4.9	5.7	6.5
Capital cost, 1998$/ BPD						
average [b]	-	0	344	378	441	501
range[c]	-	-	54 to 804	84 to 792	128 to 898	170 to 1,220
Operating cost, 1988$ / bbl						
average[b]	-	-	.37	.43	.49	.56
range[c]	-	-	.24 to 1.04	.25 to 1.34	.27 to 1.64	.30 to 1.90

[a] new emissions in tons/year, estimated at 0.03 lb/million BTU

[b] total cost / California gasoline volume

[c] among refineries

Summary of Responses: Refineries with Coking and Cracking

	1987	1995				
		benz. limit: none	1.2%	1.0%	0.8%	0.6%
Calif. gasoline, 1000 bbl/day (BPD)	555	684	684	684	688	689
MTBE, 10^3 BPD	.13	10.4	16.0	19.1	19.5	24.2
NOx, tpy[a]	-	0	120	164	183	231
Capital cost, 1988$ / BPD						
average [b]	-	0	730	853	1,110	1,420
range[c]	-	-	281 to 3,720	281 to 4,000	498 to 4,380	579 to 5,060
Operating cost, 198$ / bbl						
average[b]	-	-	.39	.58	.69	.92
range[c]	-	-	-.05 to 1.28	-.07 to 2.66	-.01 to 2.66	.31 to 2.74

---

[a] new emissions in tons/year, estimated at 0.03 lb/million BTU

[b] total cost / California gasoline volume

[c] among refineries

Summary of Responses: Refineries with Cracking but No coking

	1987		1995			
		benz. limit: none	1.2%	1.0%	0.8%	0.6%
Calif. gasoline, 1000 bbl/day (BPD)	234	256	256	256	256	256
MTBE, 10^3 BPD	2	5	9.42	9.51	9.98	10.3
NOx, tpy[a]	-	0	14	20	28	45
Capital Cost, 1988$ / BPD						
average [b]	-	0	460	555	640	817
range[c]	-	-	54 to 742	84 to 785	128 to 898	170 to 1,350
Operating cost 1988$ / bbl						
average[b]	-	-	.42	.40	.50	.66
range[c]	-	-	-.01 to .79	-.01 to .79	-.01 to .89	.12 to 1.14

[a] new emissions in tons/year, estimated at 0.03 lb/million BTU

[b] total cost / California gasoline volume

[c] among refineries

Process Means of Removing Benzene and Recovering Octane

benzene limit:	1.2%	1.0<%	0.8%	0.6%
	number of refineries*			
Split (or heart cut) & hydrogenate				
reformate	7	7	9	9
lt. hydro-crackate	2	2	2	3
lt. cat. gas.	0	0	1	2
lt. str. run	4	4	4	4
Split (or heart cut) & extract				
reformate	7	7	7	6
lt. hydro-crackate	1	1	1	1
lt. cat.gas.	0	0	3	3
Isomerization	6	7	7	6

"Split or heart cut" means distill the stock to isolate a portion that contains most of the benzene.

"Hydrogenate" means saturate (convert to single-bonded) the benzene and any other species that accept hydrogen.

"Extract" means solvent-extract the aromatic content, distill the benzene from the extracted material, and restore the other aromatic material to the gasoline. The benzene is sold.

Isomerization is the conversion of light straight-chain hydrocarbons into higher octane isomers.

---

* Column sums exceed 19 because of multiple processes in refineries

Number of Refineries Projecting Average Benzene Content in a Grade Greater Than the Limit on the Pool Average

	Regular	Mid-Grade	Premium
Case 1	2	0	1
Case 2	2	0	1
Case 3	1	0	1
Case 4	2	0	0

Volume-weighted Average Gasoline Data, 1987 Actual and 1995 Projected Baseline

	Pool	Regular	Mid-Grade	Premium
1987				
Volume,[a] 1000 BPD	801[b]			
octane	88.5			
% benzene	1.89			
% aromatic	32.5			
% MTBE	0.26 (=2,100 BPD)			
1995 baseline				
Volume,[a] 1000 BPD	955[c]	465[d]	161	212
octane	88.7	87.1	89.0	92.0
% benzene	1.99	1.94	1.66	2.43
% aromatic	34.4	32.5	26.5	42.1
% MTBE	1.60 (=15,300 BPD)	0.23	3.93	3.70

[a] total among all (19) responding refineries

[b] equals 90% of the gasoline consumed in the state in 1987

[c] greater than the sum of grade volumes because of incomplete information by grade

[d] 3% leaded; 97% unleaded

Average Projected Gasoline Compositions in Cases with Reduced Benzene (1995)

	Pool[b]	Regular	Mid-Grade	Premium
Case 1 (1.2% benzene)				
Volume,[a] 1000 BPD	954	476	151	212
% benzene	1.11	1.19	1.02	1.02
% aromatic	32.0	30.6	26.4	39.4
% MTBE	2.69 (=25,700 BPD)	1.69	3.65	4.92
Case 2 (1.0% benzene)				
Volume,[a] 1000 BPD	954	476	151	212
% benzene	.92	.96	.84	.88
% aromatic	31.5	30.2	25.3	38.9
% MTBE	3.03 (=28,900 BPD)	2.25	4.98	4.27

[a] total among responding refineries

[b] Pool volume is less than the sum of grade volumes because of incomplete data by grade.

(continued on next page)

Average Projected Gasoline Compositions in Cases with Reduced Benzene (1995)

	Pool[b]	Regular	Mid-Grade	Premium
Case 3 (0.8% benzene)				
Volume,[a] 1000 BPD	958	476	151	216
% benzene	.74	.78	.66	.70
% aromatic	31.5	30.3	25.1	38.5
% MTBE	3.19 (=30,600 BPD)	2.37	4.98	4.68
Case 4 (0.6% benzene)				
Volume,[a] 1000 BPD	958[c]	476	151	216
% benzene	.54	.58	.46	.51
% aromatic	31.5	29.9	25.8	38.8
% MTBE	3.63 (=34,800 BPD)	2.88	5.61	5.13

[a] total among responding refineries

[b] Pool volume is less than the sum of grade volumes because of incomplete data by grade.

Appendix 4

ESTIMATION OF AVERAGE AMBIENT CONCENTRATIONS OF BENZENE 1986

In 1986, the ARB monitored the concentration of benzene in the ambient air at 18 sites in the state. At each, a 24-hour sample was collected and analyzed about once every two weeks. These data are by themselves rather scant for estimating an annual average concentration over the state or over an air basin. However, the benzene data can be related to simultaneous measurements of carbon monoxide (CO) taken at the same or nearby sites. By applying these relationships to the daily observations of CO at the numerous CO monitors (94), the staff has developed a much larger pool of data providing information related to benzene concentrations.

The simultaneous benzene/CO data are summarized in Table 4-1 along with the linear relationships derived by least-squares analyses [estimated benzene (ppb) = slope x measured CO (ppm) + intercept]. All observations from all benzene monitoring sites (362 pairs) yield a relationship with correlation coefficient r=.89. Relationships at the individual sites have r-values from .67 to .98. For the 18 CO monitors that were also benzene monitors, the relationships for the particular sites have been applied to the CO data. For the other CO monitors, the "all stations" relationship has been used. Table 3-2 shows the average measured CO and the predicted benzene at each monitor in 1986.

We have used an inverse-square (distance) program to interpolate the CO-monitor benzene concentrations to the centroids of all census tracts in the state. For census tracts in areas (rural) where CO is not monitored, we have used the value 0.8 ppb benzene, which is the approximate lowest annual benzene concentration predicted for any monitoring site. By multiplying the centroid concentrations by the census tract populations for 1980, we have computed population-weighted mean benzene concentrations in the 1986 for the air basins and for the state. (We assume that the mean concentrations apply to all persons in 1986 who were not in the 1980 census.) Table 4-3 shows the results. For the state, the mean concentration is 2.71 ppb; for the South Coast, it is 3.55 ppb.

For other years, the benzene concentrations have been projected as if concentration is proportional to the total emission rate (tons of benzene per year) in the air basin or state.

Table 4-1

BENZENE/CO REGRESSION STATISTICS FOR 1986

STATION	OBS	Observed		CORR COEF	SLOPE	INTERCEPT
		AVERAGE CO (PPM)	AVERAGE BENZENE (PPB)			
All Stations	362	1.55	2.86	.89	1.669	.27
Richmond	14	1.38	2.04	.90	1.874	- .55
Concord	15	1.78	2.69	.94	1.914	- .71
Fresno	14	1.83	4.04	.96	1.797	.75
Bakersfield	17	1.07	2.96	.82	1.537	1.31
Rubidoux	29	1.22	2.52	.88	1.591	.59
Citrus Heights	9	1.22	2.43	.86	1.607	.48
Upland	29	1.44	2.80	.67	1.074	1.26
Stockton	14	1.14	2.25	.73	2.195	- .25
Santa Barbara	25	1.54	2.98	.89	1.727	.32
San Jose	14	2.64	4.83	.98	1.948	- .31
Modesto	13	.96	1.88	.86	1.697	.25
Simi Valley	30	1.53	2.31	.77	1.588	- .12
Fremont	10	1.42	2.00	.70	.971	.63
Long Beach	30	2.00	4.11	.95	1.696	.72
Los Angeles	30	2.28	4.22	.97	1.498	.81
Chula Vista	29	.94	1.67	.78	1.404	.35
El Cajon	29	1.35	2.62	.95	1.865	.11
San Francisco	11	2.35	2.04	.89	1.695	-1.94

Table 4-2

ANNUAL MEASURED CO AND ANNUAL PREDICTED BENZENE AT CALIFORNIA MONITORING STATIONS DURING 1986

AIR BASIN STATION	ARB NUMBER	ANNUAL MEASURED CO(PPM)	ANNUAL PREDICTED BENZENE(PPB)	HOURS
NORTH COAST				
WILLITS-FIREHOUSE	2300753	1.07	2.0	2144
SAN FRANCISCO BAY AREA				
FREMONT-CHAPEL WAY	6000336	1.41	2.0	8559
LIVERMORE OLD FST ST	6000340	0.79	1.6	8447
OAKLAND-ALICE	6000339	1.08	2.1	8504
BETHEL ISLAND RD	0700442	0.09	0.4	6137
CONCORD-2975 TREAT BLVD	0700440	1.45	2.1	8562
PITTSBURG	0700430	1.15	2.2	8651
RICHMOND-13TH ST	0700433	1.20	1.7	8518
SAN RAFAEL	2100451	1.41	2.6	8457
NAPA-JEFFERSON ST	2800783	0.97	1.9	8571
SAN FRANCISCO-ELLIS ST	9000303	2.31	2.0	8260
SAN FRANCISCO-10 ARKANSAS	9000306	1.53	2.8	8447
SAN FRANCISCO-23RD ST	9000304	1.31	2.5	6209
REDWOOD CITY	4100541	1.38	2.6	8643
GILROY-9TH ST	4300389	0.86	1.7	8466
SAN JOSE-4TH ST	4300382	1.74	3.1	8517
VALLEJO-TUOLUMNE	4800879	1.13	2.2	8631
SANTA ROSA-837 FIFTH ST	4900893	1.16	2.2	8644
NORTH CENTRAL COAST				
SALINAS II	2700544	1.07	2.1	3565
SAN LUIS OBISPO-MARSH	4000835	0.60	1.3	8195
SOUTH CENTRAL COAST				
GOLETA	4200363	0.62	1.3	8654
LOMPOC-128 SOUTH H ST	4200381	0.35	0.9	7845
SANTA BARBARA-CANON PERDI	4200378	1.70	3.2	7962
VANDENBERG AFB-HERADO AVE	4200383	0.04	0.3	6905
VANDENBERG AFB-WATT RD	4200382	0.08	0.4	8008
EL RIO-RIO MESA SCHOOL	5600419	0.71	1.4	7990
SIMI VALLEY-5400 COCHRAN	5600434	1.53	2.3	8289

Table 4-2
(cont'd)

ANNUAL MEASURED CO AND ANNUAL PREDICTED BENZENE AT CALIFORNIA MONITORING STATIONS DURING 1986

AIR BASIN STATION	ARB NUMBER	ANNUAL MEASURED CO(PPM)	ANNUAL PREDICTED BENZENE(PPB)	HOURS
SOUTH COAST				
AZUSA	7000060	1.31	2.5	8352
BURBANK	7000069	2.71	4.8	8320
HAWTHORNE	7000094	1.91	3.5	8354
LOS ANGELES-NO MAIN	7000087	2.12	4.0	8199
LYNWOOD	7000084	3.02	5.3	8063
NORTH LONG BEACH	7000072	1.92	4.0	8166
PASADENA-WILSON	7000088	2.10	3.8	8323
PICO RIVERA	7000085	1.87	3.4	8356
POMONA	7000075	1.95	3.5	8273
RESEDA	7000074	1.87	3.4	8347
WEST LOS ANGELES-VA HOSP	7000091	1.37	2.6	8253
WHITTIER	7000080	1.78	3.2	8352
ANAHEIM	3000176	1.75	3.2	8234
COSTA MESA-PLACENTIA	3000192	1.25	2.3	8264
EL TORO	3000186	1.00	1.9	8208
LA HABRA	3000177	2.29	4.1	8360
RIVERSIDE-MAGNOLIA	3300146	2.62	4.6	8610
RUBIDOUX	3300144	1.22	2.5	8393
FONTANA-ARROW HWY	3600197	1.25	2.4	8324
SAN BERNARDINO-FOURTH ST	3600203	1.72	3.1	4877
UPLAND ARB	3600175	1.37	2.7	8183
SAN DIEGO				
CHULA VISTA	8000114	1.02	1.8	8284
EL CAJON-REDWOOD AVE	8000131	1.38	2.7	8252
ESCONDIDO-VALLEY PKWY	8000115	1.70	3.1	8463
OCEANSIDE-1701 MISSION AV	8000134	0.92	1.8	8487
SAN DIEGO-ISLAND AVE	8000120	1.58	2.9	8222
SAN DIEGO-OVERLAND	8000123	0.96	1.9	6723
SAN DIEGO-1133 UNION ST	8000130	1.59	2.9	8585
SACRAMENTO VALLEY				
CHICO-MANZANITA	0400628	0.72	1.5	7305
CHICO-SALEM ST	0400633	1.00	1.9	8576
CITRUS HTS-SUNRISE BLVD	3400293	0.94	2.0	7860
NORTH HIGHLANDS-BLACKFOOT	3400294	0.59	1.3	8091
SACRAMENTO-DEL PASO MANOR	3400295	0.70	1.4	8254
SACRAMENTO-EL CMNO/WATT	3400289	2.31	4.1	3703
ANDERSON-CENTER ST	4500558	0.53	1.2	4688
WOODLAND-W MAIN ST	5700569	0.39	0.9	6583

Table 4-2
(cont'd)

ANNUAL MEASURED CO AND ANNUAL PREDICTED BENZENE AT CALIFORNIA MONITORING STATIONS DURING 1986

AIR BASIN STATION	ARB NUMBER	ANNUAL MEASURED CO(PPM)	ANNUAL PREDICTED BENZENE(PPB)	HOURS
SAN JOAQUIN VALLEY				
FRESNO-CAL STATE #2	1000241	0.97	1.9	8054
FRESNO-OLIVE	1000234	1.35	3.2	7445
FRESNO-SIERRA SKYPARK #2	1000245	0.77	1.6	3404
FRESNO-4232HERNDON-SKYPA	1000243	0.49	1.1	4699
FRESNO-4706 E DRUMMOND	1000244	1.16	2.2	3289
PARLIER	1000230	0.67	1.4	4052
BAKERSFIELD-CHESTER ST	1500203	0.83	2.6	7831
OILDALE-3311 MANOR	1500243	0.64	1.3	3993
STOCKTON-HAZELTON ST	3900252	1.02	2.0	7264
STOCKTON-4310 CLAREMONT	3900266	1.55	2.9	2753
MODESTO-814 14TH ST	5000568	1.10	2.1	8159
VISALIA-CHURCH STREET	5400568	1.06	2.0	7197
GREAT BASIN VALLEYS				
MAMMOTH LAKES-GATEWAY HC	2600785	0.51	1.1	8150
SOUTHEAST DESERT				
LANCASTER	7000082	0.78	1.6	8279
PALM SPRINGS-FIRE STN	3300137	0.52	1.1	8345
BARSTOW	3600155	0.35	0.9	5668
HESPERIA-17288 OLIVES	3600201	0.27	0.7	5308
MOUNTAIN COUNTIES				
QUINCY-SO. REDBURG AVE	3200817	0.76	1.5	3795
LAKE TAHOE				
S LAKE TAHOE-3377 TAHOE	0900684	0.94	1.8	7688
S LAKE TAHOE-BIJOU SCHOOL	0900680	0.64	1.3	8367
S LAKE TAHOE-STATELINE	0900683	3.34	5.9	8234

Table 4-3

1986 STATEWIDE EXPOSURE TO BENZENE
BY AIR BASIN
ANNUAL POPULATION WEIGHTED MEAN
(PPB)

AIR BASIN	POPULATION WEIGHTED MEAN (PPB)	POPULATION
GREAT BASIN VALLEYS	.90	20,741
LAKE COUNTY	.84	37,715
LAKE TAHOE	1.54	36,525
MOUNTAIN COUNTIES	.91	230,520
NORTH CENTRAL COAST	1.17	469,120
NORTH COAST	.88	206,879
NORTHEAST PLATEAU	.80	36,118
SACRAMENTO VALLEY	1.33	1,510,209
SAN DIEGO	2.45	1,882,144
SAN FRANCISCO BAY AREA	2.33	5,127,387
SAN JOAQUIN VALLEY	1.99	1,960,884
SOUTH CENTRAL COAST	1.96	1,001,368
SOUTH COAST	3.55	10,649,876
SOUTHEAST DESERT	1.30	361,202
TOTAL	2.71	23,530,688

Appendix 5

TEST METHOD SOP 116

August 1991

AIR RESOURCES BOARD

PROCEDURE FOR THE ANALYSIS OF BENZENE AND OTHER AROMATIC COMPONENTS OF GASOLINE

SOP NO. MLD 116

Southern Laboratory Branch
Monitoring and Laboratory Division
State of California

Haagen-Smit Laboratory
9528 Telstar Avenue
El Monte, CA 91731

This report has been reviewed by the staff of the California Air Resources Board and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

S.O.P. No. 116
Effective Date: 8/01/91
Revision No.
Approved: /s/ SHM
Page 1

CALIFORNIA AIR RESOURCES BOARD
MONITORING AND LABORATORY DIVISION

Procedure for the Analysis of Benzene and other Aromatic Components of Gasoline

1 INTRODUCTION

1.1 This method describes a procedure for quantifying benzene, other aromatics, and the total aromatic fraction in gasoline by gas chromatography (GC) (see 9.1). This method can also be used to analyze gasolines containing up to 10 % (v/v) ethanol (gasohol).

1.2 Approximately 30 aromatic gasoline components (C6-C12) have been identified (using GC/MS and GC/IR) and can be quantified by this method. Coelution of aromatic isomers occurs for some of the C9-C12 components (see Exhibit 1).

1.3 No interferences from non-aromatic compounds are known.

2 SUMMARY OF METHOD

2.1 A highly polar capillary column (DB-WAX) is used to achieve early, aggregate elution of the non-aromatic components followed by gradual elution of the individual aromatic compounds. A photoionization detector (PID) is used in series with a flame ionization detector (FID) to quantify the eluting components.

2.2 Benzene coelutes with ethanol and/or C9 paraffins. Because of its higher aromatics selectivity, the PID signal is used to quantify benzene. The quantification of all other components is based on the FID signal. The ratio of the FID/PID result for o-xylene is used as a normalization factor to correct the benzene (PID) result for detector response deterioration caused by build-up of heavy hydrocarbons on the UV lamp.

2.3 Calibration of the response of each detector is carried out using external standards prepared volumetrically.

2.4 Samples are diluted volumetrically in isooctane and transferred to autosampler vials from which they are injected into the GC.

3 INSTRUMENTS AND APPARATUS

3.1 Gas chromatagraph (GC), Varian model 6000 or equivalent, equipped with DB-Wax (J & W) or equivalent megabore column and PID/FID, connected in series.

3.2 Autosampler, Varian model 8000 or equivalent.

3.3 Data system, Varian Vista 401 or equivalent.

4 REAGENTS STANDARDS

4.1 All gases used to support the GC analysis shall equal or exceed the following purity:

Helium shall have a minimum purity of 99.995%
Hydrogen shall have a minimum purity of 99.995%
Air shall be zero grade (purity: 1 ppm THC)

4.2 Reagent grade chemicals (EM Science or equivalent) are used in the preparation of the calibration standard:

Benzene
Toluene
Ethylbenzene
m-Xylene
p-Xylene
o-Xylene
1,2,4-trimethylbenzene
2,2,4-trimethylpentane (isooctane)

4.3 A calibration standard of 6% toluene, 2% each of benzene, ethylbenzene, o-, m-, and p-Xylene, and 1,2,4-trimethylbenzene is prepared by dilution of the appropriate volume of reagent grade aromatic with isooctane.

4.4 The control standard is a commercially available unleaded gasoline.

4.5 All standards are refrigerated during storage.

5 PROCEDURE

5.1 Each gasoline sample is diluted 1:10 with isooctane in an autosampler vial.

5.2 A 0.5 ul aliquot of each diluted sample is injected via autosampler into a gas chromatograph (GC), configured as follows:

Column:	DB-wax, 30 m, 0.53 mm ID, 1.0 micron film thickness
Carrier gas:	Helium at 5 mL/min
Make-up gas:	Helium at 25 mL/min
Detectors:	PID/FID in series; hydrogen at 30 mL/min and air at 300 mL/min
Injector:	Packed column injector with megabore adapter insert; on-column injection at 175 deg C.
Temperature:	35°C (4 min), 35°C to 50°C (5°C/min), 50°C to 120°C (10°C/min), 120°C to 160°C (20°C/min), hold 17min
Data system:	Varian Vista 401.

5.3 An FID and a PID chromatogram are recorded simultaneously by the data system and peak areas determined for both signals (Exhibit 2).

CALCULATIONS

6.1 <u>Individual Aromatic Compounds Except Benzene:</u>

6.1.1 Compound concentrations are determined from the FID response factors. The response factor is the component concentration divided by the area counts of the appropriate chromatographic peak.

6.1.2 Response factors for components not found in the calibration standard are assigned by the software to be identical to those of the previous calibration peak.

6.1.3 Compound concentrations in volume percent are determined from the area under the appropriate chromatographic peak:

Concentration (Aromatic) = Area (FID) * Response Factor (FID)

6.2 Benzene:

6.2.1 Benzene is quantified from the PID area counts and a corrected PID response factor as follows:

Benzene = Area(PID)*RF(PIDCorr)

Where, Benzene is the concentration in percent (vol/vol), Area (PID) is the area under the benzene PID signal and RF(PIDCorr) is the corrected response factor of the PID for benzene.

6.2.2 The correction factor for the PID is the ratio of results for o-xylene as determined from the FID and PID signals respectively:

RF(PIDCorr) = o-xylene(FID)/o-xylene(PID)

6.3 Total Aromatics:

6.3.1 All FID peaks after and including ethylbenzene are considered to be aromatic compounds as long as the corresponding PID signal is present.

6.3.2 All aromatic peaks are quantified using the calculations described in 6.1 and 6.2.

6.3.3 The sum of all the individual aromatic compound concentrations is the total aromatic fraction of the sample.

7 LINEARITY, PRECISION AND LIMITS OF DETECTION

7.1 Linearity

7.1.1 A reformulated gasoline containing a nominal concentration of 1% benzene and 20% total aromatics was diluted successively with isooctane. Repeat measurements were made at various concentrations and the results subjected to regression analysis.

7.1.2 Exhibit 3 shows the calibration results from 12 measurements for benzene.

Slope (m) = 38279 area counts/volume percent
Intercept (b) = -557 area counts
Correlation Coefficient = .9992

7.1.3 Exhibit 4 gives the calibration results from 12 measurements for total aromatics.

Slope (m) = 62860 area counts/volume percent
Intercept (b) = 9600 area counts
Correlation Coefficient = .9998

7.2 Precision

7.2.1 Precision of this method was determined from repeat measurements of gasoline samples including some that were diluted with isooctane to reduce aromatic concentrations.

7.2.2 For benzene in the range of concentrations from .1% to 3% (v/v), the precision of the method (at a 95% level of confidence) is 4.7% of the measured value. This value was determined from repeat measurements of different gasoline samples.

7.2.3 For total aromatics in the range of concentration from 1% to 40% (v/v), the precision of the method (at a 95% level of confidence) is 4.6% of the measured value.

7.3 Limit of Detection (LOD)

7.3.1 The LOD is calculated from the multi-point calibration, as follows (see 9.2):

$$\text{LOD} = \frac{|b| + (3)(\text{std. dev.})}{m}$$

where std. dev. is the standard deviation of the lowest measured concentration.

7.3.2 Benzene LOD = .02 volume percent

7.3.3 Total Aromatics LOD = .15 volume percent

8 QUALITY CONTROL

8.1 Two calibration standards, one control standard, and one isooctane blank are analyzed daily at the beginning of each set of samples.

8.2 Calibration and control standards (working standards) are prepared every six months and analyzed daily.

8.3 The control standard is repeated every ten samples and again at the end of the batch.

8.4 Quality Control (QC) charts are maintained for both calibration and control standards (see Exhibit 5).

8.5 A replicate analysis is performed on one of every ten samples, or at least once per day.

8.6 If results of repeat analysis vary by more than 10 percent, the whole batch is reanalyzed.

8.7 An isooctane blank is analyzed daily to check the analytical system for contamination.

8.8 A multi-point calibration for linearity check is performed semi-annually. At this time, the precision and LOD of the method are determined.

8.8.1 A multi-point calibration is also performed when the column is changed, major instrument repair or modification is performed, or analysis of additional compounds is required.

8.9 Confirmation of compounds is performed by GC/Mass Spectroscopy (GC/MS) or GC/Fourier Transform Infrared Spectroscopy (GC/FTIR).

9 REFERENCES

9.1 Rieger, P.L. and Shikiya, J.M., "Analysis of Aromatics in Motor Fuel by Gas Chromatography/Photoionization Detection-Flame Ionization Detection." Paper 89-34B.3, Presented at the 82nd Annual Meeting and Exhibition of Air & Waste Management Association Annual Meeting (1989).

9.2 Long, G. L. and Winefordner, J.D., Anal. Chem., 55, 712A (1983).

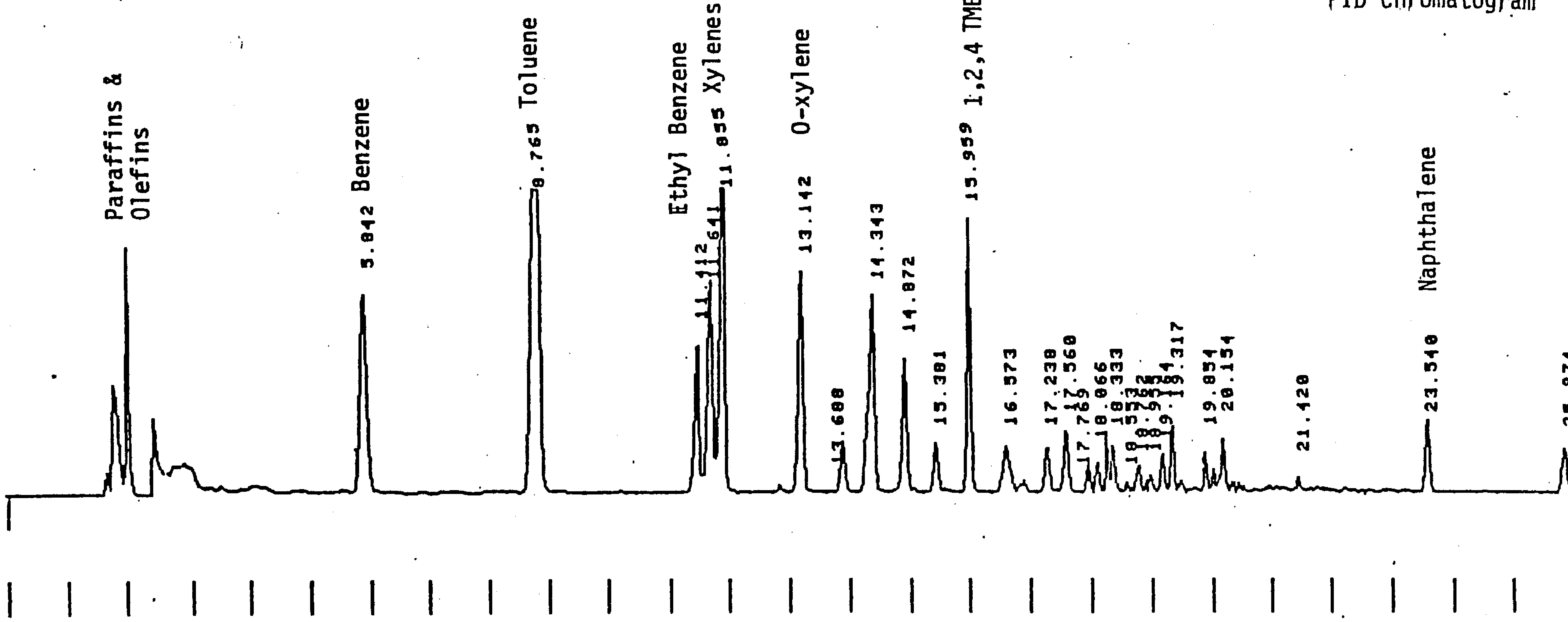
Exhibit 1.

Aromatic Compounds in Gasoline

Benzene
Toluene
Ethylbenzene
p-Xylene
m-Xylene
o-Xylene
Propylbenzene
1-Ethyl-3-methylbenzene
1,3,5-Trimethylbenzene
1-Methyl-1-propylbenzene
1-Ethyl-2-methylbenzene
1-Ethyl-1,4-dimethylbenzene
1,2,4-Trimethylbenzene
C4-Alkylbenzenes
Ethyldimethylbenzenes
C5-Alkylbenzenes
1,2,4,5-Tetramethylbenzene
Methyl-2,3-dihydro-1H-indenes
1,2,3,4-Tetramethylbenzene
Naphthalene
Methylnaphthalenes
Ethylnaphthalene
Dimethylnaphthlenes

Exhibit 2.

PID Chromatogram



FID Chromatogram

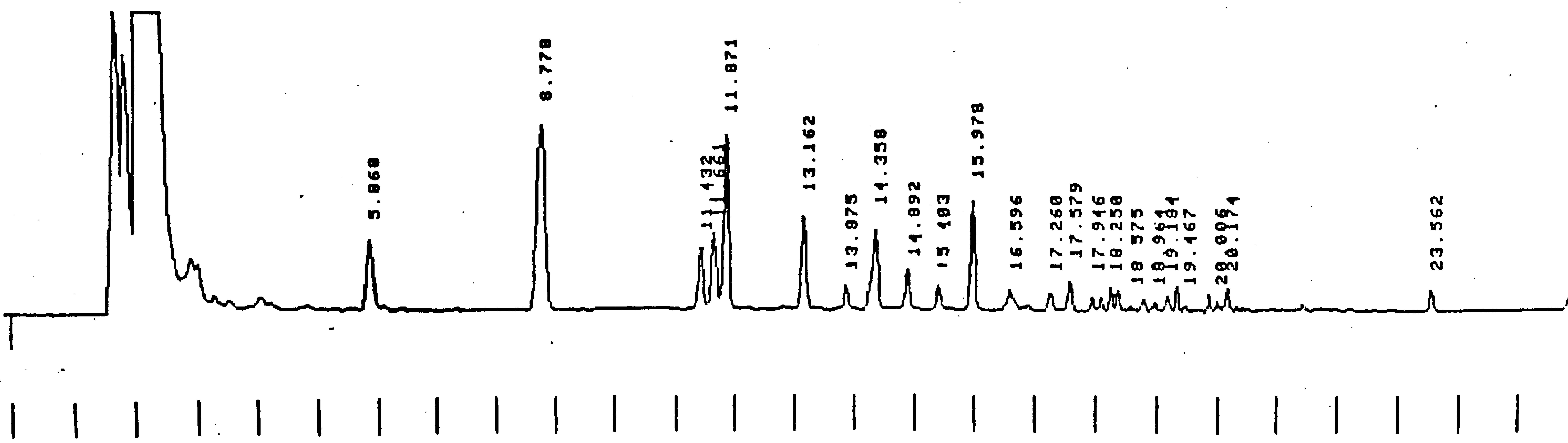


Exhibit 3. Area Counts Vs Concentration

Benzene in Gasoline

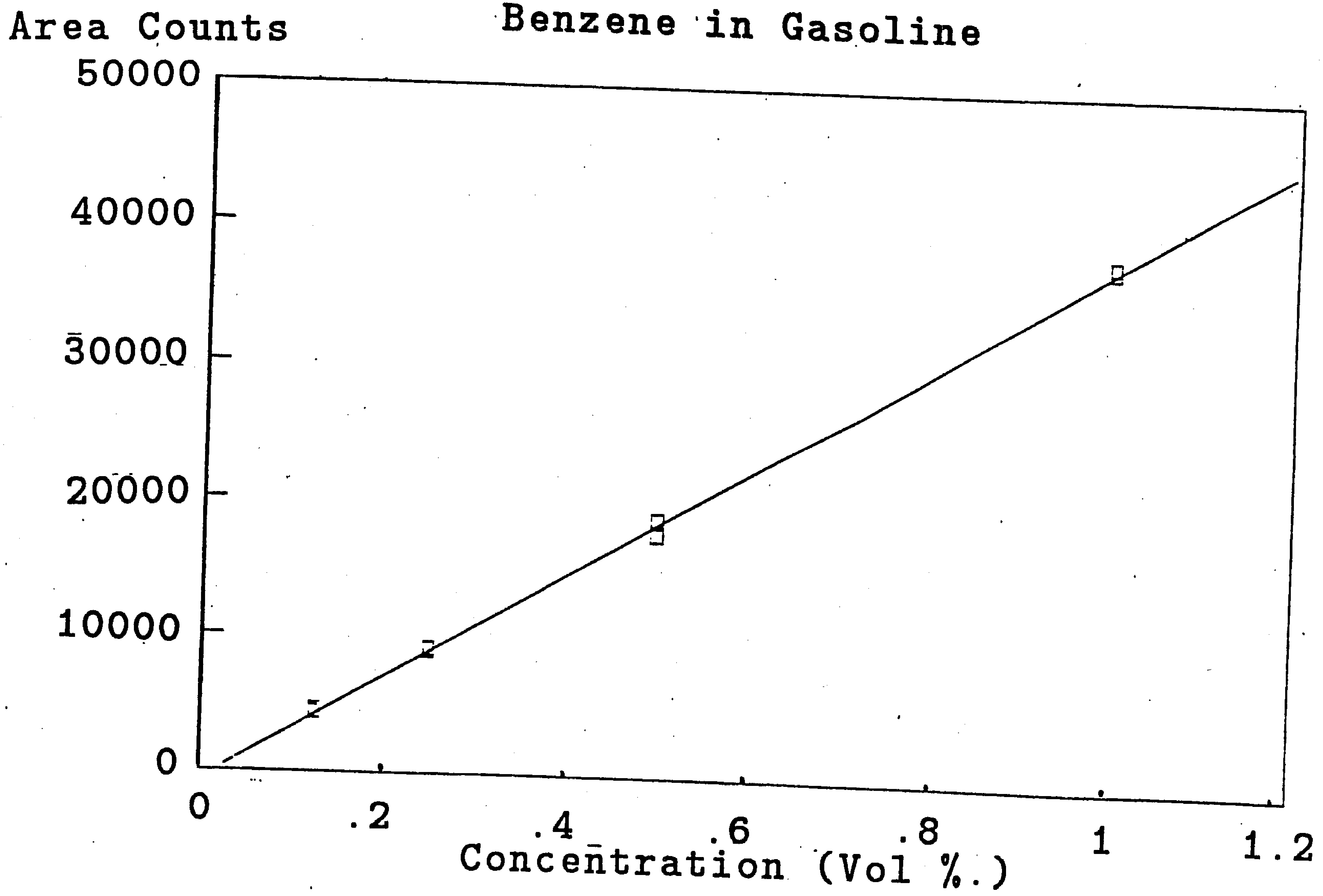


Exhibit 4. Area Counts Vs Concentration

Total Aromatics in Gasoline

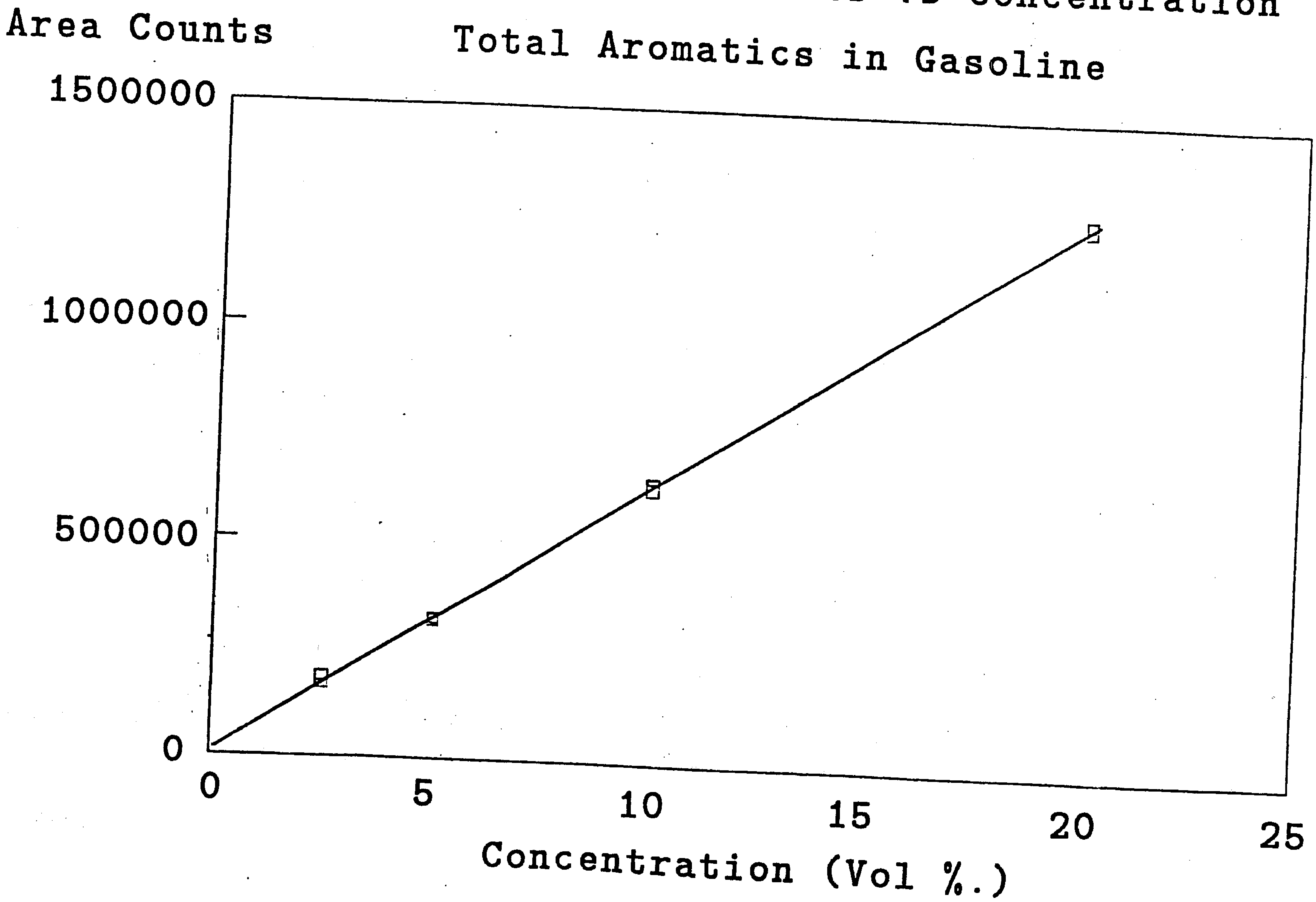


Exhibit 5.
Sample Control Chart

```
WLD DAILY QUALITY CONTROL analyst:CHRIS      filename:b2poall.ctr       02/27/91
instrument:VARIAN 6000     method:FID\PID     item:BENZENE (NORMALIZED)  15:18:02
 Low Ctrl. Low Warn. (CONTROL) High Warn. High Ctrl.  unit:PERCENT       n = 26 ¦#-#-#-#-#    C-O-N-T-R-O-L  C-H-A-R-T    #-#-#-#-#¦
(mean-3sd) (mean-2sd)  (mean)  (mean+2sd)  (mean+3sd)    (sd) precision(100sd/m)¦
     1.9        1.9        2.0        2.0        2.1       0.0          1.4     ¦ L.C.    L.W                             H.W.  H.C.¦
D A T E  time   sample ID  no.   v  a  l  u  e    100(v-m)/m 100(v-m)/sd status ¦m-3sd  m-2sd            mean           m+2sd m+3sd¦
MM/DD/YY hh:mm  *********  ###   ===============  REL.ERROR% F>300 W>200 O K¦W¦F¦IvI¦I¦I¦IvI¦I¦I¦I¦I¦I¦I¦IvI¦I¦I¦I¦I¦I¦I¦IvI¦I¦I¦IvI
02/01/91 00:00  11915.15   1                2.040      2.63      187.59    O K   ¦       I               ¦              1I       ¦
02/01/91 00:00  1191.02    2                2.000      0.62       44.14    O K   ¦       I               ¦   2           I       ¦
02/01/91 00:00  1191.03    3                1.940     -2.40     -171.04    O K   ¦       I 3             ¦               I       ¦
02/01/91 00:00  1191.04    4                1.940     -2.40     -171.04    O K   ¦       I 4             ¦               I       ¦
02/01/91 00:00  1191.05    5                1.920     -3.41     -242.76 WARNING  ¦    5  I               ¦               I       ¦
02/01/91 00:00  1191.06    6                1.970     -0.89      -63.45    O K   ¦       I          6    ¦               I       ¦
02/01/91 00:00  1191.07    7                1.970     -0.89      -63.45    O K   ¦       I          7    ¦               I       ¦
02/04/91 00:00  1191.27    8                2.000      0.62       44.14    O K   ¦       I               ¦   8           I       ¦
02/04/91 00:00  1191.18    9                2.020      1.63      115.86    O K   ¦       I               ¦        9      I       ¦
02/04/91 00:00  1191.19    10               2.010      1.12       80.00    O K   ¦       I               ¦     0         I       ¦
02/08/91 00:00  1845.15    11               2.020      1.63      115.86    O K   ¦       I               ¦        1      I       ¦
02/08/91 00:00  1845.16    12               2.000      0.62       44.14    O K   ¦       I               ¦   2           I       ¦
02/08/91 00:00  1845.16    13               2.000      0.62       44.14    O K   ¦       I               ¦   3           I       ¦
02/08/91 00:00  1845.05    14               2.000      0.62       44.14    O K   ¦       I               ¦   4           I       ¦
02/08/91 00:00  1845.06    15               1.980     -0.39      -27.59    O K   ¦       I             5 ¦               I       ¦
02/08/91 00:00  1845.07    16               2.010      1.12       80.00    O K   ¦       I               ¦     6         I       ¦
02/08/91 00:00  1845.08    17               1.970     -0.89      -63.45    O K   ¦       I          7    ¦               I       ¦
02/11/91 00:00  1972.01    18               2.000      0.62       44.14    O K   ¦       I               ¦   8           I       ¦
02/11/91 00:00  1972.02    19               1.980     -0.39      -27.59    O K   ¦       I             9 ¦               I       ¦
02/11/91 00:00  1972.03    20               2.020      1.63      115.86    O K   ¦       I               ¦        0      I       ¦
02/22/91 00:00  2350.01    21               2.010      1.12       80.00    O K   ¦       I               ¦     1         I       ¦
02/22/91 00:00  2350.02    22               1.990      0.12        8.28    O K   ¦       I               ¦2              I       ¦
02/22/91 00:00  2350.05    23               1.970     -0.89      -63.45    O K   ¦       I          3    ¦               I       ¦
02/22/91 00:00  2350.06    24               1.970     -0.89      -63.45    O K   ¦       I          4    ¦               I       ¦
 2/22/91 00:00  2350.09    25               1.980     -0.39      -27.59    O K   ¦       I             5 ¦               I       ¦
 2/22/91 00:00  2350.10    26               1.970     -0.89      -63.45    O K   ¦       I          6    ¦               I       ¦
 LD DAILY QUALITY CONTROL analyst:CHRIS      filename:to329.ctr         03/22/91
 nstrument:VARIAN 6000     method:FID\PID     item:TOTAL AROMATICS      15:57:57
 Low Ctrl. Low Warn. (CONTROL) High Warn. High Ctrl.  unit:PERCENT       n = 16 ¦#-#-#-#-#    C-O-N-T-R-O-L  C-H-A-R-T    #-#-#-#-#¦
 mean-3sd) (mean-2sd)  (mean)  (mean+2sd)  (mean+3sd)    (sd) precision(100sd/m)¦
     34.0       34.9       36.7       38.5       39.3      0.9          2.4     ¦ L.C.    L.W                             H.W.  H.C.¦
  A T E  time   sample ID  no.   v  a  l  u  e    100(v-m)/m 100(v-m)/sd status ¦m-3sd  m-2sd            mean           m+2sd m+3sd¦
  /DD/YY hh:mm  *********  ###   ===============  REL.ERROR% F>300 W>200 O K¦W¦F¦IvI¦I¦I¦IvI¦I¦I¦I¦I¦I¦I¦IvI¦I¦I¦I¦I¦I¦I¦IvI¦I¦I¦IvI
 2/01/91 00:00  1196.18    1               35.770     -2.43      -99.54    O K   ¦       I       1       ¦               I       ¦
  /01/91 00:00  1196.21    2               35.970     -1.88      -77.19    O K   ¦       I         2     ¦               I       ¦
  /01/91 00:00  1196.19    3               36.790      0.35       14.44    O K   ¦       I               ¦3              I       ¦
  /01/91 00:00  1196.20    4               35.360     -3.55     -145.36    O K   ¦       I   4           ¦               I       ¦
  /04/91 00:00  1196.25    5               35.160     -4.09     -167.71    O K   ¦       I  5            ¦               I       ¦
  /08/91 00:00  1847.02    6               37.580      2.51      102.71    O K   ¦       I               ¦       6       I       ¦
  /08/91 00:00  1847.08    7               37.460      2.18       89.30    O K   ¦       I               ¦      7        I       ¦
  /08/91 00:00  1847.09    8               37.780      3.05      125.06    O K   ¦       I               ¦         8     I       ¦
  /08/91 00:00  1847.10    9               37.470      2.21       90.42    O K   ¦       I               ¦      9        I       ¦
  /11/91 00:00  1975.04    10              36.120     -1.48      -60.43    O K   ¦       I          0    ¦               I       ¦
  /11/91 00:00  1975.05    11              36.530     -0.36      -14.62    O K   ¦       I              1¦               I       ¦
  /22/91 00:00  2351.02    12              36.152     -1.39      -56.86    O K   ¦       I          2    ¦               I       ¦
  /22/91 00:00  2351.04    13              36.174     -1.33      -54.40    O K   ¦       I           3   ¦               I       ¦
  /22/91 00:00  2351.06    14              38.010      3.68      150.76    O K   ¦       I               ¦           4   I       ¦
  /20/91 00:00  3748.02    15              37.537      2.39       97.91    O K   ¦       I               ¦      5        I       ¦
  /20/91 00:00  3748.04    16              36.710      0.13        5.50    O K   ¦       I               6               I       ¦
```

Appendix 6

ESTIMATION OF COST, PRICE, AND FINANCIAL EFFECTS FOR THE BENZENE LIMIT

Table of Contents

Page

I. REFINERS' COST....................3

- A. Survey Results....................3
- B. Annualized Cost of Regulation....................4
  - 1. Limit on Average Benzene Content....................4
  - 2. Absolute Limit (Accompanying Limit on the Average....................7
  - 3. Single Limit at 1.0% (Regulatory Alternative)....................8

II. POTENTIAL PRICE INCREASE....................8

III. COST PER POTENTIAL CASE AVOIDED....................15

- A. First Method of Calculation....................16
- B. Second Method of Calculation....................18

IV. FINANCIAL EFFECTS ON SMALL REFINERS....................20

- A. Summary....................20
- B. Financial Analysis....................20
- C. Financial Condition in 1990....................22
- D. Outlook for Future....................23

I. REFINERS' COST

A. SURVEY RESULTS

In 1988, the ARB staff surveyed refiners in California on the costs of reducing the benzene content in their typical or average gasolines. The data returned from the survey, shown in Appendix 3, are the initial capital investment and the subsequent annual cash outlays for fuel, utilities, feedstocks, labor, overhead, and other periodic expenses associated with new process equipment. The capital investment is assumed to occur in 1995. All the costs are increments over the base case of no limit on benzene in gasoline (nor any other Phase-2 gasoline regulations). Since some refiners would export some of their low-benzene gasoline, the costs apply to making more low-benzene gasoline than California would use. The costs reflect meeting the indicated limits as limits on the average production over time, not as limits applicable to each batch of gasoline.

The cost data obtained in 1988 have been adjusted to 1991 dollars by these factors obtained from the Nelson-Farrar refinery price indices: capital expense--1.06, operating expenses--1.15. Table 6-1 shows the results.

Table 6-1. **Aggregated Survey Responses**
(1991 $)

	Benzene Limit (on average)			
	1.2 v%	1.0 v%	0.80 v%	0.60 v%
Gasoline produced[a] (1000 barrels/day)	954	954	958	958
Capital expenditure				
sum (million $)	663	778	995	1,270
$ per barrel/day[b]	695	816	1040	1,330
Annual outlay[c]				
sum (million $/yr)	156	208	251	333
$ per barrel	.450	.600	.720	.950

[a] for use in California in 1995

[b] sum $ / production volume

[c] operating and maintenance expenses, feedstock costs, and decreased value of products

B. ANNUALIZED COST OF REGULATION

The cost to refiners for meeting the proposed regulation can be split into the component for meeting a limit on the average benzene content as implemented by the averaging mechanism and the component for meeting the absolute limit of 1.20%.

1. Limit on Average Benzene Content

The staff has used the survey data to estimate the cost to refiners of meeting various benzene limits on the average benzene content of gasoline. The initial capital outlay, the annual outlays over 15 years, and the effect of income taxes have been discounted to present value at ten percent per year (after tax), and the total present value has been expressed as its equivalent annual cost over 15 years. This would be a refiner's reduction in profit if it could not increase its revenues (i.e., if the price of gasoline would not increase under a benzene limit). The annual equivalent cost includes the cost of capital (whether equity funds, borrowing capital, or a mix) at ten percent per year. To arrive at cost per gallon produced, we have divided the annual equivalent cost by the production rate of gasoline meeting the benzene limit, as calculated for 1995 from the survey responses and excluding gasoline that would be destined out-of-state.

An example calculation for an initial capital outlay of $9.90 million and an annual outlay of $2.06 million is in Table 6-2. For computing state taxable income, the initial capital outlay has been depreciated with the double-declining balance method over ten years. For federal taxable income, we have used a seven-year double-declining depreciation. State and federal tax rates are 9.6 and 34 percent. State tax benefits have been added to federal taxable income.

Table 6-3 shows the costs for 1) all survey respondents, 2) small refiners (crude oil capacity less than 50,000 barrels per day) who responded, 3) refineries with cracking but no cokers, and 4) refineries with cracking and coking. (Only two refineries with no coking or cracking responded. Their aggregate costs cannot be shown without jeopardizing confidentiality.) Small refiners, who usually operate the least complex plants, would have lower costs per gallon. The most complex refineries, which produce most of the gasoline, would have higher costs.

Table 6-2. Example Calculation of Refiner's Cost

Yr.	Capital Depreciation		Annual Outlay (a)	Reduction in Taxable Income[b]		Reduct. in Income Tax[c]		Net Expense (d)	Present Value (e)
	Calif.	fed.		Calif.	fed	Calif.	fed.		
0								9.90	9.90
1	1.98	2.83	2.06	4.04	4.50	.388	1.53	.142	.129
2	1.57	2.02	2.06	3.64	3.73	.350	1.27	.442	.365
3	1.27	1.44	2.06	3.33	3.13	.319	1.08	.658	.494
4	1.01	1.03	2.06	3.07	2.80	.295	.950	.814	.556
5	.811	.859	2.06	2.87	2.64	.276	.899	.886	.550
6	.649	.859	2.06	2.78	2.66	.260	.904	.896	.506
7	.649	.859	2.06	2.78	2.66	.260	.904	.896	.460
8	.649	0	2.06	2.78	1.80	.260	.612	1.19	.555
9	.649	0	2.06	2.78	1.80	.260	.612	1.19	.505
10	.649	0	2.06	2.78	1.80	.260	.612	1.19	.459
11	0	0	2.06	2.06	1.86	.198	.633	1.23	.431
12	0	0	2.06	2.06	1.86	.198	.633	1.23	.392
13	0	0	2.06	2.06	1.86	.198	.633	1.23	.356
14	0	0	2.06	2.06	1.86	.198	.633	1.23	.324
15	0	0	2.06	2.06	1.86	.198	.633	1.23	.295
tot.	9.90	9.90	30.9					24.4	16.3
								Total present value:	16.3
								Equivalent annual[f] cost:	2.13

[a] operating, maintenance and overhead costs

[b] annual outlay plus depreciation

[c] reduction in income x tax rate

[d] annual outlay - reductions in income tax (state + federal)

[e] net expense discounted to year 0 at 10% per year

[f] at 10% over 15 years

Table 6-3. Aggregated Survey Respondents' Costs[a]
(1991 $)

Refineries	Benzene Limit (on average)			
	1.20 v%	1.00 v%	0.80 v%	0.60 v%
	cents per gallon[b]			
All responding (19)	1.05	1.34	1.64	2.15
Small (5)	.79	.89	1.03	1.19
With cracking but no coking (7)	.92	.97	1.18	1.55
With cracking and coking (10)	1.09	1.47	1.80	2.37
	million $/yr			
All responding	154	196	241	316

[a] annual equivalent of capital investment plus annual outlays, after taxes; 10% after-tax discount rate

[b] pool (volume-weighted) mean

For 1987, respondents to the survey reported producing gasoline for California totalling about 90 percent of the amount reported to ARB in that year under the lead-in-gasoline regulation. Therefore, to estimate total costs of universal compliance with a benzene limit, the capital outlays and annual outlays in Table 6-1 and the annualized total costs (but not cents per gallon) in Table 6-3 have been divided by 0.9. The results are in Table 6-4.

These costs are based on the continuation of gasoline as the fuel for all LDVs except diesel LDVs. The adjustments for the case wherein no-low emission vehicles use gasoline (and the volume of gasoline made declines) is treated in the next chapter of this appendix.

Table 6-4. Total Refiners' Costs of Reducing Benzene[a]

	Benzene Limit (on average)			
	1.20	1.00	0.80	0.60
	(million 1991 $)			
Capital expenditure	737	864	1,110	1,410
Annual outlay	173	231	279	370
Annualized total[b]	171	217	268	351
cents/gallon[c]	1.05	1.34	1.64	2.15

[a] for all complying gasoline, including imports and exports

[b] includes capital recovery and annual outlays, after tax

[c] annualized cost / (1,060,000 barrel per day (California gasoline volume, per survey responses)

2. Absolute Limit (accompanying limit on the average)

Additional expense would be incurred to ensure never exceeding a limit on benzene at a value higher than a limit on the average. The cost of meeting such a limit was not requested of refiners in the staff's survey. However, an approximation can be made from the survey data. The cost of never exceeding a value of benzene in gasoline can be modelled as an increment in capital cost relative to the cost of meeting a limit on the average. The increment could derive from two factors.

First, the equipment installed to reduce the benzene in a refiner's typical or average gasoline might be undersized for achieving a fixed limit in every batch of gasoline. When the gasoline blending stocks have unusually high benzene contents, the equipment might not be able to process enough of the stocks to get the blended concentration below the fixed limit. A capacity shortfall like this could be a major cost factor if the absolute limit were not much higher than the limit on the average. However, since the proposed absolute limit, 1.20%, is considerably higher than the proposed limit on the average, 0.80%, this factor should not be important. I.e., equipment sufficient to meet 0.80% on most gasoline should seldom be unable to keep benzene below 1.20%.

The second factor is the need for back-up equipment to maintain the ability to control the benzene content when the primary equipment (the equipment discussed in the survey responses) must be removed from service. The staff has assumed that to meet a limit at 1.20% while the primary equipment is down would require the equipment designed to meet 1.20% as a limit on the average or typical gasoline.* From Table 6-4, the capital expenditure would be $737 million dollars above the expediture for meeting the proposed limit on the average benzene content.

We assume that there would be minimal operating cost associated with the $737 million incremental capital expenditure because the equipment would seldom be used. Amortized over 15 years, the incremental cost of an absolute limit at 1.20% would be $68.0 million per year. Per gallon, this is 0.42 cents over the 1.64 cents shown in Table 6-4.

3. Single Limit at 1.0% (regulatory alternative)

One possible strategy of a refiner opting to meet the optional 1.00 v.% limit with all gasoline would be to install process equipment designed to meet 0.80 % benzene in typical gasoline and install redundant equipment designed for 1.00%. The revenue required in this case would be to amortize the capital investment for both sets of equipment plus meet operating expense in the equipment designed for 0.80 %. This is similar to the case above wherein the 0.80% limit on the average and the 1.20% absolute limit apply, except for replacing the redundant equipment designed for 1.20% with equipment designed for 1.00%. Thus, in general, the revenue required for this option (under the postulated strategy) would be somewhat higher than the values already presented. However, this option could be cheaper for some refiners. Since any refiner could choose either regulatory option (0.80% / 1.20% dual limit or 1.00% flat limit), a refiner would be expected to use the cheaper alternative. Therefore, the costs estimated above for the dual limit option can serve as an upper bound on the cost of the flat limit option for any refiners who might use it.

II. POTENTIAL PRICE INCREASE

A refiner's revenue requirement is the increase in revenue that would "pass" all costs to the consumer, i.e., leave the company's profits unchanged. In this situation, the expenditures to comply with the regulation would be returned to a company at an after tax rate-of-

---

* Rather than install redundant equipment, a refiner might install excess storage capacity and maintain or buy a stock of low-benzene gasoline so that high-benzene gasoline could be held until diluted down to 1.20% benzene. This measure would be less secure than the redundant process capacity. Its cost would be difficult to estimate.

return equal to the discount rate. The method of calculation is exactly as in the example in Table 6-2 with the inclusion of a constant annual revenue large enough to reduce the equivalent annual cost to zero. That annual revenue is the revenue requirement. Under the parameters used in the analysis, the total revenue requirement equals 1.68 times the refiners' total annualized cost. (The 68 percent revenue above the refiner's cost is needed to pay the extra income tax when all the deductible expenses are offset.) The corresponding increase in price is 1.68 times the average refiners' cost per gallon.

1. If No Alternative Fuels Displace Gasoline

Table 6-5 shows the total revenue required to offset all costs (for limits on the average benzene content) among all refiners for the full complement of gasoline reflected in the survey responses. For a benzene limit at 0.80 volume percent, the needed revenue would be $450

Table 6-5. **Revenue Requirements for Reducing Benzene**

Refineries	Benzene Limit (on average)			
	1.20	1.00	0.80	0.60
	average cents per gallon[a]			
All	1.77	2.24	2.76 (.70)*	3.61
Small refiners	1.32	1.49	1.73	1.99
With cracking but no coking	1.55	1.62	1.98	2.61
With cracking and coking	1.84	2.46	3.03	3.97
	total revenue, million $/yr			
All[b]	288	364	450 (114)*	589

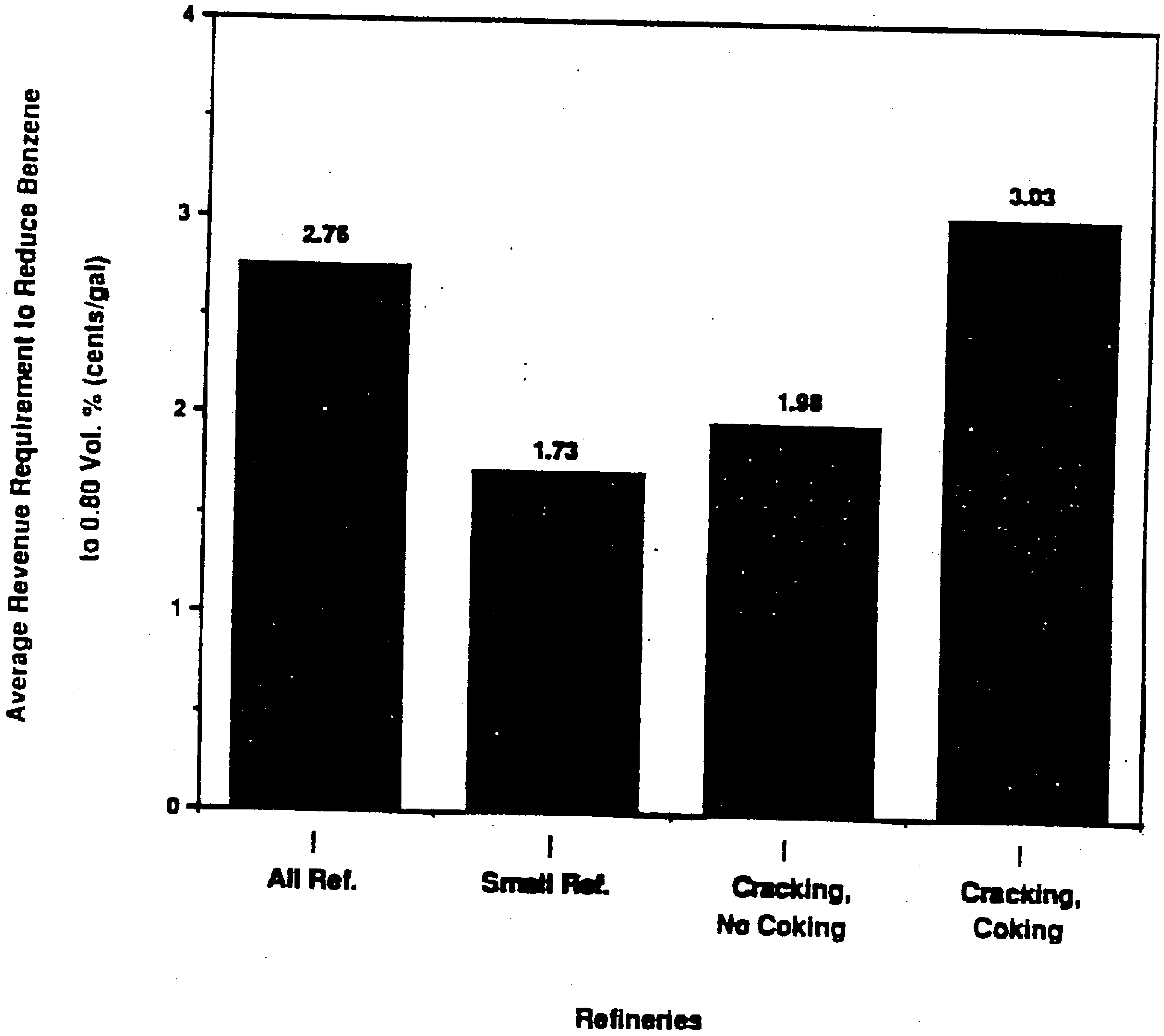
[a] volume-weighted (pool) average over 1,060,000 gallons/yr

[b] covers all gasoline complying with the limit

* addition to meet absolute limit at 1.20 v.%

million per year. The table also shows the required revenue per gallon produced, which is 2.76 cents per gallon in the 0.80 % case. This is the average over all gallons of the price increase needed to pass all costs to consumers. I.e., if the price of gasoline would increase by this amount, the total cost to industry for removing benzene from gasoline would be zero. Refiners with costs lower than average would profit at this price; those with costs higher than average would have net costs. The table also shows average revenue required per gallon by type of refinery, as does Figure 6-1.

Figure 6-1. Revenue Requirement by Type of Refiner (cents/gallon)



The additional revenue required to offset the (capital) cost to comply also with an absolute limit at 1.20% benzene would be $114 million per year. This is equivalent to an additional 0.70 cents per gallon for each price in the table. Thus, the combination of a limit at 0.80% for the average benzene content and an absolute limit at 1.20% would require revenue of 3.46 cents per gallon, on average.

Wickland Oil Company, which in 1988 imported all gasoline that it sold in California, also provided information on its revenue requirements for meeting a benzene limit by processing its imported gasoline. Wickland's number for the 0.80 percent case is 7.7 to 11.5 cents per gallon (1988$), depending upon the choice of hydrogenation or benzene extraction to treat the gasoline. These numbers were calculated somewhat differently than the numbers in Table 6-5. On the same basis as Table 6-5, Wickland's revenue requirement would be about nine cents (1991$) per gallon in the 0.80 percent case, for either benzene extraction or hydrogenation. This exceeds the revenue requirement for every refinery in California in the staff's survey. The cost does not change much for lower or higher values of the limit. The staff does not know if Wickland remains in the same situation.

2. If Gasoline is Only Half of LEV Fuel

If gasoline will be only half of all fuel used by low-emission vehicles (LEVs*), the amount used, as a fraction of all motor fuel, will decline. This would reduce the operating cost associated with reducing the benzene content. The staff has assumed that this cost would be proportional to the volume of gasoline produced. However, we have assumed that a declining production of gasoline would not affect the capital cost of reducing benzene, since the investment would be made before alternative fuels could displace much demand for gasoline.

The fraction of all motor fuel (expressed as equivalent gasoline volume) demanded by LEVs is determined by their use rate (vehicle-miles travelled) and fuel economy relative to those parameters for the rest of the fleet. The relationship is:

$$F = \frac{(vmt/mpg)_{LEV}}{(vmt/mpg)_{LEV} + (vmt/mpg)_{others}}$$

where vmt is the fraction of all miles travelled and mpg is fuel economy (e.g., miles per gallon). "F" must be calculated separately for light-and medium-duty vehicles and then combined with weights equal to the relative fuel demands in the two categories. The values assumed for vmt, mpg, and fuel demand are those used by the staff in

---

* The acronym "LEV" stands for transitional low-, low-, and ultra-low-emission vehicles.

Appendix B-6 of Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Technical Support Document, August 13, 1990. The values of vmt correspond to the assumed rate of sales of LEVs in Tables I-6 and I-7 of that document. The split between light- and medium-duty fuel volumes is from California Motor Vehicle Stock, Travel, and Fuel Forecast, December 1990.

Table 6-6 shows "F" by year. 1 - F/2 is the residual gasoline use for the case under consideration. Table 6-7 shows the sequence of operating costs corresponding to the declining rate of gasoline demand.

Table 6-6. Fuel for LEVs[a] as Fraction of Total Motor Fuel Demand

Year	Light-duty vehicle fuel				Med-duty vehicle fuel			All fuel[b] (F)
	TLEVs	LEVs	ULEVs	sum	LEVs	ULEVs	sum	
1996	.044	0	.002	.046	0	0	0	.040
1997	.046	.034	.003	.083	0	0	0	.071
1998	.045	.087	.004	.136	.024	.002	.026	.121
1999	.041	.165	.005	.211	.084	.005	.089	.194
2000	.037	.261	.008	.306	.172	.007	.179	.288
2001								.38 *
2002	.028	.427	.024	.479	.377	.022	.339	.459
2003								.53 *
2004								.60 *
2005	.017	.578	.068	.663	.552	.071	.623	.657
2006								.70 *
2007								.73 *
2008								.76 *
2009								.80 *
2010	.006	.704	.119	.829	.695	.112	.807	.826
15-year mean:								.477

[a] excluding diesel

* interpolated value

[b] .86 * sum, light-duty + .14 * sum, med.-duty

Table 6-7 **Annual Operating Costs for Decreasing Gasoline Demand** (million 1991$)

Year	F/2[a]	Benzene Limit (on average)			
		1.20%	1.00%	0.80%	0.60%
	base[b]:	173	231	279	370
		operating costs[c]			
1996	.020	170	226	273	363
1997	.0355	167	223	269	357
1998	.0605	163	217	262	348
1999	.097	156	209	252	334
2000	.144	148	198	239	317
2001	.19	140	187	226	300
2002	.230	133	178	215	285
2003	.265	127	170	205	272
2004	.30	121	162	195	259
2005	.329	116	155	187	248
2006	.35	113	150	181	241
2007	.365	110	147	177	235
2008	.38	107	143	173	229
2009	.40	104	139	167	222
2010	.413	102	137	164	217

[a] F is from Table 6-6.
[b] annual outlay from table 6-4
[c] base cost times 1-F/2

Table 6-8 shows the corresponding average revenue requirements over the 15 years 1996 to 2010 and the revenues per gallon when the declining series of operating expenses is discounted at 10% per year. Although revenue requirements go down, the revenue required per gallon rises about 16 percent relative to the case of gasoline as the sole LEV fuel. This reflects the invariant capital expense in Table 6-4 and the declining volume of gasoline.

Meeting an absolute limit at 1.20% would add 0.70 cents per gallon to the prices in Table 6-8 if gasoline is the only LEV fuel and 1.34 cents if gasoline half of LEV fuel.

Table 6-8. Revenue Requirement by Status of Gasoline (1991$)

Gasoline status	Benzene Limit (on average)			
	1.20%	1.00%	0.80%	0.60%
the only LEV fuel[a]				
million $/yr	288	364	450 (114)*	589
cents/gal	1.77	2.24	2.76 (.70)*	3.61
half of LEV fuel[b]				
million $/yr	254	321	397 (114)*	518
cents/gal	2.05	2.59	3.23 (1.34)*	4.17

[a] repeated from Table 6-5

[b] 15-year averages; average 23.9% decline in gasoline volume

* addition needed to meet absolute limit at 1.20%.

3. Price to Prompt Importation of Gasoline

A limit on the possible increase in the price of gasoline is the price that would prompt the importation of gasoline from the Gulf Coast.

Information from the Lundberg Letter and Octane Week was used to determine the average wholesale price difference for regular unleaded gasoline between the West Coast and the Gulf Coast. The average data are summarized:

Period	Comparison	Price difference
2/86 to 12/87	West Co. - Gulf	$.057/gal
"	L.A. - Houston	$.087/gal
3/89	L.A. - Houston	$.070/gal
2/90 to 6/90	West Co. - Gulf	$.045/gal

From KAN International Company in Los Angeles, the cost of shipping gasoline from Houston to L.A. in a 20,000-barrel shipment averages 9.5 cents/gallon.

The Gulf Coast marketer's cost of providing low-benzene (0.80 v%) gasoline on the West Coast would be:

$.028 (to refine it) + $.095 (shipping) = $.123

The value of the Gulf gas relative to current West Coast price would be:

(current Gulf price - current West Coast price) + $.123

= (-$.045 to -$.087) + $.123

= $ .04 to $.08

Therefore, a (firm) price increase of from four to eight cents per gallon in California should prompt shipments of low-benzene gasoline from the Gulf Coast.

III. COST PER POTENTIAL CANCER CASE AVOIDED

The staff has calculated costs per cancer case avoided by two methods. The first calculation is:

$$\frac{\text{annual revenue required} \times 70 \text{ years}}{\text{cases avoided over 70 years}}$$

where the cases avoided, from Tables 1-17 to -21 in Appendix 1, are values corresponding to a fixed population exposed to a constant reduction of ambient benzene concentration over 70 years. The annual revenues are for meeting a limit on the average benzene content, as in Table 6-8. The second calculation is:

$$\frac{\text{annual revenue required} \times 15 \text{ years}}{\text{sum [risk reduced} \times \text{population], over 15 years}}$$

where the risk reduced in a year is the reduction in ambient benzene concentration in that year times the lifetime risk factor divided by 70 years. The first calculation yields a <u>rate</u> of cost per case avoided calculated for the conditions in a particular year. The second calculation is an integral of that variable rate over the 15-year amortization period assumed for capital expenses. It is valuable because it takes account of the varying emission inventory and population and because it involves a meaningful period of time.

The unit risk from benzene exposure is 93 per million per ppb per lifetime. Costs per case avoided for other values of unit risk would be the values shown here times unit 93/unit risk.

A. FIRST METHOD OF CALCULATION

The reduction of ambient concentration due to a limit on benzene in gasoline has been calculated for three years--1994 *, 2000, and 2010. Thus, there are three base years for calculating lifetime cases avoided. Tables 6-9a shows the inputs and the results of the cost-per-case calculations for the limit on the average benzene content at 1.20 and 0.80 v.%. The values of $/year are from Table 6-8. The values of cases avoided are from Appendix 1, Tables 1-17 through 1-21. Results for other values of the limit can be obtained by interpolation.

The costs per case in Table 6-9a include only the revenue required to meet the limit on the average benzene content of gasoline, not the added revenue ($114 million per year) required to meet the absolute limit of 1.20%. Since the costs requiring this latter revenue are not associated with reducing benzene emissions, they should not be mixed in cost-per-case calculations with revenues that are asociated with reducing emissions. Instead, Table 6-9b shows separately the added revenue required for the 1.20% limit per case avoided by the 0.80% limit on the average.

---

* The proposed benzene limit would not go into effect until 1996. However, an emission inventory for 1996 is not available. The staff has calculated cost per case for 1994 as a surrogate for 1996 to provide a third value to compare to those for 2000 and 2010.

Table 6-9a. **Calculation of Cost per Cancer Case Avoided by Limit on Average** (million $/case)

	Limit at: 1.20 v.%			0.80 v.%		
	$/yr[a]	cases[b]	$/case[c]	$/yr	cases	$/case
			1994 basis			
	288	902	22.2	450	1,356	23.2
			2000 basis			
Gasoline is the only LEV fuel	288	838	24.1	450	1,255	25.1
Gasoline is 1/2 of LEV fuel	254	821	21.7	397	1,233	22.5
			2010 basis			
Gasoline is the only LEV fuel	288	590	34.2	450	887	35.5
Gasoline is 1/2 of LEV fuel	254	497	35.8	397	747	37.2

[a] millions; revenue required to meet limit on average benzene content
[b] potential cases avoided over 70 years at conditions in base year
[c] million $/yr x 70 years / cases

Table 6-9b. **Added Cost of Absolute Limit (1.20 v.%), per Case Avoided by the 0.80 v.% Limit on the Average** (million $/case)

	1994 basis	2000 basis	2010 basis
Gasoline is the only LEV fuel	5.88	6.36	9.00
Gasoline is 1/2 of LEV fuel	5.88	6.47	10.7

B. SECOND METHOD OF CALCULATION

Appendix 1 shows the estimates of reduced lifetime risks that would result from limiting benzene in gasoline under the conditions in 1994, 2000, and 2010. Risk reductions on the basis of intermediate years have been determined by interpolation. Each lifetime risk reduction has been divided by 70 to put it on an annual basis. These risk reduction measures multiplied by the predicted population for the year and summed from 1996 to 2010 give a measure of the effectiveness of the proposed benzene limit over 15 years. This measure divided into the revenue required under the 15-year cost amortization gives the second measure of cost per case avoided.

Tables 6-10 and 6-11 show the results for meeting a limit on the average benzene content (which reduces emissions) and the increment for also meeting the absolute limit of 1.20 % (which does not reduce emissions). Results for other values of the average limit can be obtained by interpolation.

Table 6-10. Second Calculation of Cost per Cases Avoided (15-year integration for 0.80% basic limit)

Gasoline is the only LEV fuel

Year	70-year cases Avoided	Population (millions)	Risk avoided (a)	Risk avoided per yr.[b]	Cases avoided per yr.[c]
1994	1,356	32.75	41.40	.59	19.37
1995		33.34	40.27	.58	19.18
1996		33.92	39.14	.56	18.97
1997		34.51	38.01	.54	18.74
1998		35.09	36.88	.53	18.49
1999		35.68	35.74	.51	18.22
2000	1,255	36.26	34.61	.49	17.93
2001		36.73	33.31	.48	17.48
2002		37.21	32.02	.46	17.02
2003		37.68	30.72	.44	16.54
2004		38.16	29.42	.42	16.04
2005		38.63	28.12	.40	15.52
2006		39.10	26.82	.38	14.99
2007		39.58	25.53	.36	14.43
2008		40.05	24.23	.35	13.86
2009		40.53	22.93	.33	13.28
2010	887	41.00	21.63	.31	12.67

sum, 1996-2010: 244.15

- -

	0.80% basic limit	1.20% absolute limit
$/yr (million)	460	114
15 x $/yr / "sum" (million $/case avoided)	27.7	7.00

[a] per million, lifetime

[b] risk avoided/70

[c] risk/year X population

* interpolated vlue

Table 6-11. **Second Calculation of Cost per Cases Avoided**
(15-year integration for 0.80% basic limit)

Gasoline half of LEV fuel

Year	70-year cases Avoided	Population (millions)	Risk avoided (a)	Risk avoided per yr.[b]	Cases avoided per yr.[c]
1994	1,356	32.75	41.40	.59	19.37
1995		33.34	40.17	.57	19.13
1996		33.92	38.94	.56	18.87
1997		34.51	37.70	.54	18.59
1998		35.09	36.47	.52	18.28
1999		35.68	35.24	.50	17.96
2000	1,233	36.26	34.00	.49	17.61
2001		36.73	32.43	.46	17.02
2002		37.21	30.85	.44	16.40
2003		37.68	29.27	.42	15.76
2004		38.16	27.69	.40	15.09
2005		38.63	26.11	.37	14.41
2006		39.10	24.53	.35	13.71
2007		39.58	22.95	.33	12.98
2008		40.05	21.38	.31	12.23
2009		40.53	19.80	.28	11.64
2010	747	41.00	18.22	.26	10.67
				sum, 1996-2010:	224.43

	0.80% basic limit	1.20% absolute limit
$/yr (million)	397	114
15 x $/yr / "sum" (million $/case avoided)	25.8	7.40

---

[a] per million, lifetime

[b] risk avoided/70

[c] risk/year X population

* interpolated vlue

IV. FINANCIAL EFFECTS ON SMALL REFINERS

A. SUMMARY

In 1989, the small refiners in California were in a weaker financial condition, overall, than were the large refiners. Most small and large refiners were able to meet their short-term obligations. However, the average long-term debt of small refiners was more than twice that of large refiners.

Among the small refiners, the gasoline-producing refiners were less leveraged than was the entire group.

Small refiners, particularly small gasoline-producing refiners, were less profitable than were large refiners. In 1990, the profitability of large refiners increased. However, no comparison could be made with the profitability of small refiners because data for 1990 are lacking.

In the past decade, many small refiners have gone out of business or have been acquired by other companies. The trend toward consolidation is expected to continue in response to financial pressure. New environmental regulations that require refiners to modify their plants cause part of that pressure. Small refiners that lack the financial resources to modernize might not be able to stay in business.

B. FINANCIAL ANALYSIS

Table 6-12 provides a snapshot of the financial condition of the California refining industry in 1989. It shows seven financial ratios that carry important information on the financial performance and financial condition of segments of the industry. These ratios are calculated from the 1989 financial data that the staff was able to obtain for 17 small refiners and eight large refiners in California.

Complete financial data were not available for all small refiners. Of the 17 small refining companies, we had sufficient data to calculate all seven ratios for seven companies, four ratios for one company, and two ratios for one company. No financial information was available for the other eight companies. Of the eight large refining companies, we had complete financial data for all except one. All large refiners produce gasoline but only ten of the small refiners produce gasoline.

The table shows that the small refiners were generally in a weaker financial condition than were the large refiners. However, despite having a weaker financial performance (returns) than did the industry in 1989, the small refiners that produce gasoline were financially stronger than the small refiners as a whole.

Table 6-12. **Average Financial Ratios for Refiners in California in 1989**

	Small Refiners		Large Refiners
	gasoline producers	all	
<u>Liquidity (short-term solvency) ratios</u>			
current ratio	2.01	1.69	1.16
current debt:equity	0.66	1.20	0.59
<u>Leverage ratios</u>			
debt:equity	2.23	3.16	1.79
debt:assets	0.71	0.72	0.62
<u>Profitability ratios</u>			
return on assets	6.92 (%)	8.63 (%)	14.39 (%)
return on equity	3.02	4.21	5.10
return on sales	2.47	3.02	4.86

The current ratio (liquid assets divided by short-term debt) and its companion, current debt:equity, are key indicators of short-term solvency. The current ratio measures a refiner's ability to pay its short-term debts. A value greater than one is usually desirble. Small refiners' current ratios ranged from a healthy 3.54 to a troubled 0.71, compared with a range of 1.58 to 0.75 for large refiners. The average ratio for all small refiners was 1.69, compared with 1.16 for the large refiners and 2.01 for the small gasoline-producing refiners. This indicates that on average, the small refiners, especially small gasoline-producing refiners, were better able to meet their short-term obligations than were the large refiners.

The ratio of current debt to equity supplements the current ratio. A high ratio shows that a refiner's current debt might be too high relative to its equity capital, implying that short-term suppliers and creditors might become cautious in providing additional credits to the refiner. This ratio ranged from 0.32 to 4.92 with an average of 1.20 for small refiners and 0.66 for small gasoline-producing refiners, compared with a range of 0.29 to 0.73 with an average of 0.59 for large refiners. This represents a healthy short-term financial condition for large refiners and small gasoline-producing refiners but an unhealthy condition for other small refiners. Most small refiners, however, were in better shape than is indicated by the average ratio. The ratio is skewed by an extreme case of a small refinery which was being liquidated in 1989.

The small refiners in California were generally in a weaker long-term financial position than were the large refiners. Both the average debt:equity and debt:asset ratios indicate that small refiners were burdened with heavier debts than were the large refiners. The debt:equity ratios of small refiners ranged from 0.68 to 12.02 with an average of 3.16, compared with a range of 0.72 to 3.03 with an average of 1.42 for large refiners. Among small refiners, the gasoline-producing refiners had a lower debt burden, 2.23 times equity, but it still exceeded the burden of the large refiners. A heavy debt burden makes a refinery vulnerable to adverse economic conditions.

The debt:asset ratios reveal a similar situation. In 1989, debt averaged about 72 percent of total assets for small refiners, compared with about 62 percent for large refiners. The debt for small gasoline-producing refiners was about 71 percent of their total assets. This indicates that small refiners have financed a higher portion of their assets through borrowing than have the large refiners. Among small refiners, two had total debts in excess of their total assets, indicating that they were bankrupt.

Small refiners generally performed less well than did large refiners in California in 1989. Among the small refiners, the performance of small gasoline-producing refiners was worse. Returns on equity, assets, and revenues (key indicators of profitability) averaged 8.63, 4.21, and 3.02 percent, respectively, for small refiners, compared with an average of about 14.39, 5.10, and 4.86 percent for large refiners. The profitability ratios for small gasoline-producing refiners averaged 6.92, 3.02, and 2.47 percent, respectively, moderately lower than the small refining industry as a whole.

C. FINANCIAL CONDITION IN 1990

A comparison of the financial condition of small refiners with large refiners in 1990 was not possible due to lack of financial data for small refiners. According to available data, most large refiners in California reported higher revenues and profits for 1990. Revenues were up 18.46 percent from a year earlier. Returns on equity, assets, and revenues increased to 15.23, 5.93, and 5.03 percent, respectively, in 1990 from 14.39, 5.10, and 4.86 percent in 1989.[3] The improvement in profitability were due mainly to improved margins on refinery products. Product sales rose outside the U.S., but fell inside the U.S. A slowdown in U.S. sales is not usually good for small refiners' profits because they tend to operate on small profit margins and to depend more on increasing product sales to improve their profitability.

D. OUTLOOK FOR FUTURE

Economic recession in the U.S. has reduced demand for petroleum products so far this year. For the first 122 days of 1991, the U.S. demand for petroleum products declined by 2.4 percent from a year earlier. Internatioanal sales, however, are up so far this year. This is good news for large refiners. But small refiners with no international sales are going to be hurt by the decline in the U.S. demand for petroleum products. U.S. economic activities are expected to rise in the second half of the year. But the recovery might not come in time to improve the 1991 results of small refiners.

Longer-term, we expect the decade-old consolidation in the refining industry to continue. In recent years, five small refiners in California went out of business. Assets of four were acquired by other firms. The other is in the process of liquidation. One acquired refinery also became idle recently and its equipment is being scrapped. We expect weaker refiners to continue to exit the industry or be acquired by other firms.

Appendix 7

UPDATED EMISSION INVENTORIES, CONCENTRATION AND RISK ESTIMATES

All numbers below are revisions based on new data to numbers presented in Motor Vehicle Toxics control Plan, ARB, 1990.

Table 7-1. Updated Emission Inventories

Substance	Emissions from gasoline MVs		Emissions from other sources	
	tpy	year	tpy	year
(1) benzene	23,239 a	87	3,579	87
(2) 1,3 butadiene	2,872 b	87,90	832	87,88,91
(3) formaldehyde	8,894 a	87	157,048-159,098	81-83,87-89
(4) styrene	1,654-1,709 b	87,88	923-968	87,88
(6) acetaldehyde	2,655-6,054 a	87	23,343-48,638	87
(9) benzo[a]pyrene	0.4-2.2 b	87	7.9-11	85-88

a) Emission estimates from gasoline vehicles included only on-road vehicles, off-road vehicles, mobile equipment/utility equipment.

b) Emission estimates from gasoline vehicles included on-road vehicles and "other" sources. Thus, emissions from vehicles that may not use Phase II gasoline were included, e.g., aircraft.

Table 7-2. Updated Ambient Air Concentration Estimates

Substance	Ambient Air Concentration (ug/m3)	(ppb)	Year
(2) 1,3 butadiene	0.82	.37	1988 - 1989
(3) formaldehyde	5.4	4.39	1988 - 1989
(6) acetaldehyde	4.19	2.34	1987
(9) benzo[a]pyrene	0.00053	n/a	1988 - 1989

All ambient air concentrations are population weighted

Table 7-3. **Updated Unit Risk Values**

Substance	Unit Risk[b]
(1) benzene	29
(2) 1,3 butadiene	140 a
(3) formaldehyde	4 a
(5) asbestos	1.9
(8) cadmium	4,200
(7) ethylene dichloride	22
(10) ethylene dibromide	71

a) calculated from <u>draft</u> inhalation potencies. Source: DHS, Feb 1991, source: Department of Health Services, Feb 1991

b) # cancer cases/1,000,000 people per ug/m^3 for 70 year exposure, except for asbestos where unit risk is expressed as: # cancer cases/1,000,000 people per PCM fiber/cubic meter

All unit risks are calculated from inhalation potencies listed in "Memorandum: Risk Assessment Procedure", July 24, 1991, Genevieve Shiroma, Toxic Air Contaminant Identification Branch, ARB

Appendix 8

CALCULATIONS CONCERNING TOXIC POLLUTANTS

CALCULATIONS CONCERNING TOXIC POLLUTANTS

I. ARB EMISSION MODELS

A. BENZENE MODEL BASED ON 1989 AUTO/OIL CARS ("Benzmod.cal")

Nomenclature:

A = total aromatic content, vol.%
A'= aromatic content less benzene
b = benzene emission rate, g/mi
B = benzene content, vol.%
M = MTBE content, vol.%
O = olefinic content, vol.%
S = sulfur content, ppm
T = 90% temperature
HC = hydrocarbon emission rate, g/mi
%b = benzene emissions as weight pct. of HC

subscripts:

A/O ... per Auto/Oil model predictive model
ARB ... per ARB predictive model

Form of Model:

The model is $b(A',B,M,O,S,T) = (b_{A/O} + .01 * \%b_{ARB} * HC_{A/O}) * f(S)$

where: $b_{A/O}$ is benzene emissions (mass rate) as a function of {A',M,O,T}, based on the Auto/Oil predictive model,

$\%b_{ARB}$ is an adjustment to the benzene fraction of HC for the effect of varying the benzene content of gasoline from its (typical) value in the Auto/Oil experiments,

$HC_{A/O}$ is the Auto/Oil predictive model for HC,

and f(S) is an adjustment for the effect of varying the sulfur content of gasoline from its (typical) Auto/Oil value.

(Note that emissions predicted by the model are valid in terms of grams per mile only for cars with the HC emission rates of the Auto/Oil cars that were used to develop the $b_{A/O}$ and $HC_{A/O}$ models.)

The Auto/Oil predictive model for benzene, using only statistically significant terms, is given in Technical Bulletin 5 as:

$$\ln(b_{A/O}) = -4.443 + .02166*(A-32.8) + .001326*(T-321) \\ -.000536*(A-32.8)*(O-11.8)$$

$$b_{A/O} = \exp(-4.443) * \exp[.02166*(A-32.8)] * (\text{etc.})$$

$$= \exp(-4.443) * \exp(.02166*A) * \exp(-.02166*32.8) * (\text{etc.})$$

$$= .0118 * \exp(.02166*A) * .4914 * \exp(.001326*T) * .6534 \\ * \exp(-.000536*A*O) * \exp(.00625*A) * \exp(.01758*O) * .8127$$

$$= .003069 * \exp(.0280*A + .001326*T + .01758*O - .000536*A*O)$$

In the Auto/Oil work, B was held approximately constant at 1.43%. Thus, the aromatic variable actually was A' = A - 1.43, and the model applies only at B = 1.43%.

$$b_{A/O} = .003069 * \exp[.0280*(A' + 1.43) + .001326*T + .01758*O \\ - .000536*(A' + 1.43)*O]$$

Adding B to the Model:

In Appendix 1, the relationship between B and %b has been estimated as: $d(\%b)/d(B) = .85$ wt.%/vol.% when A' is constant. Thus, $\%b_{ARB} = .85 * (B - 1.43)$. This multiplies HC emissions, which, for the 1989 test fleet, are predicted by (Technical Bulletin 1):

$$HC_{A/O} = \exp[-1.511 + .002582*(A-32.8) - .003496*(M-7.37) - .003951*(O-11.8) \\ + .003030*(T-321) + .0000795*(A-32.8)*(T-321) \\ - .0000764*(O-11.8)*(T-321)]$$

$$= .1425 * \exp[(-.02294 + .0000795*T)*A - .003496*M \\ + (.02057 - .0000764*T)*O + .001324*T]$$

$$= .1425 \exp[(-.02294 + .0000795*T)*(A+1.43) - .003496*M \\ + (.02057 - .0000764*T)*O + .001324*T]$$

Of the twenty 1989 cars used in the Auto/Oil program to develop $HC_{A/O}$, only ten were used to develop $b_{A/O}$. The average HC measured among the 10 and 20 cars was .20 and .2207, respectively. Therefore, to meld the models for $b_{A/O}$ and $\%b*HC_{A/O}$, it is appropriate to multiply $HC_{A/O}$ as given above by .20/.2207:

$$HC_{A/O} = .1291 \exp[(-.02294 + .0000795*T)*(A+1.43) - .003496*M + (.02057 - .0000764*T)*O + .001324*T]$$

Adding Sulfur Effect:

Sulfur in gasoline increases HC. The A/O study saw a 16.1% decrease as sulfur was decreased in gasoline from 466 ppm to 30 ppm. The linear function with the same property is:

$HC = HC_o * (1 + 4.71E-4 * S)$ where HC_o is HC at zero sulfur.

$$\text{Thus, } HC(S)/HC_{A/O} = \frac{1 + 4.71E-4 * S}{1 + 4.71E-4 * 296} = .8776 + 4.134E-4 * S$$

where 296 ppm is the average sulfur content in the experiments corresponding to $HC_{A/O}$. ARB staff assumes that this multiplier applies to $b_{A/O}$ as well as to $HC_{A/O}$.

The entire model for benzene, based on the Auto/Oil models for 1989 cars, is:

$$b = \{.003069 * \exp[.0280*(A' + 1.43) + .001326*T + .01758*O - .000536*(A' + 1.43)*O] + .001097*(B-1.43) * \exp[(-.02294 + .0000795*T)*(A+1.43) - .003496*M + (.02057 - .0000764*T)*O + .001324*T]\} * (.8776 + 4.134E-4 * S)$$

B. BENZENE MODEL BASED ON 1983-1985 AUTO/OIL CARS

The Auto/Oil predictive model for benzene, using only statistically significant terms, is given in Technical Bulletin 5 as:

$$\ln(b_{A/O}) = -4.063 + .01552*(A-32.8) - .007541*(M-7.37) + .005284*(O-11.8) + .000143*(M-7.37)*(T-321)$$

$$b_{A/O} = \exp(-4.063) * \exp[.01552*(A-32.8)] * (\text{etc.})$$

$$= .01720 * \exp(.01552*A) * .6011 * \exp(-.007541*M) * 1.057 * \exp(.005284*O) * .9396 * \exp(.000143*M*T) * \exp(-.04590*M) * \exp(-.001054*T) * 1.403$$

$$= .01440 * \exp(.01552*A - .05344*M + .005284*O - .001054*T + .000143*M*T)$$

$$= .01440 * \exp[.01552*(A+1.43) - .05344*M + .005284*O - .001054*T + .000143*M*T]$$

Adding B to the Model:

As for the preceding model, $\%B_{ARB} = .85 * (B-1.43)$, which multiplies the HC emissions before adjustment for sulfur content. The Auto/Oil model for HC is (<u>Technical Bulletin 4</u>):

$$\begin{aligned} HC_{A/O} = \exp [&-.6987 - .005109*(A-32.8) - .006383*(M-7.37) - .003714*(O-11.8) \\ &+ .0007445*(T-321) + .0001723*(A-32.8)*(O-11.8) \\ &+ .0000621*(A-32.8)*(T-321) - .0000913*(O-11.8)*(T-321) \\ &- .0000234*(A-32.8)*(M-7.37)*(O-11.8)] \end{aligned}$$

Of the twenty 1983-1985 cars used in the Auto/Oil program to develop $HC_{A/O}$, only ten were used to develop $b_{A/O}$. The average HC measured among the 10 and 20 cars was .44 and .4972, respectively. Therefore, to properly meld the models for $b_{A/O}$ and $\%b * HC_{A/O}$, $HC_{A/O}$ is multiplied by .44/.4972.

Adding Sulfur Effect:

As for the preceding model, the sulfur adjustment is:

$$.8776 + 4.134E\text{-}4 * S$$

The entire model is:

$$\begin{aligned} b = \{&.01720 * \exp(.01552*A) * .6011 * \exp(-.007541*M) * 1.057 \\ &* \exp(.005284*O) * .9396 * \exp(.000143*M*T) * \exp(-.04590*M) \\ &* \exp(-.001054*T) * 1.403 + .003740*(B-1.43) * \exp[-.005109* \\ &(A-32.8) - .006383*(M-7.37) - .003714*(O-11.8) + .0007445*(T-321) \\ &+ .0001723*(A-32.8)*(O-11.8) + .0000621*(A-32.8)*(T-321) \\ &- .0000913*(O-11.8)*(T-321) - .0000234*(A-32.8)*(M-7.37)*(O-11.8)]\} \\ &* (.8776 + 4.134E\text{-}4*S \end{aligned}$$

C. MODELS FOR OTHER POLLUTANTS

ARB uses the Auto/Oil predictive models (Tech. Bull. 5). The model results for the aldehydes are adjusted for the actual sulfur content as discussed in the benzene models.

II. EPA EMISSION MODELS

A. "SIMPLE" MODEL FOR TYPICAL LATE-MODEL CAR

A = aromatic content, v%; B = benzene content, v%; OX = oxygen content, wt%

$$\text{Exhaust benzene, g/mi} = .01 * [1.818 + .9154*B + .109*(A - B)] * EXH * (1 - .04704*OX)$$

$$EXH = .46\ (\text{g/mi})\ \text{in summer, } .68\ \text{in winter}$$

$$\text{Butadiene, g/mi} = .00539 * EXH * (1 - .04704*OX)$$

$$\text{Formaldehyde, g/mi} = .005515 * (1 + .1556*OX)$$

$$\text{Acetaldehyde, g/mi} = .003928 * (1 + .0289 *OX)$$

$$\text{POM, g/mi} = .0014 * (1 - .0374*OX)$$

The following apply only in winter:

$$\text{Hot-soak benz., g/mi} = .01 * B * EVAP * (.981 - .05451 * RVP - .02322*OX)$$

$$EVAP = .813 - .2393*RVP + .021239*RVP^2$$

$$\text{Diurnal benzene, g/mi} = .01 * B * EVAP * (.4416 - .02577*RVP - .009293*OX)$$

$$\text{Run. loss benz, g/mi} = .01 * B * RUN * (1.446 - .0342*OX -.08027*RVP)$$

$$RUN = .2963 - .1306 *RVP + .016255*RVP^2$$

$$\text{Refueling benz., g/mi} = .01 * B * REF * (1.397 - .02955*OX - .08151*RVP)$$

$$REF = .006667*RVP - .0180$$

(Note that the model predictions are valid in terms of grams/mile for only vehicle with HC emissions of .46 g/mi in summer and .68 g/mi in winter.)

B. APPROXIMATION OF EPA'S EVENTUAL "COMPLEX" MODEL

We assume that EPA will incorporate the sulfur results (Tech. Bull. 2) and the slope .915 wt.%/vol.% for benzene in HC vs. benzene in gasoline into the Auto/Oil emission models for AMOT (1989 model, Tech. Bull. 5). The .915 number is "grafted" into the A/O model for benzene in the same way as the the ARB value of .85 is used in the ARB benzene model in I. Emissions computed by the A/O models (except butadiene) are adjusted by the factor [.8776 + 4.13 E-4 * S (ppm)], which adjusts emissions from the A/O-AMOT average sulfur content of 296 ppm and which yields a 16.1% reduction between 466 and 49 ppm sulfur.

III. FUEL PROPERTIES

	Phase 1	Phase 2	CAA Summer Base	EPA Winter Base
Aromatic, v%	32	20	32	26.4
Oxygen, wt.% (MTBE, v.%)	0	2 (11)	0	0
Olefins, v%	10	5	9.2	11.9
T-90, °F	330	300	330	331
Benzene, v%	2.0	.80	1.53	1.64
RVP, psi		7.0	8.7	11.5
Sulfur, ppm	150	30	339	338

IV. REDUCTION IN 2000 VEHICULAR INVENTORY, RELATIVE TO PHASE-1 BASELINE

A. BASELINE EMISSIONS IN 2000

Benzene

From Appendix 1,	on-road exhaust	24.2 tpd
	other mobile exh.	11.4
		----
	total exhaust	35.6
	evaporative	3.8

	Total	39.4 tpd from vehicles

1,3-Butadiene

1,3-Butadiene emissions from gasoline vehicles are estimated as:

	TOG (tpd)*	13-BD/TOG	1,3BD (tpd)
non-catalyst	53	.0097	.51
catalyst	441	.0059	2.60
other mobile	271	.0097	2.63

			5.74

* Emfac-7Ep/Burden-7C

Formaldehyde

	Tpd in 1987, per draft CH2O report	TOG, 2000 ---------- TOG, 1986 *	tpd in 2000 (tpd in 1987 x ratio)
non-cat.	8.48	.096	.81
catalyst	14.32	.718	10.28
other mobile	6.85	1.49	10.21

			21.3 tpd

* surrogate for 1987

Acetaldehyde

Table 1 of Chapter III of TSD gives 2,600 tpy (7.1 tpd) acetaldehyde from all gasoline vehicles in 1987. The total exhaust TOG inventory for on-road and other-mobile vehicles decreases by about 40% from 1987 to 2000. Therefore, acetadehyde emissions in 2000 are estimated as .6 * 7.1 = 4.3 tpd.

Total Baseline

	Exhaust		Evaporative		
benzene	35.6		3.8		
1,3-BD	5.74				
CH2O	21.3				
acetald.	4.3				

	66.9	+	3.8	=	70.7 tpd

B. CHANGE IN BENZENE EMISSIONS

Applying the ARB-A/O combined benzene model (Benzmod.cal) based on the 1989 A/O model:

	A	B	A'	O	M	S	T	b (g/mi)
Phase-1	32	2	30	10	0	150	330	.01181
Phase-2	20	.8	19.2	5	11	30	300	.00659
							difference:	.00522
							% diff.:	44.17
Phase-1	32	2	30	10	0	150	330	.01181
Phase-2 w/o benz.	20	2	18	5	11	30	300	.00806
							difference:	.00375
							% diff.:	31.76

With and without the benzene limit, the Phase-2 limits would reduce exhaust benzene emissions by 44.17 and 31.76 percent, respectively, according to this model.

Applying the second ARB-A/O model:

	A	B	A'	O	M	S	T	b (g/mi)
Phase-1	32	2	30	10	0	150	330	.01854
Phase-2	20	.8	19.2	5	11	30	300	.00951
							difference:	.00903
							% diff.:	48.70
Phase-1	32	2	30	10	0	150	330	.01854
Phase-2 w/o benz.	20	2	18	5	11	30	300	.01359
							difference:	.00495
							% diff.:	26.72

With and without the benzene limit, the Phase-2 limits would reduce exhaust benzene emissions by 48.70 and 26.72 percent, respectively, according to this model.

Taking the average results of the two models yields these percent changes from the Phase-1 baseline:

All Phase 2 limits except benzene limit	--	-29.24 %
All Phase 2 limits	--	-46.44 %

From Appendix 1 to the TSD, the change in exhaust benzene due to the benzene limit adopted by itself would be -21.62 %.

Applying these factors to the Phase 1 exhaust emissions (35.6 tpd) and adding changes in evaporative emissions due to the benzene limit (Appendix 1):

Change in Benzene Emissions, tpd

	exhaust	evap.	total
Benzene limit alone	-7.70	-2.30	-10.00
All Phase 2 limits except benzene limit	-10.41	0	-10.41
All Phase 2 limits	-16.53	-2.30	-18.83

C. CHANGES IN OTHER THREE POLLUTANTS

Per the Auto/Oil models for the effects of AMOT, the percent changes in emissions from Phase 1 to Phase 2 gasoline are:

	1989 cars	'83-'85 cars	avg.
1,3-BD	-26	-28	-27
CH2O	17	53	35
acetald.	3.7	15	9.4

Use the average values.

Assume that the five percent reduction of HC emissions from the reduced sulfur content of gasoline applies to the aldehyde emissions but not to the butadiene emissions. Example using formaldehyde:

Phase 2 emissions = (1 + .35) x .95 x Phase 1 emissions

= 1.28 x Phase 1 emissions

The resulting total changes are:

1.3-BD -- -27%   formaldehyde -- +28%   acetaldehyde -- +3.9%

Under the assumption that these factors apply to all the baseline emissions, regardless of type of vehicle, the changes in emissions are:

	Baseline	% Change	Change, tpd
1,3 BD	5.74	-27	-1.55
CH2O	21.3	28	5.96
acetald.	4.3	3.9	.17

			4.58 tpd (increase)

D. TOTAL CHANGE, tpd

	Benzene limit only	Phase 2 limits w/o benz. limit	All Phase 2 limits
benzene	-10.00	-10.41	-18.83
1,3-butadiene		-1.55	-1.55
formaldehyde		5.96	5.96
acetaldehyde		.17	.17
		-----	-----
Total, tpd	-10.00 *	-5.83	-14.3 *
Total, % of baseline (70.7 tpd)	-14	-8.2	-20

* Stationary sources would provide an another increment of -.6 tpd

V. REDUCTION IN EMISSIONS FROM LATE-MODEL CAR, RELATIVE TO EPA BASELINE

A. PER EPA'S SIMPLE MODEL

grams/mile

	Summer		Winter	
	baseline	Phase 2	baseline	Phase 2
Benzene				
exhaust	.0301	.01935	.0409	.02860
hot soak	.0037	.000790		
diurnal		.000347		
run. loss	.0045	.00116		
refueling	.0004	.00018		
Butadiene	.0025	.00225	.0037	.00332
Formaldehyde	.0055	.00723	.0055	.00723
Acetaldehyde	.0039	.00416	.0039	.00416
POM	.0014	.0013	.0014	.0013
Total	.0520	.0368	.0554	.0446
difference		-.0152		-.0109
% of baseline		- 26		- 20

B. PER SURROGATE FOR EPA'S COMPLEX MODEL

Summer Baseline

Exhaust Emissions

	Model	Baseline Emiss. g/mi		Phase-2 Emiss., g/mi		Difference	
		modelled	S-adjusted	modelled	S-adjusted	g/mi	%
Benzene	BenzEpa .cal	*	.01207	*	.00653	-.00554	-46
1,3-BD	A/O,'89	.000970	.000970	.000731	.000731	-.00024	-25
Form.	"	.001663	.001692	.001946	.001732	+.00004	+2
Acet.	"	.000972	.000989	.001008	.000897	-.00009	-9
total			.01572		.009890	-.0058	-37

* BenzEpa.cal incorporates sulfur effect

Evaporative and Fueling Emissions
(from simple model)

	Baseline	Phase 2	difference
hot soak	.0037	.000790	
diurnal		.000347	
running	.0045	.00164	
refueling	.0004	.00018	
	.0086	.00296	-.00564 (-66%)

Estimate overall percent reduction in summer by weighting the reductions in exhaust and evaporative emissions by the baseline emissions per the simple summer model:

$$\frac{-37\% * .0434 \text{ g/mi (exh.)} + -66\% * .0086 \text{ g/mi (evap.)}}{.0434 + .0086} = -42\%$$

Winter

Exhaust Emissions

	Model	Baseline Emiss. g/mi		Phase-2 Emiss., g/mi		Difference	
		modelled	S-adjusted	modelled	S-adjusted	g/mi	%
Benzene	BenzEpa .cal	*	.01092	*	.00653	-.00440	-40
1,3-BD	A/O,'89	.001046	.001046	.000731	.000731	-.00032	-30
Form.	"	.001754	.001784	.001946	.001732	+.00005	-3
Acet.	"	.001017	.001035	.001008	.000897	-.00014	-13
total			.01478		.009890	-.0049	-33

VI. CHANGE IN POTENCY-WEIGHTED EMISSIONS, PHASE 1 BASELINE (ARB Models)

A. FOR A LATE-MODEL VEHICLE

Using the combined ARB-A/O benzene model based on the 1989 cars and A/O models for the other pollutants (with sulfur adjustments for aldehydes):

	Phase 2, g/mi		Phase-1, g/mi		Diff., g/mi	Unit risk (a)	Diff. x risk
	modelled	S-adj'd	modelled	S-adj'd			
Benzene							
exhaust		.00659		.01181	-.00522	.21	-.001096
evap/run[b]	.00074	.00074		.00185	-.00111	.21	-.000233
1,3-BD	.000731	.000731	.000988	.000988	-.000257	1.0	-.000257
Formald.	.001946	.001732	.001658	.001558	.000174	.17	.0000296
Acetald.	.001008	.000897	.000968	.000909	-.000012	.016	-1.9E-7
Total		.01069		.01712	-.00643		-.001557

[a] relative, with risk for 1,3-BD set to 1.0

[b] derived from Appendix 1

% reduction in emissions = 100 * (.00643/.01712) = 38%

$$\text{\% reduction in PWS emissions} = \frac{100 * .001557}{(.01181+.00185)*.21 + .000988 + .001558*.17 + .000909*.016} = 38\%$$

B. FOR OLDER MODEL VEHICLE

Using the analogous models for 1983-1985 cars:

	Phase 2, g/mi		Phase-1, g/mi		Diff., g/mi	Unit risk (a)	Diff. x risk
	modelled	S-adj'd	modelled	S-adj'd			
Benzene							
exhaust		.00951		.01854	-.00903	.21	-.001896
evap/run[b]	.00116	.00116	.00290	.00290	-.00174	.21	-.000365
1,3-BD	.001348	.001348	.001878	.001878	-.000530	1.0	-.000530
Formald.	.01495	.01331	.009777	.009187	.004123	.17	.000701
Acetald.	.003817	.003397	.003330	.003129	.000268	.016	.000004
Total		.02873		.03563	-.00690		-.002086

[a] relative, with risk for 1,3-BD set to 1.0 [b] derived from Appendix 1

% reduction in emissions = 100 * (.00690/.03563) = 19%

$$\text{\% reduction in PWS emissions} = \frac{100 * .002086}{(.01854+.00290)*.21 + .001878 + .009187*.17 + .003129*.016} = 26\%$$

C. FOR EMISSION INVENTORY IN 2000

Using the baseline emissions and emission reduction calculated in A.1 (which use average results from the two A/O models):

	Baseline emissions	Unit risk	Baseline x risk	Change (tpd)	Change x risk
Benzene					
exhaust	35.6	.21	7.47	-16.5	-3.47
evap, run	3.8	.21	.798	- 2.3	- .48
1,3-BD	5.74	1.0	5.74	- 1.55	-1.55
Formald.	21.3	.17	3.62	5.96	1.01
Acetald.	4.3	.016	.069	.17	.0027
Total	70.7		17.7	-14.2	-4.49
% change from baseline				-20	-25

VII. POTENTIAL CANCER CASES AVOIDED, RELATIVE TO PHASE 1 BASELINE

A. IN 2000

1. Benzene Cases

The average reductions from the two ARB-A/O models are:

All Phase 2 limits
except benzene limit -- -29.24 %

All Phase 2 limits -- -46.44 %

From Appendix 1 to the TSD, the change due to the benzene limit adopted by itself would be -21.62 %.

The portion of the 46.44 overall percent change in benzene emissions that is due to the reduction of the benzene content of gasoline can be estimated as:

$$\left.\frac{b}{B}\right|_{mp} * B / b$$

where "mp" indicates evaluation at the midpoint between the Phase 1 and Phase 2 values of the gasoline properties and b is evaluated at Phase 1. Using values from the first (1989 car) model:

(.001538 * (2.0 - .8))/.01181 *100 = 15.63% (out of 44.17%)

Using values from the other model:

(.003647 * (2.0 - .8))/.01854 * 100 = 23.61% (out of 48.70%)

The average is 19.62%.

Per Appendix 1, total potential cases in 2000 due to exhaust emissions, on-road and other mobile, are 4,211 in 70 years, or 60.16 per year. Overall reduction = .4644 * 60.16 = 27.94 cases/year. Likewise, the portion of these cases due to the benzene limit as part of Phase 2 is computed as .1962 * 60.16 = 11.80 cases/year

The cases avoided by the Phase-2 limits if a benzene limit were not included is estimated as .2924 * 60.16 = 17.59 cases/year.

Adding cases avoided in other categories by the benzene limit (from Appendix 1):

	Phase 2 total	Part due to benz. limit	
exhaust	27.94	11.80	
on-road evaporative	3.89	3.89	
stationary source	1.05	1.05	
	-----	-----	
	32.88	16.74	cases/year

2. Butadiene Cases

The annual potential cancer incidence due to butadiene emissions from vehicular sources and annual emissions of butadiene, both estimated for the late 1980's, are 34 cases and 2,900 tons/year. From these data and the emission decrease of 1.55 tpd due to Phase 2 (from IV.C.), the reduction of cancer cases in 2000 is estimated as :

$$\frac{\text{34 cases/yr}}{\text{2,900 tpy/365}} * \frac{\text{1.55 tpd}}{} * \frac{\text{36.3 million people in 2000}}{\text{28 million people in late 1980's}}$$

= 8.60 cases avoided/year

3. Formaldehyde Cases

The annual potential cancer incidence due to formaldehyde emissions from vehicular sources and annual emissions of formaldehyde, both estimated for the late 1980's, are 2.5 cases and 8,900 tons/year. From these data and the emission increase of 5.96 tpd (from IV.C.), the increase in cancer cases in 2000 is estimated as :

$$\frac{\text{2.5 cases/yr}}{\text{3,900 tpy/365}} * \frac{\text{5.96 tpd}}{} * \frac{\text{36.3 million people in 2000}}{\text{28 million people in late 1980's}}$$

= .79 cases added/year

4. Acetaldehyde Cases

Acetaldehyde accounts for only a minor part of baseline toxic emissions from vehicles; and according to the Auto/Oil results, it would be affected very little by the change from Phase-1 to Phase-2 gasoline. Therefore, its effect is omitted here.

5. Total Decrease in Potential Cancer Incidence

The reductions from benzene and butadiene total 41.5 cases/year. The increase from formaldehyde is .8 cases/year. The next table summarizes the above information.

Cases Avoided @2000 Conditions

Phase-2 limit:	.8% benz. (only)	Other[a] (only)	All
		cases avoided/yr	
Benzene cases			
by benzene limit	17.9[b]	0	16.7
by other limits	0	17.6	16.2
total	17.9	17.6	32.9
1,3-BD cases	0	8.6	8.6
formald. cases	0	-.8	-.8
Total	17.9	25.4[c]	40.7 [c]

[a] A,M,O,T,and S

[b] from Appendix 1

[c] excluding minor effects on acetaldehyde emissions

B. In 2010

1. Benzene Cases

The average reduction in benzene emissions from the two models based on different Auto/Oil car results is 46.44 percent between Phase-1 and Phase-2 gasoline. Assume this would apply to all gasoline exhaust emissions in 2010. Per Appendix 1, total potential cases in 2010 due to exhaust emissions, on-road and other mobile, are 3,225 in 70 years, or 46.07 per year. Reduction = .4644 * 46.07 = 21.40 cases/year. As for the 2000 estimates, the portion of these cases due to the reduction of the benzene content in gasoline is computed as .1962 * 46.07 = 9.039 cases/year

The cases avoided by the Phase-2 limits if a benzene limit were not included is estimated as .2924 * 46.07 = 13.47 cases/year.

Adding cases avoided in other categories by the benzene limit (.80 v%):

	Phase 2 total	Part due to benz. limit	
exhaust	21.40	9.04	
on-road evaporative	1.51	1.51	
stationary source	1.23	1.23	
	-----	-----	
	24.14	11.78	cases/year

2. Butadiene Cases

1,3-Butadiene emissions from gasoline vehicles are estimated as:

	TOG (tpd)*	13-BD/TOG	1,3BD (tpd)
non-catalyst	32	.0097	.31
catalyst	197	.0059	1.16
other mobile	312	.0097	3.02

			4.49

* Emfac-7Ep/Burden-7C

According to the Auto/Oil predictive equations for butadiene, emissions would decrease by about 27 percent from Phase-1 gasoline to Phase-2 gasoline, on the basis of either the 1989 cars or the 1983-1985 cars. .27 * 4.49 = 1.21 tpd

The annual potential cancer incidence due to butadiene emissions from vehicular sources and annual emissions of butadiene, both estimated for the late 1980's, are 34 cases and 2,900 tons/year. From these data, the reduction of cancer cases in 2010 is estimated as :

$$\frac{34\ \text{cases/yr}}{2{,}900\ \text{tpy}/365} * 1.21\ \text{tpd} * \frac{41\ \text{million people in 2010}}{28\ \text{million people in late 1980's}}$$

= 7.58 cases avoided/year

3. Formaldehyde and Acetaldehyde Cases

The change in cancer incidence from acetaldehyde is negligible. The added cases from formaldehyde change from the value in 2000 in the same proportion as do the butadiene cases: 7.6/8.6 * .79 = .70 case/year.

4. Total Decrease in Potential Cancer Incidence

The reductions from benzene and butadiene total 31.7 cases/year. Cases from formaldehyde increase by 0.7. The next table summarizes the above information.

Cases Avoided @2010 Conditions

Phase-2 limit:	.8% benz. (only)	Other[a] (only)	All
	cases avoided/yr		
Benzene cases			
by benzene limit	12.7[b]	0	11.8
by other limits	0	13.5	12.3
total	12.7	13.5	24.1
1,3-BD cases	0	7.6	7.6
formald. cases	0	-.7	-.7
Total	12.7	20.4[c]	31.0[c]

[a] A,M,O,T,and S

[b] from Appendix 1

[c] excluding minor effects on acetaldehyde emissions

Summary of Results

	Reduction of MV Inventory*		Reduction per Vehicle	
	in 2000	in 2010	late model[a]	older model[b]
Emissions				
Phase-1 baseline	20%		38%	19%
EPA baseline				
1995 model[c]			20%/29%[f]	
later model[d]			33%/42%[f]	
Pot.-wtd. sum[e] of emissions	25%		38%	26%
Cases avoided[e]	41/yr (43%)	31/yr (40%)		

[a] uses 1989 A/O model

[b] uses 1985-1985 A/O model

[c] EPA simple model

[d] assumed form of EPA complex model

[e] Phase 1 baseline

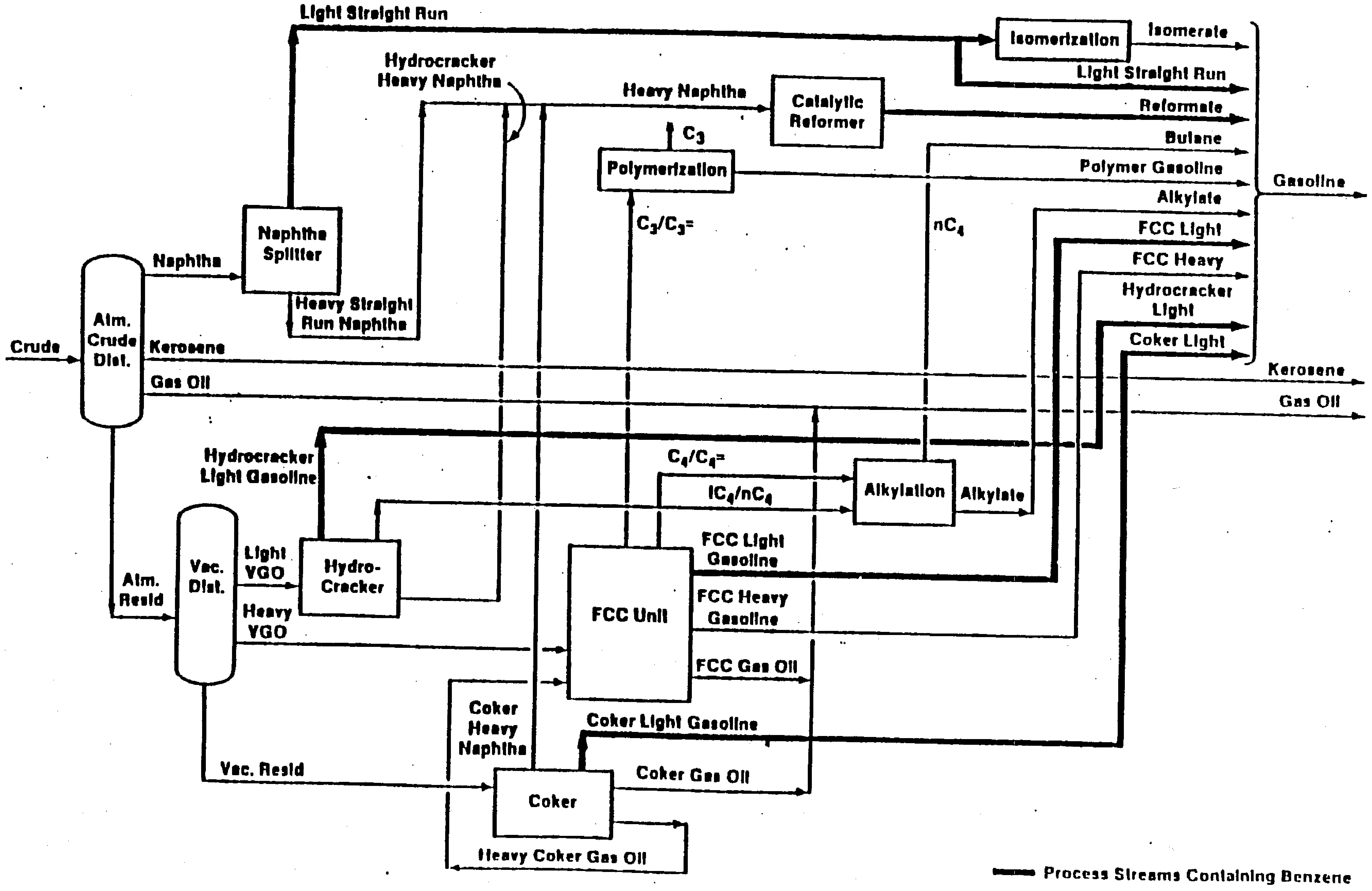
[f] winter/summer

* incorporates averages of results from 1989 and 1983-1985 Auto/Oil models

Appendix 9

PROCESSES FOR REDUCING BENZENE IN GASOLINE

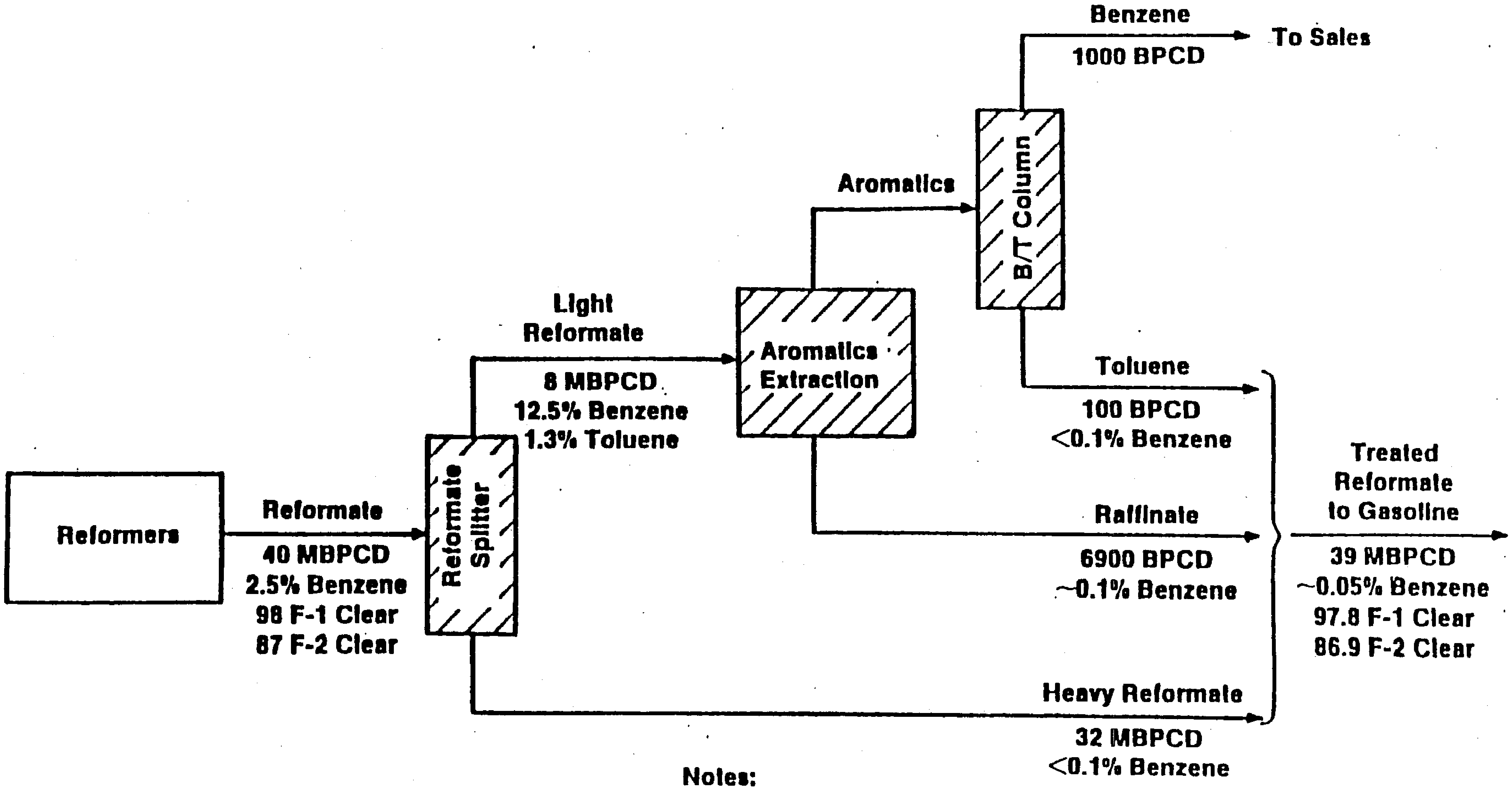
GASOLINE PRODUCTION
SIMPLIFIED REFINERY BLOCK FLOW DIAGRAM



BENZENE IN REFINERY STREAMS

	Benzene, LV %
	Typical
Reformate	1-4
FCC Gasoline	0.5-1.5
Hydrocracker Light Gasoline	0.5-1.0
Coker Light Gasoline	0.5-1.0
Light Straight Run	1-2

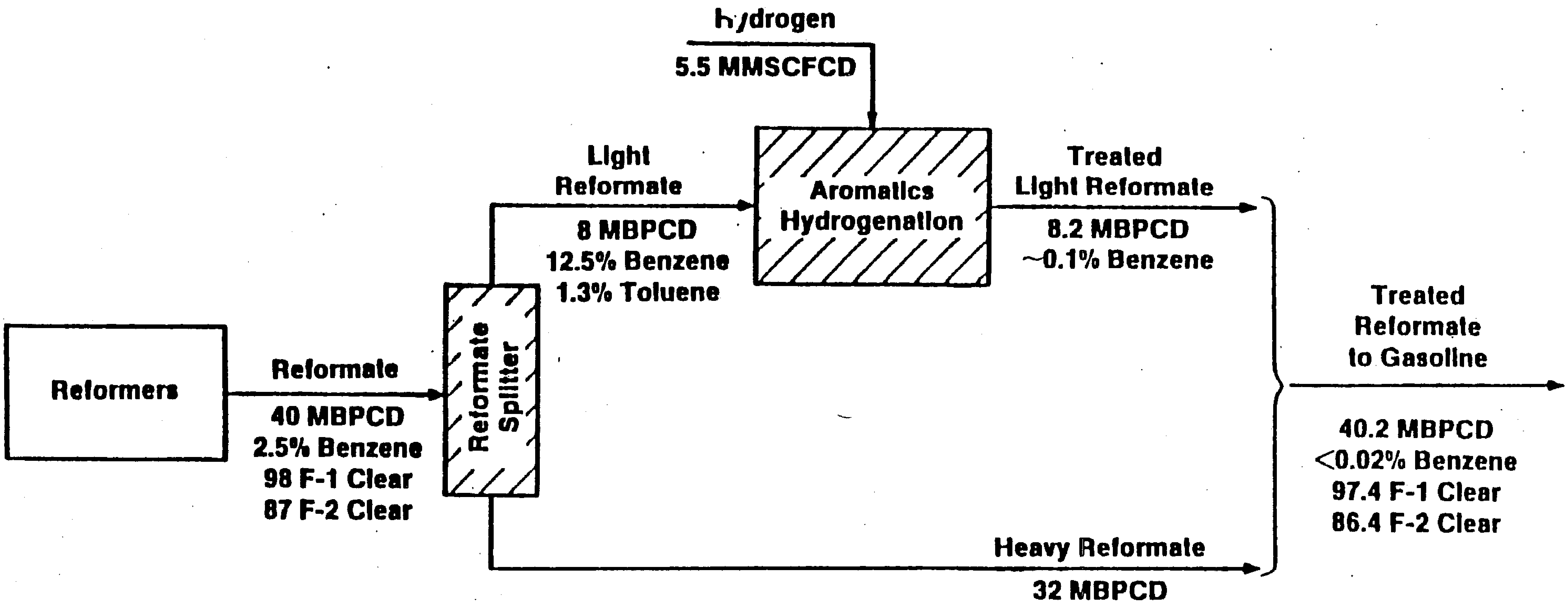
EXTRACTION OF BENZENE FROM LIGHT REFORMATE



Notes:

1. New facilities are crosshatched.

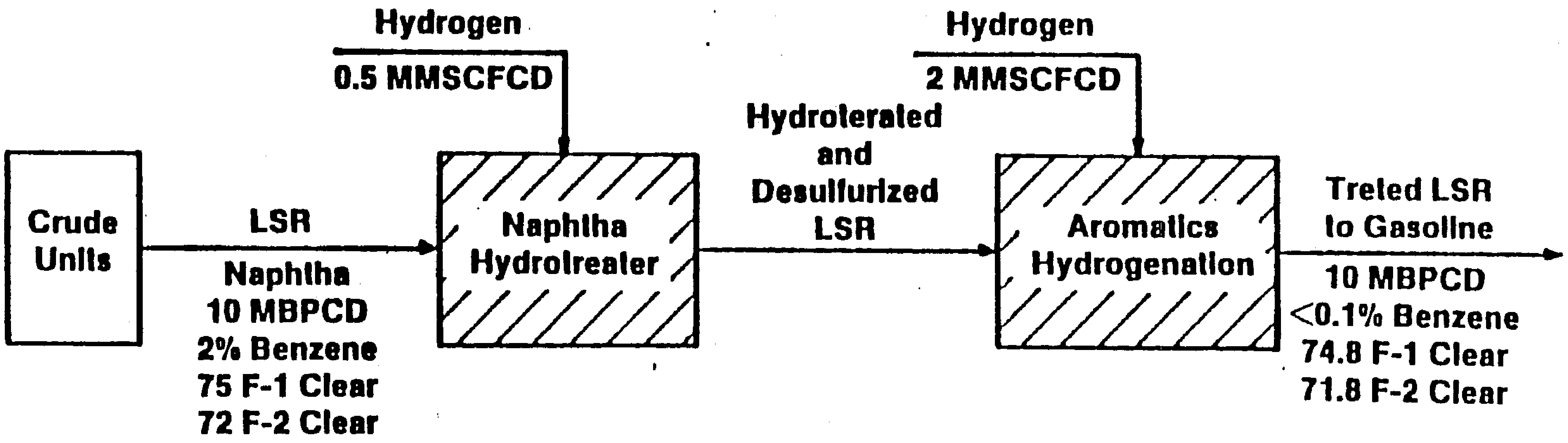
HYDROGENATION OF LIGHT REFORMATE



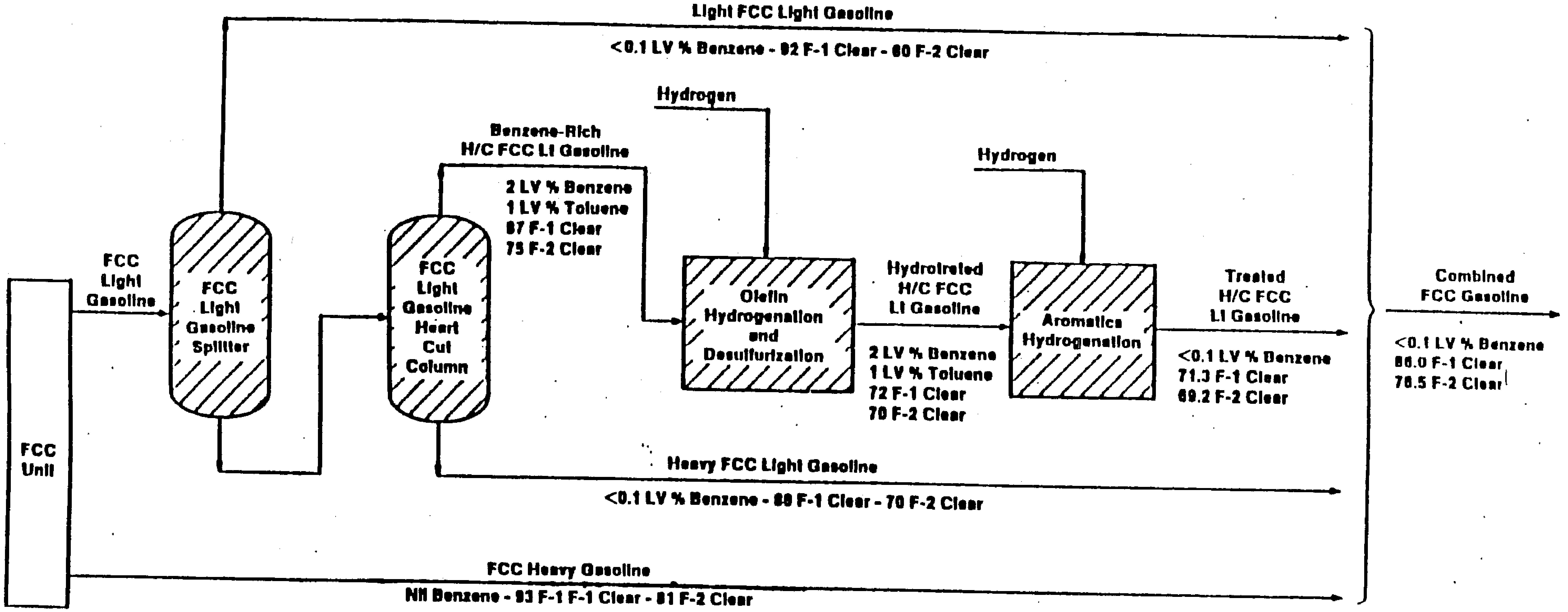
Notes:

1. Chemical hydrogen consumption for benzene saturation is about 4500 SCF per barrel of benzene.
2. New facilities are crosshatched.

HYDROGENATION OF LIGHT STRAIGHT RUN



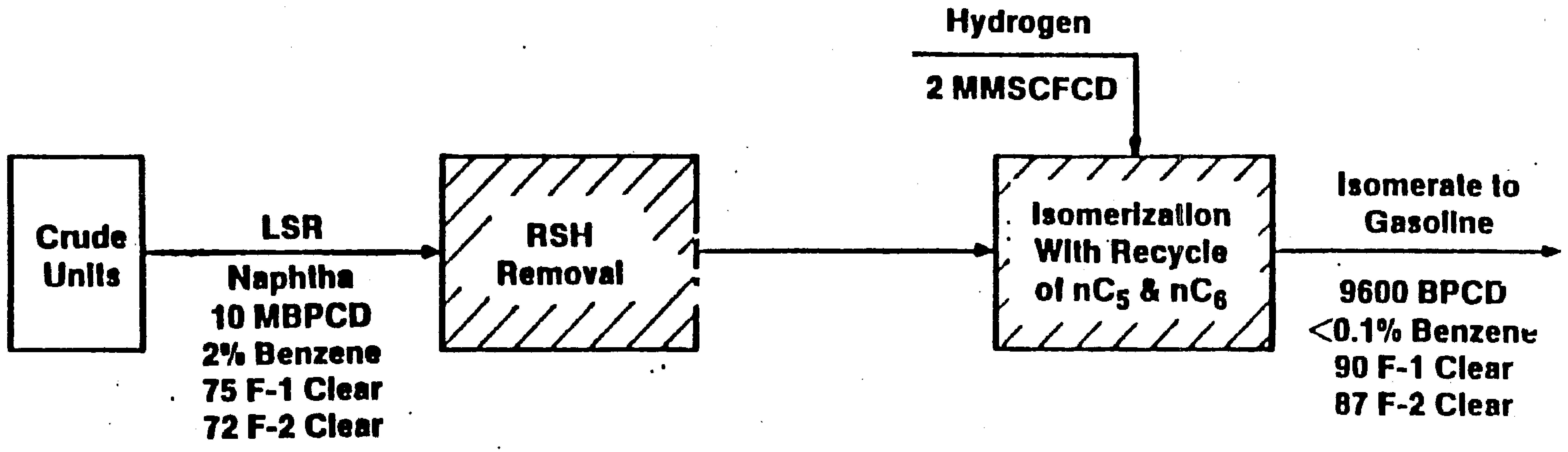
HYDROGENATION OF BENZENE-RICH HEART CUT OF FCC GASOLINE



Notes:

1. Chemical hydrogen consumption is 4500 SCF per barrel of benzene.
2. Chemical hydrogen consumption for olefin saturation is 450 SCF per barrel of heart cut FCC light gasoline.

ISOMERIZATION OF LIGHT STRAIGHT RUN



Notes:

1. Benzene is almost completely hydrogenated over isomerization catalyst.
2. LSR to isomerization should not contain more than 1 LV % C_7 and heavier nor more than 5 LV % cyclics (aromatics + naphthenes).
3. New facilities are crosshatched.

Appendix 10

STATISTICAL METHOD FOR CERTIFICATION

I. DEGREES OF FREEDOM FOR COMPOSITE EMISSION DIFFERENCE

Suppose that there are m vehicle categories and that the true mean pollution level for the cars in category i is μ_i. Suppose that c_i is a weight that reflects the miles traveled by vehicles in category i, so that the total emissions from vehicles in that category is proportional to $\sum_{i=1}^{m} c_i\mu_i$. (If these weights are divided by the total of them, so that they sum to one, the procedure suggested below remains unchanged.) Suppose that a sample of vehicles of size n_i is chosen for each category and that measurements are taken on each vehicle for the test fuel and Phase-2 gasoline. If η_i is the average amount by which emissions of the test fuel exceed Phase-2 emissions in category i, then the total increase in emissions is $\sum_{i=1}^{m} c_i\eta_i$. If d_{ij} is the average of the emissions of vehicle j in category i for the test fuel less the average of emissions for the same vehicle on Phase-2 gasoline, then $\bar{d}_i = n_i^{-1}\sum_{j=1}^{n_i} d_{ij}$ is an estimate of η_i, so that $D = \sum_{i=1}^{m} c_i\bar{d}_i$ is an estimate of the increase in pollution caused by using the test fuel.

If we assume that d_{ij} is normally distributed with mean η_i and variance σ_i^2, then the variance of the criterion statistic D is $\sum_{i=1}^{m} c_i^2\sigma_i^2/n_i$, a natural unbiased estimate of which is $S^2 = \sum_{i=1}^{m} c_i^2 s_i^2/n_i$, where $s_i^2 = (n_i-1)^{-1}\sum_{j=1}^{n_i}(d_{ij} - \bar{d}_i)^2$, the sample variance of the differences in category i. If the submitter is required to show that the difference D is less than some some criterion Δ, then a natural test statistic is $t = (D-\Delta)/S$. To show equivalence with tolerance Δ with confidence $1-\alpha$, the submitter would need a value t that was smaller than the lower α point of the distribution of t; that is, the upper confidence limit $D + t_\alpha S$ would need to be below Δ.

In large samples, this would mean that t would need to be below -1.036 if $\alpha = .15$, but "large sample" might mean at least 30 cars in each category. For small sample inference, we use a t approximation that is similar to the standard two-sample Welch procedure. The t distribution with ν degrees of freedom is defined as $t = Z/\sqrt{s}$, where Z is normally distributed with variance τ^2 and $\nu s^2/\tau^2$ has independently a χ^2 distribution with ν degrees of freedom. Although the denominator of the test statistic proposed does not have distribution that is exactly that of a multiple of a χ^2 random variable, we find the closest approximation among χ^2 multiples and use the distribution of that statistic as an approximation of the distribution of the actual statistic (this is the rationale for the Welch t that is used for two-sample problems). If C is a multiple A of a χ^2 variable with ν df, then $\mathrm{E}(C) = A\nu$ and $\mathrm{Var}(C) = 2A^2\nu$. This means that $2\mathrm{E}^2(C)/\mathrm{Var}(C) = \nu$. Now (under normality)

$$\mathrm{E}(S^2) = \sum_{i=1}^{m} \frac{c_i^2\sigma_i^2}{n_i}$$

$$\mathrm{Var}(S^2) = \sum_{i=1}^{m} \frac{2c_i^4\sigma_i^4}{n_i^2(n_i - 1)}$$

so one may estimate the degrees of freedom as

$$\hat{\nu} = \frac{2(\sum_{i=1}^{m} c_i^2 s_i^2/n_i)^2}{\sum_{i=1}^{m} 2c_i^4 s_i^4/\{n_i^2(n_i-1)\}} = \frac{(\sum_{i=1}^{m} c_i^2 s_i^2/n_i)^2}{\sum_{i=1}^{m} c_i^4 s_i^4/\{n_i^2(n_i-1)\}}$$

If all the group sizes are the same (say n), then

$$\hat{\nu} = \frac{(n-1)(\sum_{i=1}^{m} c_i^2 s_i^2)^2}{\sum_{i=1}^{m} c_i^4 s_i^4}$$

If all of the c_i's were the same and all of the s_i's were the same, this would reduce to $m(n-1)$, which is the degrees of freedom for a pooled t-test in this situation. Otherwise, $\hat{\nu}$ will be less, but not much less if the spread in variances is not too great. For example, if there are 10 categories and 5 vehicles in each category, $\hat{\nu}$ could be as great as 40, but could be less if the variance in some groups differs from that in others.

Appendix 11

UNOCAL REGRESSION EQUATION

Range of Variables Considered in the Unocal Study

Variable	Range
Aromatic Hydrocarbons	10 - 45 volume %
MTBE	0 - 15 volume %
Olefin	0 - 15 volume %
90 % Distillation Temp.	290 - 350 degrees F
50 % Distillation Temp.	170 - 240 degrees F
Motor Octane Number	84 - 87 dimensionless
Research Octane Number	90 - 95 dimensionless
Reid Vapor Pressure	8 - 10 psi

Based on the data collected, Unocal developed a predictive model which includes different variables than the Auto/Oil regression equations. The regression equations are presented below:

Hydrocarbon (grams/mile) = -0.000474 * Aromatic Hydrocarbons (vol%)
+0.00248 * Olefins (vol%)
-0.00212 * Research Octane Number
+0.00207 * T50 Distillation Temp (deg F)

Carbon Monoxide (grams/mile) = -0.00682 * Paraffins (vol %)
+0.0128 * T50 Distillation Temp (deg F)
+0.00123 * T90 Distillation Temp (deg F)

Oxides of Nitrogen (grams/mile) = +0.005595 * Olefins (vol %)
-0.000283 * Paraffin (vol %)
+0.002715 * T10 Distillation Point (deg F)
+0.02765 * Reid Vapor Pressure (psi)

Appendix 12

AUTO/OIL REGRESSION EQUATIONS

Current Fleet

Table of Regression Coefficients

		HC	CO	NOx
R^2		0.9827	0.9723	0.9883
Std. Error		0.0829	0.1471	0.0865
Variable				
Mean(1)	a_0	-1.5114042	1.0082863	-0.5066676
A	a_1	0.0025823*	0.0058362*	-0.0008132
M	a_2	-0.0034959*	-0.0079158*	0.0009509
O	a_3	-0.0039509*	-0.0009679	0.0041530*
T	a_4	0.0030304*	-0.0001049	-0.0006042*
AM	a_{12}	0.0001036	0.0000749	-0.0001905*
AO	a_{13}	-0.0000117	-0.0000829	-0.0000191
AT	a_{14}	0.0000795*	0.0000542*	-0.0000109
MO	a_{23}	0.0001009	0.0000012	-0.0001298
MT	a_{24}	0.0000179	-0.0000067	0.0000044
OT	a_{34}	-0.0000764*	-0.0000588	0.0000187
AMO	a_{123}	-0.0000111	-0.0000132	0.0000023
AMT	a_{124}	-0.0000027	0.0000019	0.0000030
AOT	a_{134}	-0.0000010	-0.0000022	-0.0000016
MOT	a_{234}	0.0000010	0.0000015	0.0000021
Block	a_{1234}	-0.0087728	0.0050379	-0.0014858

* = Significant at the 95% confidence level.

$$\begin{aligned}(HC, CO, NOx) = EXP\ [&a_0 + a_1 * (A) + a_2 * (M) + a_3 * (O) + a_4 * (T) + a_{12} * (AM) \\ &+ a_{13} * (AO) + a_{14} * (AT) + a_{23} * (MO) + a_{24} * (MT) + a_{34} * (OT) \\ &+ a_{123} * (AMO) + a_{124} * (AMT) + a_{134} * (AOT) + a_{234} * (MOT)]\end{aligned}$$

where,
A = (% Aromatics - 32.8)
M = (% MTBE - 7.37)
O = (% Olefins - 11.8)
T = (T_{90} - 321)

(32.8, 7.37, 11.8, 321) = mean values of Aromatics, MTBE, Olefins, and T_{90}, respectively, for the 16 "factorial" fuels (fuels C - R)

Block = - 0.5 for Block I
+ 0.5 for Block II

Example of interaction terms:

AM = A * M = (% Aromatics - 32.8) * (% MTBE - 7.37)

Older Fleet

Table of Regression Coefficients–Composite Exhaust

		THC	NMHC	CO	NOx
R^2		0.9698	0.9682	0.9534	0.9874
Std. Error		0.1061	0.1216	0.1501	0.0700
Variable					
Mean	a_0	-0.6987428	-0.8691925	1.7554429	0.1986705
A	a_1	-0.0051091*	-0.0039812*	0.0009933	0.0046558*
M	a_2	-0.0063830*	-0.0063235*	-0.0101534*	-0.0008483
O	a_3	-0.0037140*	-0.0044583*	0.0011969	0.0046505*
T	a_4	0.0007445*	0.0005499*	-0.0015956*	-0.0002729
AM	a_{12}	-0.0000345	-0.0000665	0.0000578	-0.0000652
AO	a_{13}	0.0001723*	0.0001789	0.0000133	0.0000925
AT	a_{14}	0.0000621*	0.0000679*	0.0000657*	-0.0000152
MO	a_{23}	-0.0002090	-0.0002461	-0.0002704	-0.0000848
MT	a_{24}	0.0000321	0.0000385	-0.0000360	-0.0000092
OT	a_{34}	-0.0000913*	-0.0000918*	-0.0001083*	0.0000279
AMO	a_{123}	-0.0000234*	-0.0000240	-0.0000084	-0.0000152*
AMT	a_{124}	0.0000011	0.0000025	-0.0000009	0.0000037*
AOT	a_{134}	0.0000001	0.0000010	0.0000000	0.0000015
MOT	a_{234}	0.0000039	0.0000042	0.0000075	-0.0000030
Block	a_{1234}	-0.0079596	-0.0048287	0.0527469*	0.0113724

* = Significant at the 95% confidence level.

$$(\mathrm{THC},\ \mathrm{NMHC},\ \mathrm{CO},\ \mathrm{NOx}) = \mathrm{EXP}\ [a_0 + a_1 * (A) + a_2 * (M) + a_3 * (O) + a_4 * (T) + a_{12} * (AM)$$
$$+ a_{13} * (AO) + a_{14} * (AT) + a_{23} * (MO) + a_{24} * (MT) + a_{34} * (OT)$$
$$+ a_{123} * (AMO) + a_{124} * (AMT) + a_{134} * (AOT) + a_{234} * (MOT) + a_{1234} * \mathrm{Block}]$$

where,
A = (% Aromatics - 32.8)
M = (% MTBE - 7.37)
O = (% Olefins - 11.8)
T = (T_{90} - 321)

(32.8, 7.37, 11.8, 321) = mean values of Aromatics, MTBE, Olefins, and T_{90}, respectively, for the "factorial" fuels (fuels C - R)

Block = - 0.5 for Block I
+ 0.5 for Block II

Example of interaction terms:

AM = A * M = (% Aromatics - 32.8) * (% MTBE - 7.37)

Appendix 13

BASIS FOR CALCULATING EVAPORATIVE EMISSION REDUCTIONS FROM ON-ROAD GASOLINE-POWERED MOTOR VEHICLES

Basis for Calculating Evaporative Emission Reductions From On-Road Gasoline-Powered Motor Vehicles

For the development of the RVP regulation for the Phase 1 reformulated gasoline specifications, the staff used test results from a number of automobile emissions test programs to develop relationships between evaporative emissions and RVP. The following emissions test programs were used to develop the relationship between emissions and RVP.

Diurnal and Hot Soak Evaporative Emissions

1. American Petroleum Institute (API) (1979)
2. Automotive Test Labs (ATL) under contract to API
3. Air Resources Board (ARB) (1988)

Evaporative Running Losses

1. Environmental Protection Agency (EPA) data base (1989)

Based on these relationships, the staff has calculated diurnal evaporative emissions, hot soak emissions, and running losses for carbureted and fuel injected vehicles at RVPs ranging from 7.8 psi to 7.0 psi.

The Technical Support Document for Phase 1 reformulated gasoline presented evaporative emissions and adjustment factors for RVPs ranging from 9.0 psi to 7.0 psi. Since the baseline emissions for the Phase 1 RVP regulations were based on a RVP of 9.0 psi, the adjustment factors were calculated as ratio of the predicted emissions of any RVP and the predicted emissions at 9.0 psi. For calculating the emission adjustment factors for the Phase 2 RVP regulation, the baseline emissions are based on 7.8 psi. Thus, the emission factors presented in this report are calculated as ratios of the emissions at any RVP to the predicted emissions at 7.8 psi. Tables 2 through 5 list the diurnal emissions, hot soak emissions emissions and emission adjustment factors for RVPs ranging from 7.8 psi to 7.0 psi. The emissions used to determine the adjustment factors were obtained at emissions tests conducted at temperatures specified by the Federal Test Procedures. Table 6 shows the evaporative running losses and adjustment factors 95 °F for for RVP values of 7.8 and 7.0 psi.

The running losses are estimated with the use of Figure 1, which is a plot of evaporative running losses as a function true vapor pressure (TVP). Figure 1 only provides running losses for TVP down to 8 psi. To estimate the running losses for RVPs at 7.8 psi and 7.0 psi at 95 degrees F, the staff had to make extrapolations from the curve. The equations of the best-fit curves fitted to the data shown in Figure 1 were used to estimate the running losses at RVP values of 7.8 and 7.0 psi.

Table 2

Predicted Diurnal Emissions and RVP Adjustment Factors - Carbureted Vehicles

RVP	API Program		ARB Program		ATL Program		Average
	g/test	Adjustment	g/test	Adjustment	g/test	Adjustment	Adjustment
7.8	0.84	1.00	0.51	1.00	0.82	1.00	1.00
7.6	0.75	0.89	0.45	0.88	0.80	0.98	0.92
7.4	0.66	0.79	0.40	0.78	0.75	0.91	0.83
7.2	0.59	0.70	0.36	0.71	0.72	0.88	0.76
7.0	0.53	0.63	0.32	0.63	0.70	0.85	0.70

Source: Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, ARB, August 1990

Table 3

Predicted Diurnal Emissions and RVP Adjustment Factors - Fuel-Injected Vehicles

RVP	ARB Program		ATL Program		Weighted Average
	g/test	Adjustment	g/test	Adjustment	Adjustment
7.8	0.092	1.00	0.95	1.00	1.00
7.6	0.089	0.97	0.92	0.97	0.97
7.4	0.086	0.93	0.88	0.93	0.93
7.2	0.083	0.90	0.85	0.92	0.92
7.0	0.080	0.87	0.82	0.86	0.86

Source: Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, ARB, August 1990

Table 4

Predicted Hot Soak Emissions and RVP Adjustment Factors - Carbureted Vehicles

	Pre 1978		1978 - 1980		Post 1980	
RVP	g/test	Adjustment	g/test	Adjustment	g/test	Adjustment
7.8	0.97	1.00	2.54	1.00	0.96	1.00
7.6	0.94	0.97	2.40	0.96	0.92	0.96
7.4	0.91	0.94	2.27	0.89	0.86	0.90
7.2	0.88	0.91	2.13	0.84	0.84	0.88
7.0	0.86	0.89	2.00	0.78	0.83	0.86

Source: Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, ARB, August 1990

Table 5

Predicted Hot Soak Emissions and RVP Adjustment Factors - Fuel Injected Vehicles

	ARB Program		ATL Program		Weighted Average
RVP	(g/test)	Adjustment	g/test	Adjustment	Adjustment
7.8	0.19	1.00	0.95	1.00	1.00
7.6	0.19	0.98	0.91	0.96	0.96
7.4	0.18	0.95	0.87	0.92	0.92
7.2	0.18	0.93	0.83	0.87	0.89
7.0	0.17	0.91	0.80	0.85	0.86

Source: Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, ARB, August 1990

Table 6

Adjustment Factors for Running Losses - Carbureted Vehicles

RVP	g/test	Adjustment Factor[1]
7.8	4.3	1.00
7.0	2.8	0.66

Adjustment Factors for Running Losses - Fuel Injected Vehicles

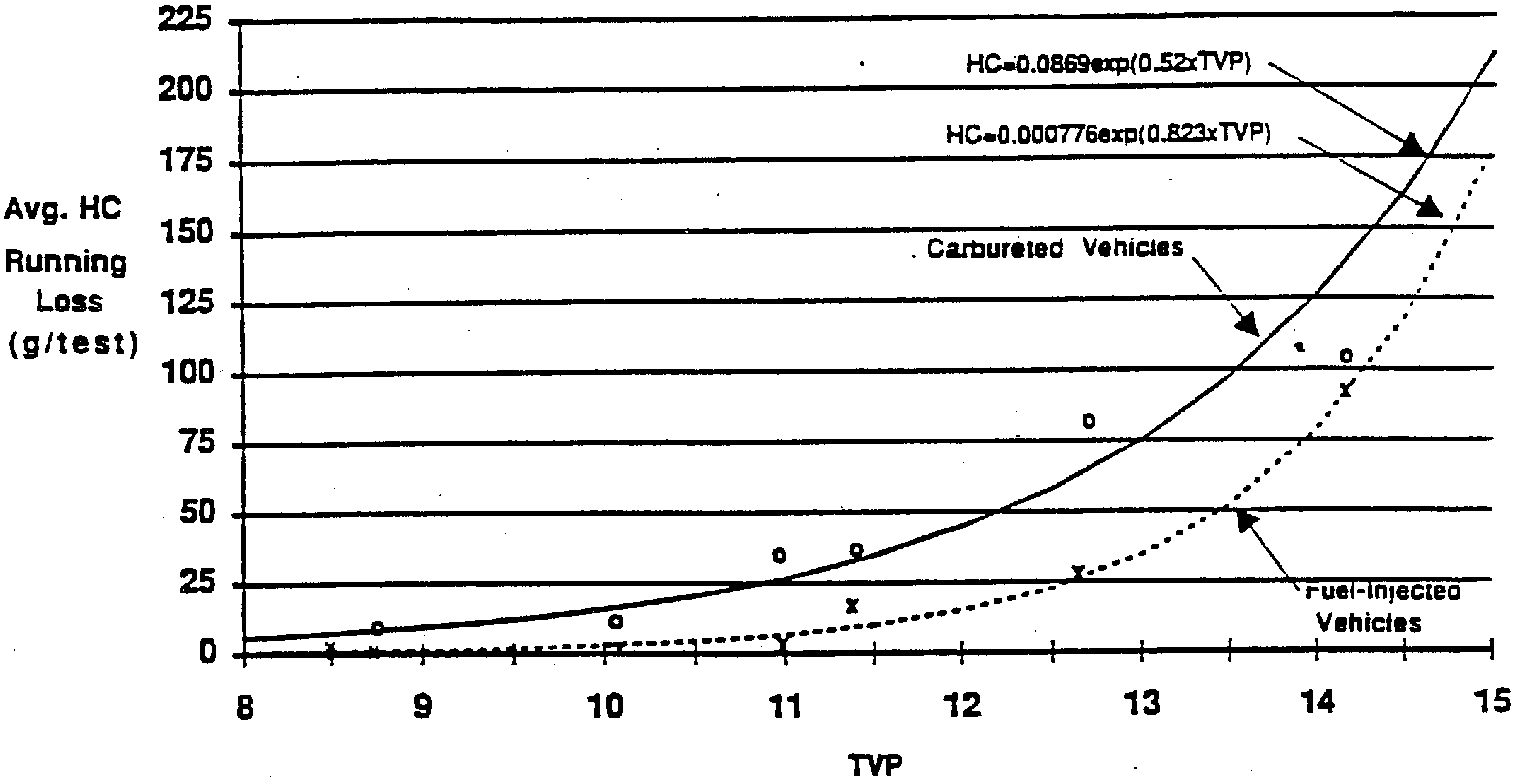
RVP	g/test	Adjustment Factor[1]
7.8	3.7	1.00
7.0	1.9	0.52

[1] Adjustment factors are based on True Vapor Pressure (TVP) at 95°F.

Source: Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, ARB, August 1990

Figure 1

Evaporative Running Losses as a Function of True Vapor Pressure



Source: Reformulated Gasoline: Proposed Phase 1 Specifications, Technical Support Document, ARB, August 1990

To determine the emission reductions, the emission inventory of the fleet of vehicle is multiplied by the appropriate emission reduction factor. A emission reduction factor is the emission adjustment factors for 7.0 RVP minus the emission adjustment factor at 7.8 RVP. Multiplying the emission reduction factor with the baseline emission for the vehicle group will yield the emission reduction for lowering RVP from 7.8 psi to 7.0 psi. Because evaporative and exhaust emissions vary between vehicles of different age, types of fuel metering system, and emission control technology, emissions are determined for groups of similar vehicles. Individual emission reduction factors were calculated for each of the vehicle classes identified in the emissions inventory. This was done by weighting the average emission adjustment factors according to the distribution of carbureted and fuel-injected vehicles.

Tables 7 and 8 show the fractions of carbureted and fuel injected vehicles that make up the vehicle groups. The staff assumes that these fractions can be applied to vehicle groups of any inventory calendar. It is assumed that carbureted and fuel injected vehicles have identical equipment life and are retired from the vehicle fleets at the same rate. Using the fractions shown in Table 9 and 10, weighted average emission adjustment factors are calculated for light duty passenger auto (LDA) and light duty trucks (LDT). The weighted average adjustment factors are calculated as follows:

WADF = [(carbureted fraction) x (carbureted EAF)] +
[(fuel injected fraction) x (fuel injected EAF)]

where

WEAF = weighted average adjustment factor
EAF = emissions adjustment factor

The weighted average adjustment factors for 7.0 RVP are listed in Table 11 and 12.

Tables 13 and 14 list the emission reduction factors for diurnal, hot soak, and running losses. The emission reduction factors for the various vehicle groups were determined by the following equation:

ERF = 1 - (weighted average adjustment factors at 7.0 RVP)

where ERF = emission reduction factor

Table 9

Breakdown of Carbureted and Fuel Injected Vehicle
Light Duty Passenger Cars

Vehicle Group	Percent Carbureted	Percent Fuel Injected
Non-catalyst	100	0
1975 - 1980	89	11
1981 - 1985	62	38
1986 - 1990	21	79
1991 - 1995	2	98
Post 1995	0	100

Source: ARB/SSD

Table 10

Breakdown of Carbureted and Fuel Injected Vehicle
Light Duty Passenger Trucks

Vehicle Group	Percent Carbureted	Percent Fuel Injected
Non-catalyst	100	0
1975 - 1980	97	3
1981 - 1985	93	7
1986 - 1990	28	72
1991 - 1995	2	98
Post 1995	0	100

Source: ARB/SSD