

Methanol Vehicle Emissions

API PUBLICATION 4262
DECEMBER 1990

American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005



Methanol Vehicle Emissions

Thomas J. Lareau, Policy Analysis Department
David H. Lax, Health and Environmental Sciences Department
Paul A. Martino, Health and Environmental Sciences Department
Willis E. Bush, Editorial and Special Issues Department

Refining Department

API PUBLICATION 4262
DECEMBER 1990

American
Petroleum
Institute



Documents
Document Sharing Hub

SPECIAL NOTES

1. API PUBLICATIONS NECESSARILY ADDRESS PROBLEMS OF A GENERAL NATURE. WITH RESPECT TO PARTICULAR CIRCUMSTANCES, LOCAL, STATE, AND FEDERAL LAWS AND REGULATIONS SHOULD BE REVIEWED.
2. API IS NOT UNDERTAKING TO MEET THE DUTIES OF EMPLOYERS, MANUFACTURERS, OR SUPPLIERS TO WARN AND PROPERLY TRAIN AND EQUIP THEIR EMPLOYEES, AND OTHERS EXPOSED, CONCERNING HEALTH AND SAFETY RISKS AND PRECAUTIONS, NOR UNDERTAKING THEIR OBLIGATIONS UNDER LOCAL, STATE, OR FEDERAL LAWS.
3. INFORMATION CONCERNING SAFETY AND HEALTH RISKS AND PROPER PRECAUTIONS WITH RESPECT TO PARTICULAR MATERIALS AND CONDITIONS SHOULD BE OBTAINED FROM THE EMPLOYER, THE MANUFACTURER OR SUPPLIER OF THAT MATERIAL, OR THE MATERIAL SAFETY DATA SHEET.
4. NOTHING CONTAINED IN ANY API PUBLICATION IS TO BE CONSTRUED AS GRANTING ANY RIGHT, BY IMPLICATION OR OTHERWISE, FOR THE MANUFACTURE, SALE, OR USE OF ANY METHOD, APPARATUS, OR PRODUCT COVERED BY LETTERS PATENT. NEITHER SHOULD ANYTHING CONTAINED IN THE PUBLICATION BE CONSTRUED AS INSURING ANYONE AGAINST LIABILITY FOR INFRINGEMENT OF LETTERS PATENT.
5. GENERALLY, API STANDARDS ARE REVIEWED AND REVISED, REAFFIRMED, OR WITHDRAWN AT LEAST EVERY FIVE YEARS. SOMETIMES A ONE-TIME EXTENSION OF UP TO TWO YEARS WILL BE ADDED TO THIS REVIEW CYCLE. THIS PUBLICATION WILL NO LONGER BE IN EFFECT FIVE YEARS AFTER ITS PUBLICATION DATE AS AN OPERATIVE API STANDARD OR, WHERE AN EXTENSION HAS BEEN GRANTED, UPON REPUBLICATION. STATUS OF THE PUBLICATION CAN BE ASCERTAINED FROM THE API AUTHORIZING DEPARTMENT [TELEPHONE (202) 682-8000]. A CATALOG OF API PUBLICATIONS AND MATERIALS IS PUBLISHED ANNUALLY AND UPDATED QUARTERLY BY API, 1220 L STREET, N.W., WASHINGTON, D.C. 20005.

Copyright © 1990 American Petroleum Institute



Documents
Document Sharing Hub

FOREWORD

This publication was prepared by members of the API Alternative Fuels Group, including Thomas J. Lareau, Policy Analysis Department; David H. Lax and Paul A. Martino, Health and Environmental Sciences Department; and Willis E. Bush, Editorial and Special Issues Department. The data in the report were provided by federal and state regulatory agencies and API member companies.

This report evolved from work initially undertaken by Paul Martino, who reviewed the emissions studies that comprise Appendix C. David Lax organized the emissions data from the various published studies and from many organizations into a spreadsheet. From this he created an initial set of emissions graphics for particular vehicle classes (the precursor to the second-level screening analysis). Thomas Lareau provided the first-level screening analysis and served as overall coordinator of the report in its later stages. Bill Bush provided editorial assistance throughout the process.

Many other API staff members contributed to the preparation and review of this report. In particular, Michael E. Canes, Ronald L. Jones, James E. Williams, and James Vail provided critical reviews and suggestions that clarified and extended the analysis in important ways. External reviews by Bruce Beyaert (Chevron), Sandra Minor (Unocal), B. D. Keller (Amoco), and James Macias (Shell) also served to improve the final version of this report. Finally, we would like to thank Constance Polite, who typed the original drafts of the report, and the API Refining Department editorial staff, who edited the final version and produced the book. The authors appreciate the efforts of all these individuals, without which this report would not have been as clear or technically sound.

Every effort has been made by the Institute to assure the accuracy and reliability of the data and analysis contained in this study. However, the contents of this publication are meant for the purposes of study and discussion of technical and regulatory issues and do not necessarily represent the views of the Institute or any of its members.

CONTENTS

	Page
SECTION 1—EXECUTIVE SUMMARY	1
SECTION 2—METHANOL VEHICLE EMISSIONS	
DATA BASE	2
Methanol Emissions Studies	2
Exhaust Emissions Focus	2
Federal Test Procedure Conditions	2
Measurement Procedures	2
Test Vehicles	2
Two Emissions Data Bases	4
Determining Emissions Trends	4
SECTION 3—MEASURING METHANOL VEHICLE	
EMISSIONS	6
Organic Material Hydrocarbon-Equivalent Emissions	7
Flame Ionization Detection	7
Measurement Bias	7
SECTION 4—METHANOL EMISSIONS TRENDS	7
Analysis of All Emissions Data With Odometer Readings	8
Formaldehyde	9
Nitrogen Oxides	10
Organics	10
Carbon Monoxide	10
Classes of Vehicles Providing Data for Analysis	10
Dedicated M85 Vehicles (Older U.S. Auto Manufacturer Technology)	11
Dedicated M85 Vehicles (Older Foreign Auto Manufacturer Technology)	11
Dedicated M85 Vehicles (Recent U.S. Auto Manufacturer Technology)	11
Dedicated M85 Vehicles (Recent Foreign Auto Manufacturer Technology)	12
Dedicated M100 Vehicles	12
Flexible-Fuel Vehicles	12
Emissions Trends From Restricted Data	13
Formaldehyde Emissions	13
Nitrogen Oxide Emissions	14
Carbon Monoxide Emissions	15
Organic Emissions	15
Analysis of Additional Methanol Emissions Data and Advanced	
Catalyst Research	30
Analysis of Prototype Vehicle Technology	30
Analysis of Advanced Catalyst Research	31
Evaporative Emissions Trends	31
SECTION 5—CONCLUSIONS	33
M85 Vehicles	33
M100 Vehicles	33
SECTION 6—REFERENCES	34
APPENDIX A—EXHAUST EMISSIONS DATA	37
APPENDIX B—EVAPORATIVE EMISSIONS DATA	67
APPENDIX C—SUMMARY OF METHANOL VEHICLE EMISSIONS	
STUDIES	77

Figures

1—Formaldehyde Emissions: Dedicated M85 Toyota Camry	4
2—Formaldehyde Emissions: 1981–1985 vs. 1986–1988 Models	8
3—Formaldehyde Emissions: M85 vs. M100	8
4—NO _x Emissions: 1981–1985 vs. 1986–1988 Models	9
5—NO _x Emissions: M85 vs. M100	9
6—OMHCE Emissions: 1981–1985 vs. 1986–1988 Models	9
7—OMHCE Emissions: M85 vs. M100	9
8—CO Emissions: 1981–1985 vs. 1986–1988 Models	10
9—CO Emissions: M85 vs. M100	10
10—Distribution of Maximum Mileage Accumulated	11
11—Formaldehyde Emissions: Full vs. Subset Data	13
12—NO _x Emissions: Full vs. Subset Data	13
13—OMHCE Emissions: Full vs. Subset Data	13
14—CO Emissions: Full vs. Subset Data	14
15—Formaldehyde Emissions: Five 1983 Carbureted Ford Escorts (M85)	14
16—Formaldehyde Emissions: Three 1983 Fuel-Injected Ford Escorts (M85)	15
17—Formaldehyde Emissions: Two 1981 Fuel-Injected Volkswagen Rabbits (M85)	15
18—Formaldehyde Emissions: Four Domestic Dedicated Vehicles (M85)	16
19—Formaldehyde Emissions: Four Dedicated Toyotas	16
20—Formaldehyde Emissions: Four Dedicated Vehicles (M100)	17
21—Formaldehyde Emissions: Seven 1987 Ford Crown Victorias (M85 Flexible-Fuel Vehicles)	17
22—Formaldehyde Emissions: 1987 Ford Crown Victoria and 1988 Chevrolet Corsica (M85 Flexible-Fuel Vehicles)	18
23—NO _x Emissions: Five 1983 Carbureted Ford Escorts (M85)	18
24—NO _x Emissions: Three 1983 Fuel-Injected Ford Escorts (M85)	19
25—NO _x Emissions: Two 1981 Fuel-Injected Volkswagen Rabbits (M85)	19
26—NO _x Emissions: Four Domestic Dedicated Vehicles (M85)	20
27—NO _x Emissions: Four Dedicated Toyotas (M85)	20
28—NO _x Emissions: Four Dedicated Vehicles (M100)	21
29—NO _x Emissions: Seven 1987 Ford Crown Victorias (M85 Flexible-Fuel Vehicles)	21
30—NO _x Emissions: 1987 Ford Crown Victoria and 1988 Chevrolet Corsica (M85 Flexible-Fuel Vehicles)	22
31—CO Emissions: Five 1983 Carbureted Ford Escorts (M85)	22
32—CO Emissions: Three 1983 Fuel-Injected Ford Escorts (M85)	23
33—CO Emissions: Two 1981 Fuel-Injected Volkswagen Rabbits (M85)	23
34—CO Emissions: Four Domestic Dedicated Vehicles (M85)	24
35—CO Emissions: Four Dedicated Toyotas (M85)	24
36—CO Emissions: Four Dedicated Vehicles (M100)	25
37—CO Emissions: Seven 1987 Ford Crown Victorias (M85 Flexible-Fuel Vehicles)	25
38—CO Emissions: 1987 Ford Crown Victoria and 1988 Chevrolet Corsica (M85 Flexible-Fuel Vehicles)	26
39—OMHCE Emissions: Two 1983 Carbureted Ford Escorts (M85)	26
40—OMHCE Emissions: Three 1983 Fuel-Injected Ford Escorts (M85)	27
41—OMHCE Emissions: Two Domestic Dedicated Vehicles (M100)	27
42—OMHCE Emissions: Four Dedicated Toyotas (M85)	28
43—OMHCE Emissions: Dedicated Toyota Carina (M100)	28
44—OMHCE Emissions: Six 1987 Ford Crown Victorias (M85 Flexible-Fuel Vehicles)	29

45—OMHCE Emissions: 1987 Ford Crown Victoria and 1988 Chevrolet Corsica (M85 Flexible-Fuel Vehicles)	29
46—Total Organic Evaporative Emissions: Seven 1987 Ford Crown Victorias (M85 Flexible-Fuel Vehicles)	32
47—Total Organic Evaporative Emissions: Three 1983 Fuel-Injected Ford Escorts (M85)	32
48—Total Organic Evaporative Emissions: Two Dedicated Toyotas (M85)	33

Tables

1—Summary of Emissions Studies	3
2—Distribution of Vehicles in the Exhaust Emissions Data Base	5
3—Mileage Dependence of Emissions	11
4—Dedicated M100 Vehicles	12
5—FTP Exhaust Emissions From Prototype M100 Vehicles	30
6—FTP Exhaust Emissions From Prototype Dedicated M85 Vehicles	31
A-1—'81 Ford Escort/License No. 276/Mix Method: Carburetion/ ECU: NFB	39
A-2—'81 Ford Escort/License No. 882/Mix Method: Carburetion/ ECU: NFB	39
A-3—'81 VW Rabbit/License No. 824/Mix Method: Fuel Injection/ ECU: FB	40
A-4—'81 VW Rabbit/License No. 995/Mix Method: Fuel Injection/ ECU: FB	40
A-5—'81 VW Rabbit/License No. 989/Mix Method: Fuel Injection/ ECU: FB	41
A-6—'81 Ford Escort/License No. 920/Mix Method: Carburetion/ ECU: NFB	41
A-7—'84 Ford Escort/License No. 154/Mix Method: Fuel Injection/ ECU: NFB	41
A-8—'83 Ford Escort/License No. 359/Mix Method: Fuel Injection/ ECU: FB	42
A-9—'83 Ford Escort/License No. 365/Mix Method: Fuel Injection/ ECU: FB	43
A-10—'83 Ford Escort/License No. 366/Mix Method: Fuel Injection/ ECU: FB	44
A-11—'85 Toyota Camry/License No. 444/Mix Method: Fuel Injection/ ECU: FB	45
A-12—'86 Toyota Carina/License No. 145/Mix Method: Fuel Injection/ ECU: FB	46
A-13—'87 Ford Crown Victoria/License No. 927/Mix Method: Fuel Injection/ ECU: FB	47
A-14—'87 Ford Crown Victoria/License No. 928/Mix Method: Fuel Injection/ ECU: FB	47
A-15—'87 Ford Crown Victoria/License No. 779/Mix Method: Fuel Injection/ ECU: FB	48
A-16—'87 Ford Crown Victoria/License No. 778/Mix Method: Fuel Injection/ ECU: FB	48
A-17—'87 Ford Crown Victoria/License No. 963/Mix Method: Fuel Injection/ ECU: FB	49
A-18—'83 Ford Escort/License No. 319/Mix Method: Carburetion/ ECU: NFB	49
A-19—'83 Ford Escort/License No. 893/Mix Method: Carburetion/ ECU: NFB	50

A-20—'83 Ford Escort/License No. 570/Mix Method: Carburetion/ ECU: NFB	50
A-21—'83 Ford Escort/License No. 571/Mix Method: Carburetion/ ECU: NFB	50
A-22—'83 Ford Escort/License No. 778/Mix Method: Carburetion/ ECU: NFB	50
A-23—'82 GM Citation/License No. 112/Mix Method: Fuel Injection/ ECU: NFB	51
A-24—'87 Ford Crown Victoria/License No. 653/Mix Method: Fuel Injection/ ECU: FB	51
A-25—'83 Ford Escort/License No. 484/Mix Method: Carburetion/ ECU: NFB	52
A-26—'83 Ford Escort/License No. 485/Mix Method: Carburetion/ ECU: NFB	52
A-27—'87 Ford Crown Victoria/License No. 610/Mix Method: Fuel Injection/ ECU: FB	52
A-28—'88 GM Corsica/License No. AHU/Mix Method: Fuel Injection/ ECU: FB	53
A-29—'87 Ford Crown Victoria/License No. 748/Mix Method: Fuel Injection/ ECU: FB	53
A-30—'87 Ford Crown Victoria/License No. 749/Mix Method: Fuel Injection/ ECU: FB	54
A-31—'86 Toyota Camry/License No. 311/Mix Method: Fuel Injection/ ECU: FB	54
A-32—'88 GM Corsica/License No. WPS/Mix Method: Fuel Injection/ ECU: FB	54
A-33—'88 GM Corsica/License No. 945/Mix Method: Fuel Injection/ ECU: FB	54
A-34—'88 GM Corsica/License No. 944/Mix Method: Fuel Injection/ ECU: FB	54
A-35—GM Prototype VFV/Mix Method: Fuel Injection/ECU: FB	55
A-36—Prototype Operated by SOHIO	55
A-37—GM M100 Prototype/Mix Method: Fuel Injection	55
A-38—'83 Ford Escort/Mix Method: Carburetion/ECU: NFB	55
A-39—'83 Ford Escort/Mix Method: Carburetion	56
A-40—'81 GM Citation/License No. 221/Mix Method: Carburetion/ ECU: FB	56
A-41—'81 GM Phoenix/License No. 616/Mix Method: Carburetion/ ECU: FB	56
A-42—'81 Ford Escort/Mix Method: Carburetion/ECU: NFB	57
A-43—'81 VW Rabbit/Mix Method: Fuel Injection/ECU: FB	57
A-44—'81 Nissan 200SX/Mix Method: Fuel Injection/ECU: FB	57
A-45—'78 Ford Pinto (3-Car Average)/Mix Method: Carburetion/ECU: FB	58
A-46—'83 Ford Escort/Mix Method: Carburetion/ECU: NFB	58
A-47—'83 Ford Escort/Mix Method: Carburetion/ECU: NFB	58
A-48—'87 Nissan Sentra/Mix Method: Fuel Injection	59
A-49—'86 Ford Crown Victoria/Mix Method: Fuel Injection/ECU: FB	59
A-50—'86 Nissan Sentra/Mix Method: Fuel Injection/ECU: FB	59
A-51—'86 Toyota Carina/Mix Method: Fuel Injection/ECU: FB	60
A-52—'86 Chevrolet S-10/License No. ME-562/Mix Method: Fuel Injection/ ECU: FB	61
A-53—'86 Chevrolet S-10/License No. ME-568/Mix Method: Fuel Injection/ ECU: FB	61

A-54—'86 Ford Crown Victoria/License No. ME-572/Mix Method: Fuel Injection/ECU: FB	61
A-55—'86 Ford Crown Victoria/License No. ME-574/Mix Method: Fuel Injection/ECU: FB	61
A-56—'87 Buick Regal/License No. 9394/Mix Method: Fuel Injection/ ECU: FB	61
A-57—'87 Buick Regal/License No. 9398/Mix Method: Fuel Injection/ ECU: FB	62
A-58—'84 GM Citation/License No. E-753/Mix Method: Carburetion/ ECU: NFB	62
A-59—'84 GM Citation/License No. E-754/Mix Method: Carburetion/ ECU: NFB	62
A-60—'84 GM Citation/License No. E-755/Mix Method: Carburetion/ ECU: NFB	62
A-61—'84 GM Citation/License No. E-756/Mix Method: Carburetion/ ECU: NFB	62
A-62—'84 GM Citation/License No. E-757/Mix Method: Carburetion/ ECU: NFB	63
A-63—'88 GM Corsica/Mix Method: Fuel Injection/ECU: FB	63
A-64—'85 Ford Escort/License No. T020/Mix Method: Fuel Injection/ ECU: NFB	63
A-65—'85 Ford Escort/License No. T022/Mix Method: Fuel Injection/ ECU: NFB	64
A-66—'87 Ford Crown Victoria/License No. T-500/Mix Method: Fuel Injection/ECU: FB	64
A-67—'87 Ford Crown Victoria/License No. T-520/Mix Method: Fuel Injection/ECU: FB	65
B-1—'81 Ford Escort/License No. 276/Mix Method: Carburetion/ECU: NFB ..	69
B-2—'81 Ford Escort/License No. 882/Mix Method: Carburetion/ECU: NFB ..	69
B-3—'81 VW Rabbit/License No. 995/Mix Method: Fuel Injection/ECU: FB ..	69
B-4—'81 VW Rabbit/License No. 989/Mix Method: Fuel Injection/ECU: FB ..	69
B-5—'81 Ford Escort/License No. 920/Mix Method: Carburetion/ECU: NFB ..	69
B-6—'83 Ford Escort/License No. 359/Mix Method: Fuel Injection/ ECU: FB	70
B-7—'83 Ford Escort/License No. 365/Mix Method: Fuel Injection/ ECU: FB	70
B-8—'83 Ford Escort/License No. 366/Mix Method: Fuel Injection/ ECU: FB	70
B-9—'85 Toyota Camry/License No. 444/Mix Method: Fuel Injection/ ECU: FB	70
B-10—'86 Toyota Carina/License No. 145/Mix Method: Fuel Injection/ ECU: FB	71
B-11—'87 Ford Crown Victoria/License No. 927/Mix Method: Fuel Injection/ ECU: FB	71
B-12—'87 Ford Crown Victoria/License No. 928/Mix Method: Fuel Injection/ ECU: FB	71
B-13—'87 Ford Crown Victoria/License No. 779/Mix Method: Fuel Injection/ ECU: FB	71
B-14—'87 Ford Crown Victoria/License No. 778/Mix Method: Fuel Injection/ ECU: FB	72
B-15—'87 Ford Crown Victoria/License No. 963/Mix Method: Fuel Injection/ ECU: FB	72

B-16—'83 Ford Escort/License No. 319/Mix Method: Carburetion/ ECU: NFB	72
B-17—'83 Ford Escort/License No. 893/Mix Method: Carburetion/ ECU: NFB	72
B-18—'83 Ford Escort/License No. 570/Mix Method: Carburetion/ ECU: NFB	72
B-19—'83 Ford Escort/License No. 778/Mix Method: Carburetion/ ECU: NFB	73
B-20—'82 GM Citation/License No. 112/Mix Method: Fuel Injection/ ECU: NFB	73
B-21—'87 Ford Crown Victoria/License No. 653/Mix Method: Fuel Injection/ ECU: FB	73
B-22—'83 Ford Escort/License No. 484/Mix Method: Carburetion/ ECU: NFB	73
B-23—'83 Ford Escort/License No. 485/Mix Method: Carburetion/ ECU: NFB	73
B-24—'87 Ford Crown Victoria/License No. 610/Mix Method: Fuel Injection/ECU: FB	74
B-25—'88 GM Corsica/License No. AHU/Mix Method: Fuel Injection/ ECU: FB	74
B-26—GM Prototype VFV/Mix Method: Fuel Injection/ECU: FB	74
B-27—Prototype Operated by SOHIO	74
B-28—GM M100 Prototype/Mix Method: Fuel Injection	74
B-29—'83 Ford Escort/Mix Method: Carburetion/ECU: NFB	75
B-30—'86 Toyota Carina/Mix Method: Fuel Injection/ECU: FB	75
B-31—'88 GM Corsica/Mix Method: Fuel Injection/ECU: FB	75

Methanol Vehicle Emissions

SECTION 1—EXECUTIVE SUMMARY

This publication (a) identifies and presents empirical data on emissions from methanol vehicles and (b) compares and evaluates emissions trends among various types of methanol vehicles over time. These emissions data are necessary to assess the impact of methanol use on ozone levels.

Researchers have tested emissions from methanol vehicles since the early 1970s, but these data have not been fully and systematically compiled. This report provides a systematic, comprehensive compilation and analysis of these data, taken from every major study of methanol vehicles for at least the last 10 years. It includes emissions measurements for 69 vehicles and organizes the data into logical subgroups that permit analysis of important emissions hypotheses.

Many of the data collected are characterized by significant uncertainties. For example, different techniques were used to measure the same kind of emission. The data are accepted at face value, though there is some indication in the literature that measurement bias has been a problem for some test procedures. Also, the data were collected from vehicles that had received care beyond what vehicles in ordinary, everyday use would receive. For example, these vehicles were more reliably maintained and repaired. This often meant replacement of key engine and emission control components. For this reason, the emissions data reported in this publication probably reflect better performance from the methanol vehicles than would be expected in common, everyday use.

Some of the emissions data collected in this report were not accompanied by odometer readings. This was a key factor in the analysis, since a lack of odometer readings made understanding of the emissions data problematic. Thus, while all of the data collected are included in Appendixes A and B, only the data with odometer readings were analyzed. Tailpipe emissions data with odometer readings were available for 54 of the 69 vehicles. A subset of this data, covering 31 of the 54 vehicles, was also analyzed.

The subset of 31 vehicles included data that were more complete, uniform, and directly comparable. Vehicles were only included when organic emission species and nitrogen oxide (NO_x) emissions were measured, when vehicles were tested in their normal emission control configurations, when emissions were measured following catalyst stabilization, and when either M85 or M100 was used as the test fuel. By applying this more restrictive set of rules, we could learn more about the performance of subsets of vehicles classified by manufacturer, vintage, technology, and type of fuel used. We could also see relationships and trade-offs relating to the control of more than one kind of emission.

Despite the limitations of the data, our analysis supports several conclusions.

For M85 vehicles, those that operate on an 85-percent methanol/15-percent gasoline blend, there are sufficient recent data to characterize emissions. The data show some improvement in emissions performance for the second-generation M85 vehicles. This improvement offers encouragement that utilitarian M85 vehicles could be built that would satisfy most of the emissions criteria of the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB). The data also indicate, however, that a number of emission problems and unanswered questions remain:

- a. Even at low mileage, M85 vehicles almost always exceeded the 50,000-mile 1993 California tailpipe standard of 15 milligrams per mile for formaldehyde emissions. Average formaldehyde emissions were about three times higher than this standard. At various test mileages, the older, 1981–1985 models had measured formaldehyde emissions below the California standard level in only 6 percent of the tests. The newer, 1986–1988 models were only slightly better, meeting the standard level in about one of four tests.
- b. M85 vehicles typically had nitrogen oxide emissions that were less than the 50,000-mile federal standard of 1.0 gram per mile, but they were only rarely able to meet the more stringent 50,000-mile California standard of 0.4 gram per mile, even at low mileage. Even the 1986–1988 models performed poorly, testing below the 0.4-gram-per-mile level just 10 percent of the time at various mileages.
- c. There was substantial improvement in meeting the 50,000-mile federal tailpipe standard of 0.41 gram per mile for organic emissions. Although the 1981–1985 models met this level in only 40 percent of the tests, the 1986–1988 models did so 90 percent of the time. However, even these newer vehicles were able to meet the 50,000-mile 1993 California standard level of 0.25 gram per mile only 40 percent of the time. No methanol vehicle was able to meet the California standards for hydrocarbon and nitrogen oxide emissions simultaneously.
- d. There was also substantial improvement in meeting the 50,000-mile federal standard for carbon monoxide of 3.4 grams per mile. The 1981–1985 models met the standard level about 40 percent of the time at various mileages. The 1986–1988 models met the standard level in more than 80 percent of the tests.
- e. At the mileages tested, M85 vehicles were generally able to meet the 50,000-mile federal standard of 2 grams per test for total organic evaporative emissions.

For M100 vehicles, that is, methanol vehicles operating on pure methanol, the data are sparse and inadequate. Few

M100 vehicles have been tested, and almost no data exist for M100 vehicles that performed acceptably or were driven more than 15,000 miles in fleet tests. What data exist do not show emissions benefits substantially in excess of those demonstrated on M85 vehicles. Thus, the benefits of a program substituting M100 for gasoline cars are entirely speculative. Further, the driveability and overall utility of dedicated M100 vehicles have yet to be demonstrated.

Very limited, recent data on the more advanced prototype M85 and M100 vehicles and catalysts were analyzed separately. They show very low organic emissions at low mileage. However, these data fail to answer questions about emissions control durability and continue to indicate difficulty in lowering organic and NO_x emissions simultaneously.

This report does not discuss a key question: whether future, practical methanol vehicles could reduce ozone-form-

ing organic compounds more than future, practical gasoline vehicles. The question cannot be answered for M100 vehicles because of a lack of data from utilitarian prototypes. The data for M85 vehicles suggest that they could produce low levels of total organic emissions. However, today's most advanced gasoline vehicles also emit low levels of organic compounds—well below existing standards. Moreover, gasoline fuel reformulation will improve the emissions performance of 1990s gasoline vehicles. Thus, either future gasoline or future M85 vehicles could contribute substantially to pollution reduction.

The following sections present an analysis of methanol emissions data and measurement techniques. Section 2 discusses the methanol emissions data. Section 3 considers the issue of measurement of methanol vehicle emissions. Section 4 analyzes emission trends. Section 5 presents conclusions.

SECTION 2—METHANOL VEHICLE EMISSIONS DATA BASE

Methanol emissions data were collected from 28 studies conducted by federal and state government agencies and by the automobile and petroleum industries. Data from every major study for at least the last 10 years were included. Most of the studies were completed between 1987 and 1989. Two data bases were created from the data contained in the studies: one for exhaust emissions and one for evaporative emissions. No data were available for running losses.

Appendix C contains an annotated review of these studies and a bibliography of the literature on methanol vehicle emissions. Table 1 summarizes basic information about the studies. Appendix A presents the exhaust emissions data from the studies, and Appendix B presents the evaporative emissions data.

Methanol Emissions Studies

The studies reviewed involved the testing of many different types of vehicles. They employed many different test procedures and measurement methods. The lack of consistency partly reflects the varying objectives of the studies and partly the development of method and protocol. Many data are from the U.S. Department of Energy's (DOE's) methanol fleet demonstration program. The primary objective of this program was to evaluate methanol vehicles in terms of consumer acceptance, performance, and durability. Emissions were measured, but according to procedures established independently by the various national laboratories. In other cases—for example, the CARB test program—procedures and measurements were more uniform, and the emissions data are more comprehensive and comparable.

EXHAUST EMISSIONS FOCUS

Most studies have focused on exhaust emissions. There is much less information on evaporative losses and virtually no

published data on refueling and running-loss emissions. This accounts for the much larger exhaust emissions data base.

FEDERAL TEST PROCEDURE CONDITIONS

Until recently, most researchers have measured emissions from vehicles operated over either the Federal Test Procedure (FTP) or the Highway Fuel Economy Test (HWFET) driving cycles. Few data are available on emissions collected under non-FTP temperature conditions or under urban driving conditions.

MEASUREMENT PROCEDURES

EPA and CARB have established procedures for measuring methanol vehicle emissions. However, the accuracy of methanol emissions measurement remains problematic. Measurement is discussed in Section 3.

TEST VEHICLES

A variety of first-generation methanol vehicles have been tested for emissions. Most of these vehicles are conversions of existing gasoline-fueled engines and are carbureted, and some are not optimized to run on methanol. Furthermore, most incorporate emissions control equipment that does not represent state-of-the-art technology that will be used in future vehicles, particularly electronic engine management systems and fuel injection. The emissions data from these early vehicles, which generally show higher emissions than from later methanol vehicles, are of questionable use for estimating air quality impacts from future methanol vehicles.

More recent domestic prototype flexible-fuel vehicles (FFVs) have also been tested. Some of these automobiles have now been operated in normal service for more than 30,000 miles. Most are part of centrally managed fleets char-

Table 1—Summary of Emissions Studies

Row	Models	No. of Vehicles	Odometer Range	Fuel Type	Exhaust Procedure			Evaporative Procedure	
					MeOH	HCHO	THC	MeOH	THC
1	'81 Escort	3	50,111–115,590	M95, M90	GC	DNPH	GC	GC	GC
2	'83 Escort	10	5030–54,088	M90, M85	GC	DNPH	GC	GC	GC
3	'84 Escort	1	8580–8620	M100	GC	DNPH	GC	GC	GC
4	'81 Rabbit	2	5344–66,486	M85, M90, M95	GC	DNPH	GC	GC	GC
5	'82 Citation	1	30,692–41,600	M85, M90	GC	DNPH	GC	GC	GC
6	'85 Camry	1	434–26,270	M85	GC	DNPH	GC	GC	GC
7	'86 Camry	1	22,438–22,474	M85	GC	DNPH	GC	GC	GC
8	'86 Carina	1	944–24,589	M85	GC	DNPH	GC	GC	GC
9	'87 Crown Victoria	7	177–26,682	M0, M25, M85, M90, M100	GC	DNPH	GC	GC	GC
10	'88 Corsica	3	3956–20,822	M0, M25, M50, M85, M100	GC	DNPH	GC	GC	GC
11	'87 Crown Victoria	2	2391–15,930	M85	GC	DNPH	GC	GC	GC
12	GM Prototype	3	NA	M0, M15, M50, M85, M90, M100	GC	DNPH	GC	GC	GC
13	'83 Escort	1	NA	M85	GC	DNPH	FID	NA	NA
14 ^a	'83 Escort	1	NA	M90	GC	DNPH	NA	NA	NA
15 ^a	'83 Escort	1	NA	M90, M100	NA	DNPH	NA	NA	NA
16	'81 Citation	1	28,597–28,669	M88	GC	DNPH	NA	NA	NA
17	'81 Phoenix	1	2325	M88	GC	DNPH	NA	NA	NA
18	'81 Escort	1	6006–6805	M100	GC-I	DNPH	NA	NA	NA
19	'81 Rabbit	1	1770–2360	M100	GC-I	DNPH	NA	NA	NA
20	'81 200 SX	1	1494–1641	M100	NA	DNPH	NA	NA	NA
21	'78 Pinto	3	1250–10,000	M100	NA	MBTH	NA	NA	NA
22	'83 Escort	1	55–850	M90, M100	GC-I	DNPH	NA	NA	NA
23	'83 Escort	1	180–13,299	M90, M100	NA	NA	NA	NA	NA
24	'87 Sentra	1	NA	M100	NA	NA	NA	NA	NA
25	'86 Crown Victoria	1	2500–3645	M85	NA	NA	NA	NA	NA
26	'86 Sentra	1	16,739–17,218	M85	FID	DNPH	FID	NA	NA
27	'86 Carina	1	NA	M85, M100	FID	DNPH	FID	NA	NA
28	'86 Carina	1	1570–10,800	M100	FID	DNPH	FID	NA	NA
29	'86 S-10	2	288–8700	M85	FID	NA	FID	NA	NA
30	'86 Crown Victoria	2	793–32,800	M85	FID	NA	FID	NA	NA
31	'87 Regal	1	323–743	M85	FID	NA	FID	NA	NA
32	'84 Citation	5	NA	M0, M85	NA	NA	FID	NA	NA
33	'88 Corsica	1	NA	M0, M25, M50, M85, M100	GC	DNPH	GC	GC	GC
34 ^b	'87 Crown Victoria	3	10,006–26,682	M0, M85	GC	DNPH	FID	NA	NA
35	'88 Corsica	1	10,184–20,822	M0, M85	GC	DNPH	GC	NA	NA
36	'87 Crown Victoria	2	NA ^c	M85, M100	FTIR	FTIR/DNPH	FID/FTIR	NA	NA
37	'85 Escort	2	NA ^c	M0, M50, M85, M100	FTIR	FTIR/DNPH	FID/FTIR	NA	NA

Note: NA = not available; GC = gas chromatograph; DNPH = DNPH-impinger method followed by liquid chromatography; MBTH = MBTH-impinger method; FID = flame ionization detector with methanol subtraction. Sources are as follows: Row 1—California Air Resources Board (1986); Row 2—California Air Resources Board (1988); Row 3—California Air Resources Board ("Quarterly Summary," 12/88–2/89); Rows 4–11—California Air Resources Board ("Quarterly Summary," 6/88–8/88); Row 12—Williams et al. (1990); Row 13—Stump and Braddock (1989); Row 14—Gabele et al. (1985); Row 15—Smuda (1984a); Rows 16 and 17—California Air Resources Board (1984); Rows 18 and 19—Smith (1985); Row 20—Smuda (1984b); Row 21—Edwards and Baisley (1981); Row 22—Smith (1984); Row 23—Mobil Research and Development Cor-

poration (1987); Row 24—Hellman (1989); Row 25—Piotrowski et al. (1987); Row 26—Blair (1988); Row 27—Piotrowski (1987) and Piotrowski and Murrell (1987); Row 28—Piotrowski (1989); Row 29—McGill, Hillis, West, and Hodgson (1989b); Row 30—McGill et al. (1989b); Row 31—McGill, Hillis, West, and Hodgson (1989a); Row 32—McGill et al. (1987); Row 33—Gabele (1990); Rows 34 and 35—Horn and Hoekman (1989); Rows 36 and 37—Nichols et al. (1988).

^aThe same '83 escort was tested in Gabele et al. (1985) and Smuda (1984a).

^bThe three Crown Victorias and the Corsica tested in Horn and Hoekman (1989) are also summarized in California Air Resources Board (1986; 1988; "Quarterly Summary," 6/88–8/88; and "Quarterly Summary," 12/88–2/89).

^cTested with catalysts aged on the dynamometer.

acterized by levels of maintenance and care that exceed the attention given by the general public. Both domestic and foreign car manufacturers have tested some vehicles dedicated for use of either M85 or M100. These prototype vehicles have been operated in carefully maintained fleets and have accumulated up to 70,000 miles. However, of the vehicles dedicated to M100 fuel, none has accumulated more than 15,000 miles.

CARB reports that some vehicles—despite high levels of maintenance—appeared to experience intermittent driveability problems caused by frequent fuel injector fouling and/or fuel filter plugging (California Air Resources Board, 1988; see Figure 1). However, design changes appear to have solved the problem of injector fouling. High levels of maintenance, which included modifications of the vehicle fuel systems in attempts to stabilize emissions performance,

as well as replacement of catalysts, raise questions about the emissions results and potential durability of emission control systems.

It should be noted that the same vehicle was sometimes tested in different studies. For example, vehicles tested in the CARB fleet program were often provided to other organizations cooperating with CARB. Also, the same vehicles were sometimes tested with different emission control configurations (for example, with and without the catalytic converter, with and without exhaust gas recirculation). Appendix A identifies the emission controls in place during the exhaust emissions tests.

Two Emissions Data Bases

From the studies, two emissions data bases were created.

Approximately 1300 observations of carbon monoxide (CO), nitrogen oxides (NO_x), formaldehyde (HCHO), methanol (MeOH), total hydrocarbons (THC) and organic material hydrocarbon-equivalent emissions (OMHCE) were collected and tabulated to form an exhaust emissions data base (see Appendix A). The data spanned 69 vehicles across 14 model car lines. Other information was also tabulated when available. This included odometer readings, fuel metering system, emission control system configuration, fuel type, measurement procedures, and relevant information about the condition of the vehicle.

In addition, 86 observations of methanol and hydrocarbon evaporative emissions were entered into an evaporative emissions data base (see Appendix B). These measurements were taken on 30 vehicles representing 11 model car lines. As with the exhaust emissions data base, available information on fuel type, vehicle characteristics, and odometer reading was tabulated.

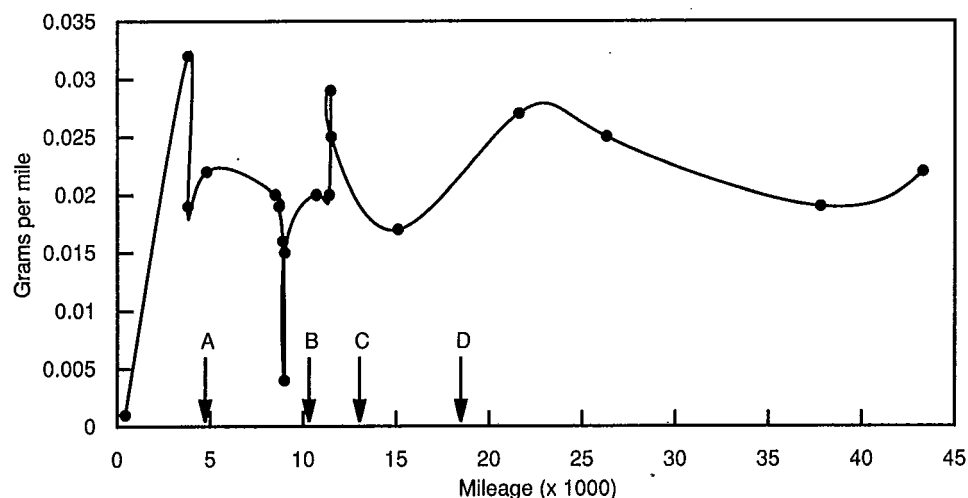
No attempt was made to exclude data representing malperforming vehicles or vehicles subjected to extraordinary levels of maintenance. In the real world, the variability inherent in emissions data is not only a function of vehicle-to-vehicle, test-to-test, and fuel-to-fuel differences; it is also highly dependent on the vehicle's state of maintenance. Thus, for example, some of the data in Appendix A reflect situations in which the emissions may have been affected by clogged fuel injectors, fouled fuel filters, and/or malperforming oxygen sensors in the test vehicle's emission control system. Also, many cars were tested immediately after maintenance or repairs were performed. Figure 1 shows formaldehyde emissions superimposed on maintenance events. Fuel injector replacement is not normal maintenance at low mileage.

Determining Emissions Trends

To track emissions trends, vehicle emissions data for a large number of vehicles of different vintage and technological refinement are desirable. Although we gathered a significant amount of data, most concerned exhaust emissions. Data on evaporative emissions are sparse.

Even the data for exhaust emissions were less than ideal. Data were collected using different measurement procedures. Many more data were recorded for some vehicles than others. And some of the data were recorded without odometer readings.

These limitations made interpretation of the data more difficult. In addition, emissions are influenced by many other variables. Emissions are particularly sensitive to vehicle vintage (emission control technology has improved over time), to age (emission control effectiveness deteriorates as mileage increases), and to fuel type.



Note: A = replaced fuel injectors; B = replaced second set of fuel injectors; C = replaced third set of fuel injectors; D = installed new ball-type fuel injectors and recalibrated computer for full stoichiometric operation.

Figure 1—Formaldehyde Emissions: Dedicated M85 Toyota Camry

It can be difficult if not impossible to distinguish emissions trends without being able to hold some variables constant—either statistically or by screening the data. Screening the data involves a trade-off between the advantages of using all (or as many as possible) of the data and the benefits of clearly seeing emissions trends as a function of single variables. Screening required eliminating some (or sometimes a substantial amount) of the data, all of which are included in Appendix A.

To try to make sense of the data—to control for some of the confounding variability—we applied two screening procedures.

In the first level of screening, we developed frequency distributions. This involved partitioning averaged data (more than one emission measurement for a single vehicle at one mileage interval was averaged) by vintage (1981–1985 and 1986–1988 vehicles) and by fuel (M85 and M100), each as a function of mileage. As shown in Table 2, in the first screening process, observations on 15 of the 69 vehicles were discarded because of the absence of mileage readings.

Restricting analysis to data for which odometer readings were available was unavoidable. Too much is unknown when mileage goes unrecorded. For example, failure to record mileage often indicates that tests were performed to

gain engineering knowledge. Such emissions data may reflect unrealistic conditions of vehicle use or emission control configuration. Also, it is unlikely that data without odometer readings were taken from vehicles operated under on-the-road conditions. In the testing of one car (a 1986 Toyota Carina; see Appendix A), 32 test sequences were run without a recorded odometer reading. Test notations indicate that engineering tests were being performed on the vehicle, engine, and emission control systems.

Also, combining emissions data for which odometer readings do not exist with data for which odometer readings do exist raises problems. In the case cited above, the 32 test sequences were probably taken at low mileage. If these are treated as one averaged set of emissions measurements to avoid overrepresentation of low mileage measurements, the number of observations is reduced substantially, though the loss of truly independent data is probably minimal.

In the second level of screening, we applied a more restrictive set of rules to control more precisely for differences in performance among vehicle models. This enabled us to show emissions trends as a function of mileage, fuel, and vintage, one at a time.

Under the second screening process, the data had to satisfy four criteria:

Table 2—Distribution of Vehicles in the Exhaust Emissions Data Base

Model	Technology/Test Fuels	No. of Vehicles	Odometer	Observations		Pollutant Measured With M85 or M100				No. of Vehicles Used In Second Analysis
				Threshold ^a	M85 or M100	CO/NO _x	HCHO	MeOH or THC	OMHCE	
'87 Crown Victoria	FI, FFV, M0–M100	9	8 ^b	9	9	9	9	9	8	8
'88 Corsica	FI, FFV/DED, M0–M88	5	4	3	4	5	4	2	3	2
'85 Camry	FI, DED, M85	1	1	1	1	1	1	1	1	1
'86 Carina	FI, DED, M85–M100	2	2	2	2	2	2	2	2	2
'86 Camry	FI, DED, M85	1	1	1	1	1	1	1	1	1
'86 Sentra	FI, DED, M85	1	1	1	1	1	1	1	1	1
'87 Sentra	FI, DED, M100	1	0	0	1	1	1	1	0	0
'81 200SX	FI, DED, M100	1	1	0	1	1	1	0	0	0
'81 Rabbit	FI, DED, M85–M100	4	4	3	3	4	4	4	2	2
'81 Phoenix	CARB, DED, M88	1	1	0	0	1	1	1	0	0
'81 Citation	CARB, DED, M88	1	1	1	1	1	1	1	0	0
'82 Citation	FI, DED, M85–M90	1	1	1	1	1	0	1	0	0
'84 Citation	CARB, DED, M0–M88	5	0	0	0	5	0	5	0	0
'78 Pinto	CARB, DED, M100	3	3	3	3	3	3	0	0	1
'86 Crown Victoria	FI, DED, M85	5	5	5	5	5	3	5	4	3
'87 Regal	FI, DED, M85	2	2	0	2	2	0	2	2	0
'86 S-10	FI, DED, M85	2	2	2	2	2	0	2	2	0
GM Prototype	FI, FFV, M0–100	3	0	0	2	3	3	3	3	0
'81 Escort	CARB, DED, M85–100	4	4	4	2	4	3	4	0	1
'83 Escort	FI, DED, M85–M90	3	3	3	3	3	3	3	3	3
'83 Escort	CARB, DED, M85–M100	11	9	8	9	11	10	11	2	5
'84 Escort	FI, DED, M100	1	1	1	1	1	1	1	0	1
'85 Escort	FI, DED, M0–M100	2	0 ^b	2	0	2	2	2	2	0
Totals		69	54	50	54	69	54	62	36	31

Note: FI = fuel injected; CARB = carbureted; FFV = flexible-fuel vehicle; DED = dedicated-fuel vehicle.

^aRequires at least one measurement of emissions above 2500 miles.

^bOne Crown Victoria and two Escorts reported catalysts aged on a dynamometer (that is, the mileage listed is for the emissions system, not for the vehicle operated on the road).

a. At a minimum, CO, NO_x, and HCHO were measured for a vehicle more than once. This ensured that the data were not "tuned" to minimize one emission at the expense of another. It also provided a complete and uniform data base. As a result, different emissions for the same vehicle could be compared.

b. The vehicles were tested in their normal emission control configurations. This eliminated measurements taken with emission control equipment disconnected. Such measurements often yielded data outliers, which did not reflect on-the-road performance.

c. To allow for catalyst stabilization, at least one set of emissions data was recorded with mileage greater than 2500.

d. Either M85 or M100 was used as the test fuel. M25 and M50 are not relevant alternatives to gasoline, and fuels like M90 and M95 are not quite the same as M85 and M100. Thus, tests of M90 and M95 cannot be aggregated with tests of M85 and M100.

These rules provided a basis for the graphic depiction of emissions trends as a function of vintage, fuel, and mileage. In addition, the second screening process encouraged examining the emissions performance of individual vehicles, many of which—as it turned out—were equipped with recent-technology engines and emission control systems. The performance of such vehicles, in particular, may help indicate the future emissions potential of methanol vehicles. As shown below, screens of the type proposed above do not materially affect the distribution of emissions and do not bias the conclusions that can be derived from the more restricted data subset.

Following the criteria above, complete exhaust emissions data were available for 31 vehicles (see Table 2). Fifteen of the 69 vehicles in the exhaust emissions data base did not have odometer information. Four more sets of emissions

data were discarded because they included no measurement above 2500 miles. Moreover, although all 69 vehicles were tested for CO and NO_x, only 62 were tested for methanol or total hydrocarbons, and only 54 were tested for formaldehyde. (As discussed in Section 3, the measurement of total hydrocarbons was confounded by measurement problems.) Finally, only 54 of 69 vehicles were tested on either M85 or M100. Simultaneous application of the four criteria accounts for substantial attrition of usable observations.

Only one complete data set existed for the latest generation of vehicles that were operated on pure methanol (M100), and this was not a vehicle that had been used in ordinary service.

The odometer information collected presented some special challenges in tabulating the data for graphic presentation. Logistical difficulties associated with vehicle availability, procurement, operation, and maintenance rarely allow emissions testing to be performed at fixed mileage intervals. To introduce a degree of clarity in the data presented in the figures accompanying the text and to eliminate overrepresentation of measurements at low mileage, arithmetic averages were calculated for all emissions tests on a single vehicle within a fixed mileage interval. For example, all emissions tests recorded on a given vehicle with less than 2500 accumulated miles were averaged, and the result was plotted at the zero-mile level. All tests between 2500 miles and 7500 miles were averaged and plotted at the midpoint of the range, the 5000-mile interval. This procedure was followed for the remaining data that fell within each successive 5000-mile increment. Without this averaging, graphs of emissions trends would look like Figure 1, in contrast with the subsequent figures.

Unadjusted data not subject to this simplifying step are presented in Appendixes A and B.

SECTION 3—MEASURING METHANOL VEHICLE EMISSIONS

For a number of reasons, measuring emissions from methanol vehicles is different and more challenging than measuring emissions from gasoline vehicles:

a. The chemical composition of methanol vehicle exhaust organics is fundamentally different from that of exhaust organics in gasoline vehicle emissions. Methanol vehicle exhaust, unlike gasoline vehicle exhaust, contains significant amounts of oxygenated compounds, primarily methanol and formaldehyde. Because EPA believes that photochemical processes are carbon dependent, it has chosen to compare methanol and gasoline vehicle emissions by calculating a "hydrocarbon equivalent" for methanol organic emissions, in which the mass of oxygen is excluded for purposes of meeting the emission standard (*Federal Register*, 1989). Also, when flame ionization detection (FID)—the traditional

method of measurement—is used, data are often adjusted to offset the insensitivity of the technique to methanol and formaldehyde. Some laboratories have used gas chromatographic and high-pressure liquid chromatographic techniques to measure methanol and formaldehyde more accurately.

b. Methanol emission test samples contain a high percentage of water vapor. If emission vapors condense, not all the emissions can be measured.

c. Methanol emission samples are more unstable, especially when sample lines are heated to reduce condensation, and degraded samples give false measurements.

d. Taking a single sample for measuring formaldehyde over the three-phase FTP provides a result that is different from what would be obtained by taking a sample during each phase of the FTP.

Organic Material Hydrocarbon—Equivalent (OMHCE) Emissions

To adjust for the contribution that oxygen makes to the mass emission rates of formaldehyde and methanol, EPA has developed an organic carbon exhaust standard for methanol vehicles, computed as follows (all emissions measured in grams per mile):

$$\text{OMHCE} = \text{HC} + (13.876/32.042)(\text{MeOH}) + (13.876/30.026)(\text{HCHO})$$

The denominators of the coefficients are the molecular weights for methanol and formaldehyde, respectively. The numerators of the coefficients represent the molecular weight of the reference hydrocarbon fuel (carbon:hydrogen ratio of 1:1.85). The equation removes the contribution of oxygen and relates total organic emissions on a carbon basis. This allows total organic emissions from methanol-fueled vehicles to be compared with those from conventionally fueled cars on a carbon-equivalent basis.

Flame Ionization Detection

Until recently, there have been no standardized procedures for testing and evaluating emissions from methanol-fueled vehicles. Consequently, researchers in government, academia, and industry have adopted a variety of techniques for collecting, measuring, and reporting methanol vehicle emissions.

For years, FID was used to measure hydrocarbon emissions from both methanol and gasoline vehicles. However, FID has low sensitivity to oxygenated compounds in methanol emissions, and researchers have had to compensate for this insensitivity. Compensation is complicated because the correct adjustment depends on the levels of both methanol and formaldehyde in the sample.

Recently, a better test standard has been used. Methanol and formaldehyde are separated from vehicle emissions and measured independently by chromatographic and spectrophotometric analysis. Although this procedure is a major improvement, measurement error and bias have not been eliminated.

Measurement Bias

A paper by Horn and Hoekman (1989) concludes that use of the current EPA- and CARB-specified test procedures for methanol vehicles likely results in an underestimation of organic emissions for fuels containing methanol. This is because methanol exhaust emissions contain a high percentage of water vapor. Emission samples tend to condense and cannot be measured. This is not generally a factor in tests of conventionally fueled vehicles, where water vapor content is much lower.

It is difficult to assess the degree to which measurement bias is controlled, even for recent studies using chromatographic methods. Horn and Hoekman also compare the effects of obtaining samples in bags with those of acquiring samples continuously. The results for methanol indicate an increase of about 25 percent for continuous measurements, compared with bagged samples above 300 parts per million (0.03 percent). This result may be due to the condensation of samples on the walls of the sample bags or to the migration of methanol to the sampling bags' walls. Methanol condensation on the trap inlets of impingers is termed "significant," although no quantitative estimate of possible sample loss is given.

Carryover effects are reduced by the heating of the sample system. For formaldehyde, this error is reduced from 26 percent to less than 4 percent at a test temperature of 45°F and from 5 percent to less than 1 percent at a test temperature of 75°F. Stability of methanol samples appears to be sample dependent. Results ranged from excellent stability to complete loss of the sample over a period of 40 days. Degradation may be most severe at low methanol concentrations.

According to CARB, measurements of aldehyde emissions from reference methanol vehicles may vary by as much as 20 percent, depending on the number of samples collected during the FTP. Before June 1988, CARB measurements were based on single samples being taken during the FTP. However, taking samples during each phase of the FTP allows one to weight aldehyde emissions data in the same way the other exhaust emissions are weighted. In June 1988, CARB changed the formaldehyde procedure to require the taking of three samples, which matches the procedure used by EPA. CARB estimates that the current procedure gives results that are about 20 percent lower than those obtained using the former procedure.

SECTION 4—METHANOL EMISSIONS TRENDS

This section provides a more detailed analysis of methanol emissions and is divided into five parts. The first part looks at all of the exhaust data with odometer readings. The second part describes the vehicle technology classes represented within the restricted data subsets. The third part then analyzes the restricted data subsets (by vehicle classes, fuel,

and so forth). The fourth part looks at subsidiary engineering data, including recent research involving prototype vehicles, advanced catalysts, and emissions measurements taken under non-FTP conditions. The fifth part looks at the evaporative emissions data.

Analysis of All Emissions Data With Odometer Readings

All of the emissions data associated with odometer readings were analyzed. The analysis included data for 54 of the 69 vehicles tested in the studies. As described above, for purposes of analysis and graphic display, the data were converted to average emissions levels per vehicle for each major mileage category (0, 5000, 10,000, and so on). Thus, if a vehicle had more than one emissions level observation within an interval of 5000 miles, those levels were averaged.

The data unaccompanied by odometer readings were not analyzed because, as discussed, these observations could not be compared in any meaningful way with measurements associated with odometer readings. Further, the significance of the observations lacking odometer readings is highly uncertain. Vehicles without odometer readings were often part of an engineering test program and were not operated under on-the-road conditions.

The data analyzed were considered first as a function of vehicle vintage—1981–1985 or 1986–1988 model cars—and second as a function of fuel type—M85 or M100. Four frequency distribution tables were created for each emission type—formaldehyde (HCHO), nitrogen oxides (NO_x), carbon monoxide (CO), and organics (OMHCE)—showing the impact of the two vehicle vintages and the two fuel categories on emissions levels over 5000-mile intervals. (These tables are not included.) The tabular data are summarized in Figures 2–9, which show the relative frequency of various emission levels. Because mileage varies in the data presented in these bar graphs, it is not always clear whether observed differences by vintage or fuel are partly due to the association of higher mileage with higher emissions. Only a few of

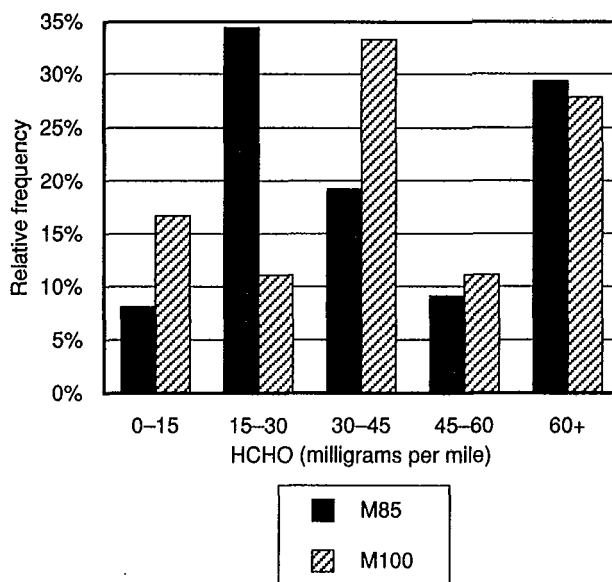


Figure 3—Formaldehyde Emissions: M85 vs. M100

the data were recorded at high mileages. To examine the overall impact of mileage, the emissions performance for each of the four emissions components of all the vehicles (without respect to vintage or fuel) was averaged as a function of mileage. This analysis is presented in Table 3.

Vehicle vintage is important because newer vehicles tend to have emission control systems that use more advanced technology. These vehicles should therefore tend to have lower emissions. However, most of the data for the newer vehicles are for low mileage, so it is difficult to separate the effects of technology and mileage, as discussed below. Fuel type is also important because different fuels have different emission characteristics. Emission levels on M85 and M100 fuels were analyzed because proposals to substitute methanol for gasoline vehicles focus on these fuels.

Analyzing the data according to these two basic variables and with respect to mileage provided basic information about methanol emissions, but it also raised questions about interpretation of the results. One problem arose from the correlation of vehicle vintage and mileage. Both affect emissions. As shown by the mileage distribution in Figure 10, the data are concentrated at low mileages. In addition, the emissions measurements for newer vehicles are concentrated at lower mileages, whereas the opposite is true for older vehicles. The tests at mileages greater than 40,000 miles were all performed on 1981–1985 vehicles. When we compare emissions as a function of vintage, we are really observing vintage effects and high-mileage/high-emissions effects together. Another problem arose in part from comparisons and implicit aggregation across dissimilar models of vehicles. The analysis of the first-level screen, which used data with odometer readings for each emissions type, follows.

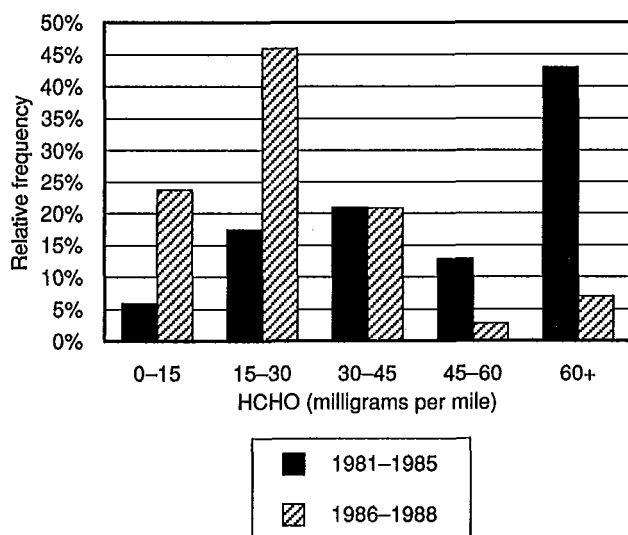


Figure 2—Formaldehyde Emissions: 1981–1985 vs. 1986–1988 Models

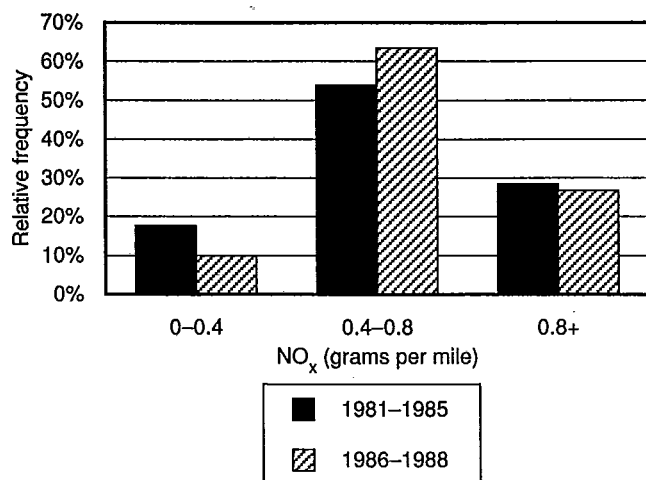


Figure 4—NO_x Emissions:
1981-1985 vs. 1986-1988 Models

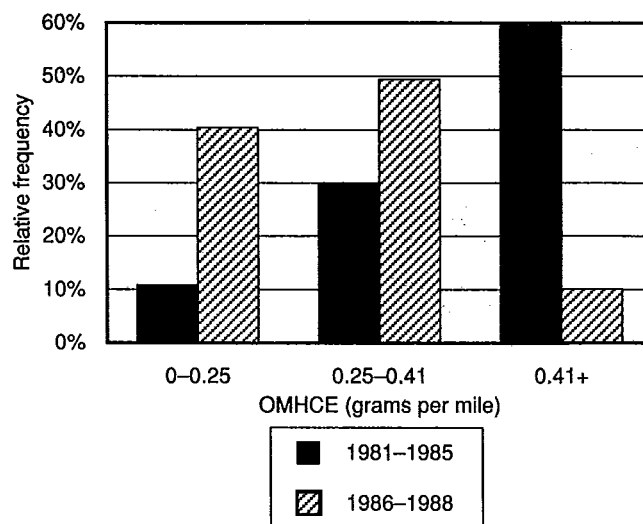


Figure 6—OMHCE Emissions:
1981-1985 vs. 1986-1988 Models

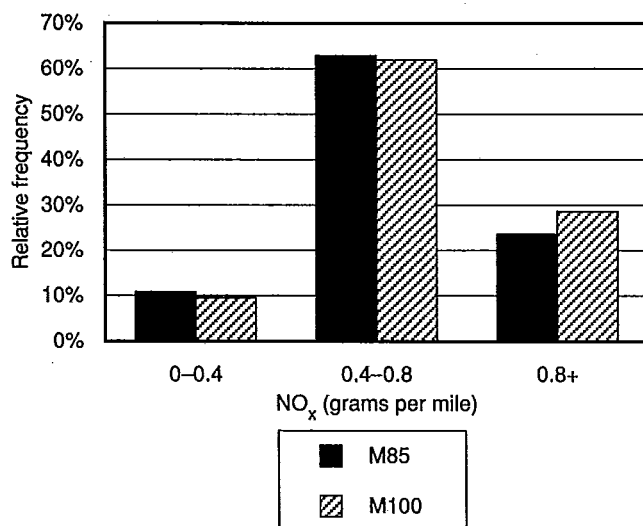


Figure 5—NO_x Emissions: M85 vs. M100

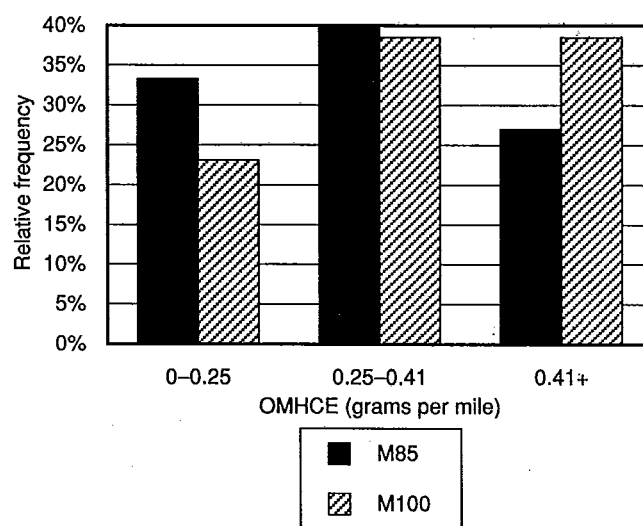


Figure 7—OMHCE Emissions: M85 vs. M100

FORMALDEHYDE

The average formaldehyde emissions level for all vehicles through the 5000-mile interval was nearly triple the new 50,000-mile California formaldehyde standard of 15 milligrams per mile, and the average level increased to three to four times the standard at higher mileages (see Table 3).¹ In general, both older and newer cars operating on either fuel had difficulty meeting the California standard (see Figures 2 and 3).

Newer cars registered formaldehyde levels that met the new 50,000-mile standard of 15 milligrams per mile less

than 24 percent of the time (see Figure 2). Older cars were able to meet this emissions level less than 6 percent of the time, exceeding 60 milligrams per mile more than 40 percent of the time (see Figure 2). As noted above, some of this effect may be caused by the concentration of higher mileage (thus, higher emitting) vehicles in the older car class. At low mileages, formaldehyde emissions from M100 vehicles were lower than the standard more often than formaldehyde emissions from M85 vehicles, but M100 vehicles still only met the standard about 17 percent of the time. The number of instances in which the California standard was exceeded was substantial for all categories, with many exceedances at levels four times the standard or higher.

¹Some of these data were gathered using the old formaldehyde procedure, which CARB believes gives results that could be overstated by 20 percent.

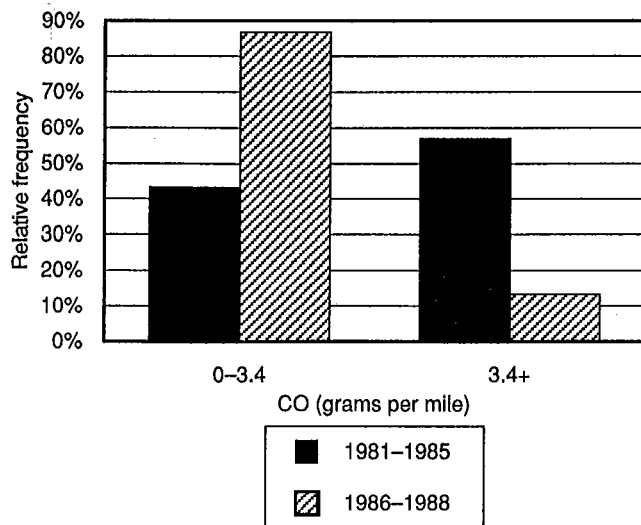


Figure 8—CO Emissions:
1981-1985 vs. 1986-1988 Models

NITROGEN OXIDES

On average, at all mileage intervals, the test cars met the 50,000-mile federal NO_x standard of 1.0 gram per mile but not the California standard of 0.40 gram per mile (see Table 3). Older cars met the California NO_x standard level only about 18 percent of the time (see Figure 4). The newer cars showed about the same NO_x performance as the older vehicles, with emissions below the 0.40-gram-per-mile level only 10 percent of the time (see Figure 4). However, not all of the vehicles (new or old) were designed to meet a standard of 0.40 gram per mile.

As shown in Figure 5, M100 vehicles performed no better than did M85 vehicles in meeting the tighter California NO_x standard. In fact, the NO_x emissions performance of cars operating on M100 was essentially identical to that of cars operating on M85.

ORGANICS (OMHCE)

For all cars, the average level of organic emissions was less than the 50,000-mile federal standard of 0.41 gram per mile only through 15,000 miles and then rose slightly above it at the 20,000- and 25,000-mile intervals (see Table 3). A significant increase to more than double the standard level at 30,000 miles and above can be accounted for by two outlier observations that appreciably affected the averages. (Without these outlier measurements, average OMHCE emissions at 30,000 or more miles would be similar to the averages at lower mileages.)

The newer cars, tested only to about 25,000 miles, met the 50,000-mile federal OMHCE standard about 90 percent of the time (see Figure 6). About 40 percent of the time they met the tighter California standard level of 0.25 gram per

mile, which takes effect in 1993. Almost 60 percent of the time the older cars did not meet the 50,000-mile federal standard (see Figure 6). Again, this result may be partly attributable to the higher mileages accumulated by older, compared with newer, vehicles.

The performance of cars operating on M85 and M100 was similar (see Figure 7). However, M85 vehicles had organic emissions less than the 50,000-mile California standard level 33 percent of the time, but M100 vehicles (which included more older than newer vehicles tested on the fuel) had lower emissions only 23 percent of the time.

CARBON MONOXIDE

The average CO level for all cars was below the 50,000-mile federal standard of 3.4 grams per mile through the 25,000-mile interval and then jumped more than 2.0 grams per mile above it at 30,000 miles and above (see Table 3). Newer cars met the 50,000-mile federal standard level 87 percent of the time—twice as frequently as did the older cars (see Figure 8). A greater proportion of lower mileage readings in new cars probably accounts for part of this difference. There was almost no difference in the performance of M100 and M85 vehicles (see Figure 9). Both met the federal standard about two-thirds of the time.

Classes of Vehicles Providing Data for Analysis

The 31 vehicles whose emissions data satisfied all of the data criteria can be grouped in several general classes. The idea was to group models using similar technology and to separate models using different technologies or different fuels. This reduces the scatter of emissions as a function of mileage and clarifies differences in performance for different

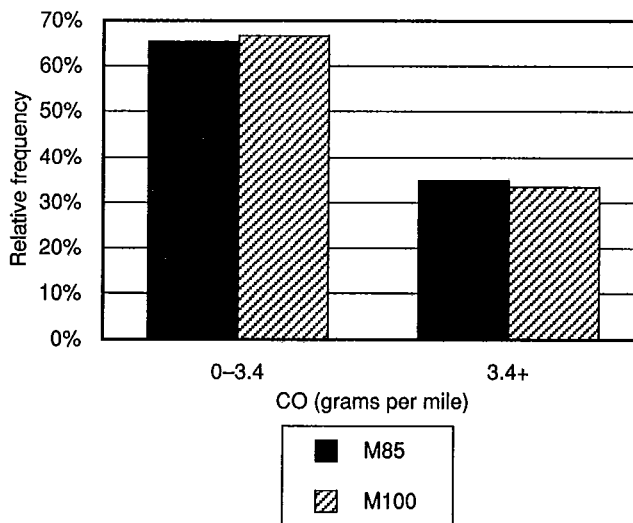


Figure 9—CO Emissions: M85 vs. M100

Table 3—Mileage Dependence of Emissions

Compound	Emissions (grams per mile)			
	0–5000 Miles	10,000–15,000 Miles	20,000–25,000 Miles	≥30,000 Miles
CO	3.05	3.17	3.41	5.92
NO _x	0.63	0.68	0.74	0.77
OMHCE	0.35	0.36	0.43	1.0 ^a
HCHO	0.042	0.045	0.057	0.062

^aStrongly influenced by two outliers.

kinds of methanol vehicles. These vehicle classes are described below.

DEDICATED M85 VEHICLES (OLDER U.S. AUTO MANUFACTURER TECHNOLOGY)

The dedicated M85 vehicles that used older U.S. auto manufacturer technology included eight model-year (MY) 1983 Ford Escorts, all designed to meet California exhaust emissions certification passenger car standards of 0.41 gram per mile HC, 7.0 grams per mile CO, and 0.4 gram per mile NO_x at 50,000 miles. Three MY 1981 Escorts were not included because they were operated on M90 or M95 fuels.

The eight MY 1983 1.6-liter Escorts included three that were equipped with multipoint electronic fuel injection, had increased compression ratios, and used a three-way closed-loop catalyst system with exhaust gas recirculation (EGR) and air injection. The five carbureted MY 1983 Escorts also used a three-way catalyst system, EGR, and air injection but no feedback.² The MY 1983 Escorts had been operated pri-

marily on M85, accumulating up to about 45,000 miles in California state government fleet service.

DEDICATED M85 VEHICLES (OLDER FOREIGN AUTO MANUFACTURER TECHNOLOGY)

The dedicated M85 vehicles that used older foreign auto manufacturer technology included two MY 1981 1.6-liter VW Rabbits designed to meet California certification standards of 0.41 gram per mile HC, 7.0 grams per mile CO, and 0.4 gram per mile NO_x. The Rabbits used multipoint fuel injection with high compression ratios, three-way catalysts, and closed-loop fuel control. They had been operated on fuels ranging from M95 to M85 in California state government fleet service, with one vehicle accumulating 70,000 miles.

DEDICATED M85 VEHICLES (RECENT U.S. AUTO MANUFACTURER TECHNOLOGY)

The dedicated M85 vehicles that used recent U.S. auto manufacturer technology included three MY 1986 Ford Crown Victorias and one MY 1988 GM Corsica. The three Crown Victorias were gasoline-fueled vehicles converted for

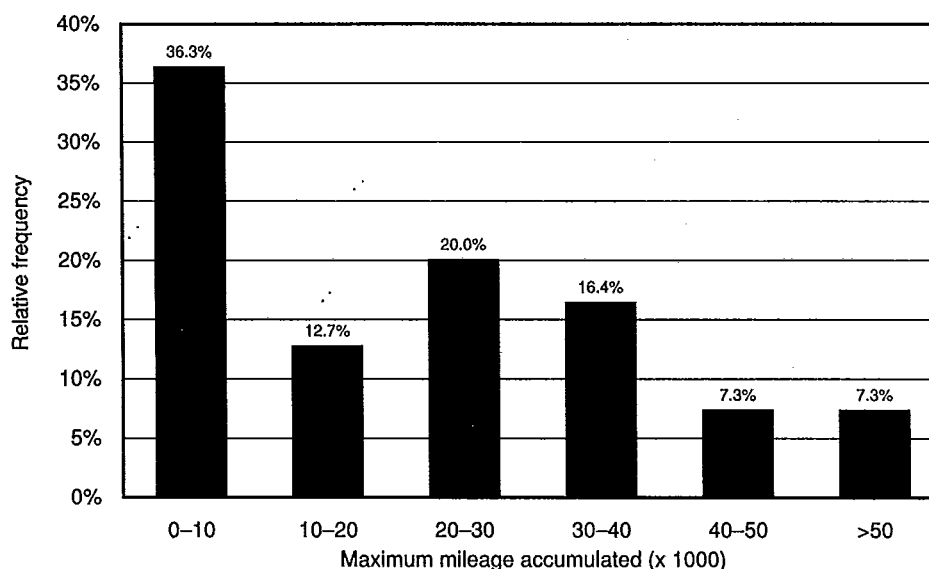


Figure 10—Distribution of Maximum Mileage Accumulated

operation on M85. They were equipped with 5.0-liter feedback-controlled sequentially fuel-injected V-8 engines with modified compression ratios. The MY 1988 GM Corsica was equipped with a 2.8-liter gasoline engine modified for operation on M85 only (by increasing the compression ratio, reprogramming for lean operation, and modifying the camshaft). These four vehicles had accumulated 5000–30,000 miles of service.

DEDICATED M85 VEHICLES (RECENT FOREIGN AUTO MANUFACTURER TECHNOLOGY)

The dedicated M85 vehicles that used recent foreign auto manufacturer technology included three Toyotas for which sufficient odometer information was available: a MY 1985 Camry, a MY 1986 Camry, a MY 1986 Carina, and one MY 1986 Nissan Sentra. The two Camrys were both equipped with 2.0-liter engines and employed EGR, lean air–fuel ratio control (under some operating conditions), multipoint electronic fuel injection, high compression ratios, and three-way catalysts with closed-loop fuel control systems. Mileage accumulation on the Camrys ranged from 22,000 to 44,000 miles.

The MY 1986 Carina used a 2.0-liter engine, close-coupled catalyst, sequential electronic fuel injection, and high compression ratio and was designed for full-time lean operation to improve fuel economy. This vehicle had accumulated 26,000 miles in California state government fleet service.

DEDICATED M100 VEHICLES

The dedicated M100 vehicles included three older Ford vehicles—a MY 1981 Escort, a MY 1984 Escort, and a MY 1978 Pinto—and one second generation vehicle, a MY 1986 Toyota Carina. The exhaust emissions data base tabulated in Appendix A contains information on 11 non-flexible-fueled vehicles tested on M100. The data available on these vehicles

are summarized in Table 4. As shown in the table, no emissions data are available on dedicated M100 vehicles at high mileage (that is, above 13,000 miles). In fact, only one dedicated M100 vehicle—the 1986 Toyota Carina—met the criteria for analysis by providing a complete spectrum of emissions (CO, NO_x, formaldehyde, methanol, total organics) data at several mileage increments up to 10,000 miles. Also, some of the tested vehicles ran very poorly. To date, there are no utilitarian vehicles in use dedicated for operation on M100.

FLEXIBLE-FUEL VEHICLES

Emissions data were analyzed for eight FFVs—MY 1987 Ford Crown Victorias—and one variable-fuel vehicle (VFFV)—a MY 1988 GM Corsica. Seven of the Crown Victorias were being operated in fleet service for state and local government agencies in California. The remaining one was operated by Ford Motor Company. All of the Crown Victorias were equipped with 5.0-liter V-8 engines with closed-loop controlled sequential port fuel injection. Emission controls included four three-way catalysts, air injection, and EGR. The seven California-based Crown Victorias were designed to meet California's emission standards of 0.41 gram per mile HC and 7.0 grams per mile CO and a NO_x emission level of 0.7 gram per mile. These vehicles had been operated on gasoline, methanol, ethanol, and combinations of these fuels. (Emission tests on ethanol blends are neither reported nor analyzed in this paper.) Most of the testing on these vehicles has focused on M85.

The variable-fuel Corsica was equipped with a 2.8-liter V-6 engine with sequential fuel injection, a three-way catalyst system, and EGR. It was operated by CARB in fleet service and was designed to meet California's emission standards of 0.41 gram per mile HC, 7.0 grams per mile CO, and 0.4 gram per mile NO_x using any mixture of gasoline and methanol.

Table 4—Dedicated M100 Vehicles

Model	Odometer Range	Emissions Data Recorded for				
		CO	NO _x	HCHO	MeOH	OMHCE
'84 Ford Escort ^a	8500–8600	Y	Y	Y	Y	Y
GM Prototype	NA	Y	Y	Y	N	N
'83 Ford Escort ^b	NA	Y	Y	Y	Y	Y
'81 Ford Escort ^b	6000–7000	Y	Y	Y	Y	N
'81 VW Rabbit ^a	1700–2400	Y	Y	Y	Y	N
'81 Nissan 200 SX ^a	1500–1600	Y	Y	N	N	N
'78 Ford Pinto	1250–10,000	Y	Y	Y	N	N
'83 Ford Escort ^b	700–1000	Y	Y	Y	N	N
'80 Ford Escort ^b	400–13,000	Y	Y	N	N	N
'87 Nissan Sentra ^a	NA	Y	Y	Y	Y	N
'86 Toyota Carina ^a	1500–10,000	Y	Y	Y	Y	Y

^aFuel injected.

^bCarbureted.

Emissions Trends From Restricted Data

More detailed analysis of the narrower subset of complete data (developed as a result of the second-level screening) provides insight into the performance of the specific methanol-fueled vehicles described above.

Before performing this analysis, however, we checked the validity of narrower subsets of the data in general by comparing distributionally the larger data set (all observations with mileage readings) with a second restricted subset of data (emission results for M85 and M100 fuels only). The second restricted subset of the data is close but not identical to the data base resulting from screening with the four criteria described above. The comparison of the large and small data bases is shown in Figures 11–14. The similar frequency distributions shown in these figures suggest that the more restrictive screening process did not introduce biases into our analysis.

Our analysis of the emissions from the 31 vehicles selected by the second-level screening is as follows.

FORMALDEHYDE EMISSIONS (SEE FIGURES 15–22)

Current-generation FFVs and dedicated M85 and M100 vehicles generally exceeded the 50,000-mile California tailpipe formaldehyde emissions standard level of 15 milligrams per mile (there is no federal standard), as shown in Figures 18–22. The exceptions were one dedicated M100 vehicle—a 1986 Toyota Carina shown in Figure 20³—and

³The reader is advised to look at the averages (denoted by solid lines) shown in the figures to gain an overall impression of emissions. At times the data are sparse, so the average tracks the data for only one vehicle as mileage accumulates. Obviously, such an average may not reflect a general trend. Figures 20, 28, and 36 each contain two lines, one for the average of the older Ford vehicles and one for the second-generation 1986 Toyota Carina.

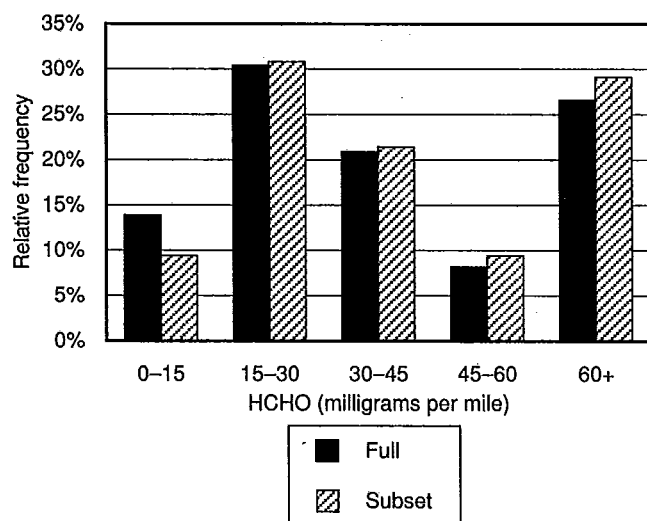


Figure 11—Formaldehyde Emissions:
Full vs. Subset Data

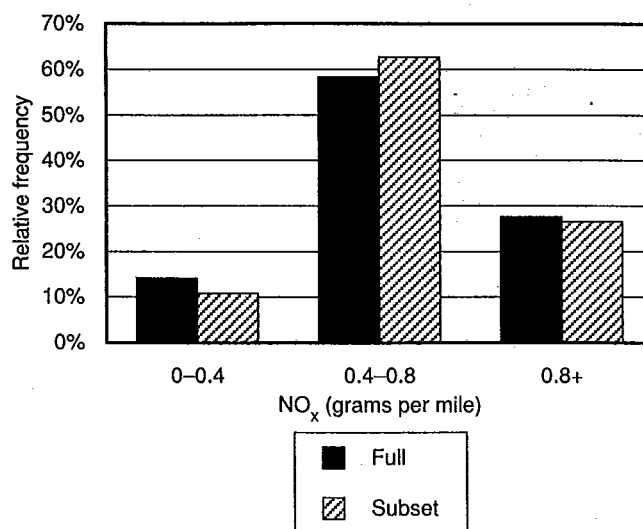


Figure 12—NO_x Emissions: Full vs. Subset Data

one dedicated M85 vehicle—a different 1986 Toyota Carina shown in Figure 19. The dedicated M100 Toyota, an experimental vehicle, consistently tested below the 50,000-mile California standard of 15 milligrams per mile. However, this vehicle accumulated only 10,000 miles and did not meet the NO_x standard of 0.4 gram per mile. In some tests, it exceeded an NO_x level of 1.0 gram per mile. The dedicated M85 Toyota also tested below the California formaldehyde standard up to 10,000 miles but then exceeded it at 20,000 and 25,000 miles. Like the M100 Toyota, this was a lean-burn vehicle and did not meet the California NO_x limits. Reducing catalysts do not function when the engine operates at a lean air-fuel ratio.

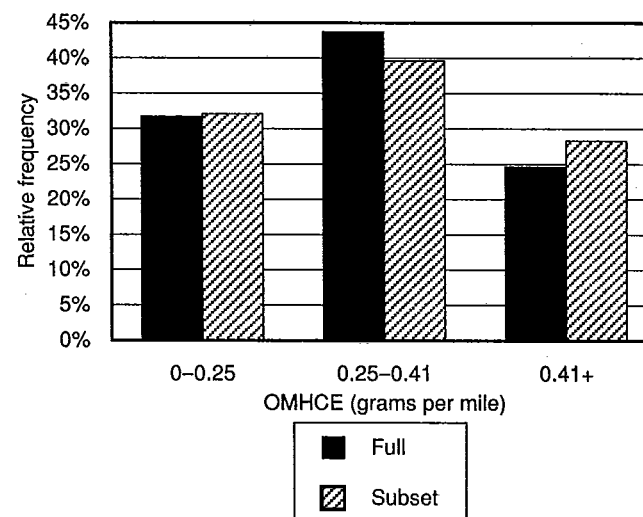


Figure 13—OMHCE Emissions: Full vs. Subset Data

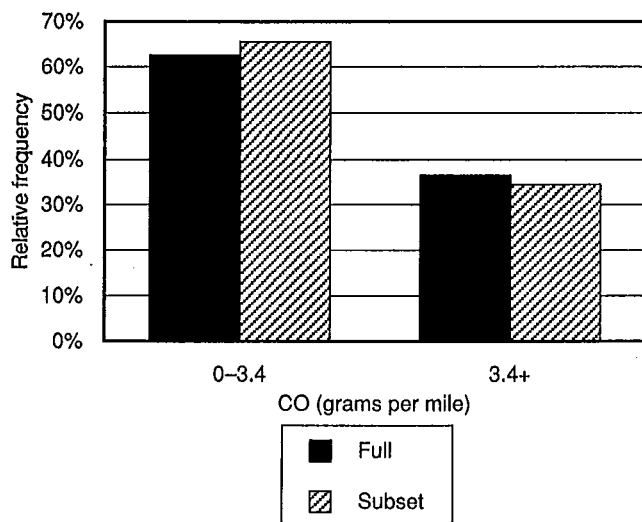


Figure 14—CO Emissions: Full vs. Subset Data

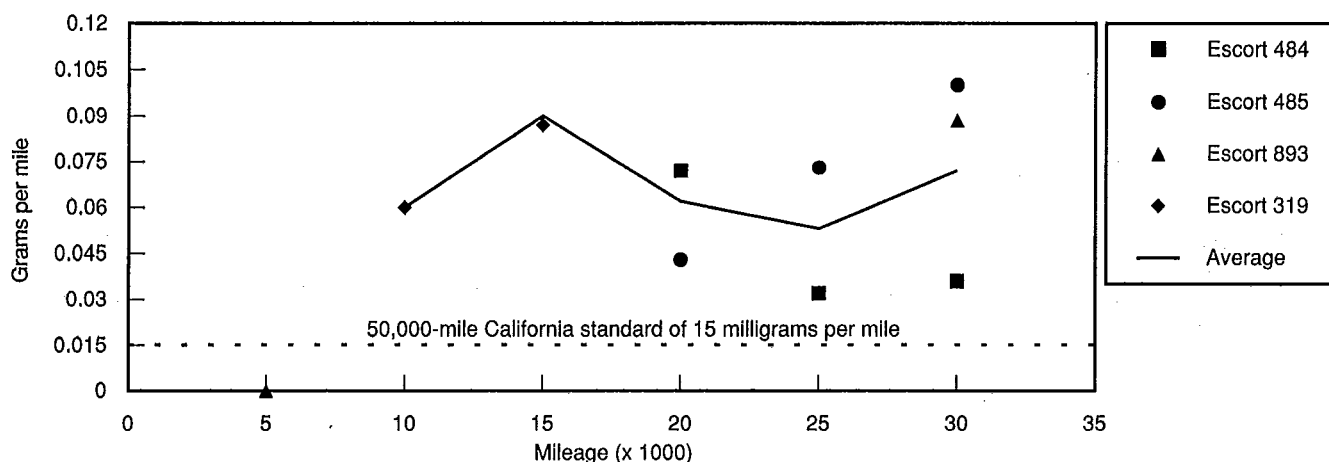
The newer vehicles (see Figures 18–20) had considerably improved formaldehyde emissions performance, compared with the older carbureted and fuel-injected Ford Escorts (see Figures 15 and 16), including two dedicated M100 vehicles (see Figure 20), and the older fuel-injected VW Rabbits (see Figure 17). Whereas the older vehicles frequently emitted five and six times what the California standard permits, the newer vehicles emitted no more than three times that amount. Note, however, that formaldehyde emissions were tested in the older cars at mileages that were generally much higher. The superiority of the newer vehicles supports the

same earlier finding based on analysis of all of the data for which odometer readings were available.

NITROGEN OXIDE EMISSIONS (SEE FIGURES 23–30)

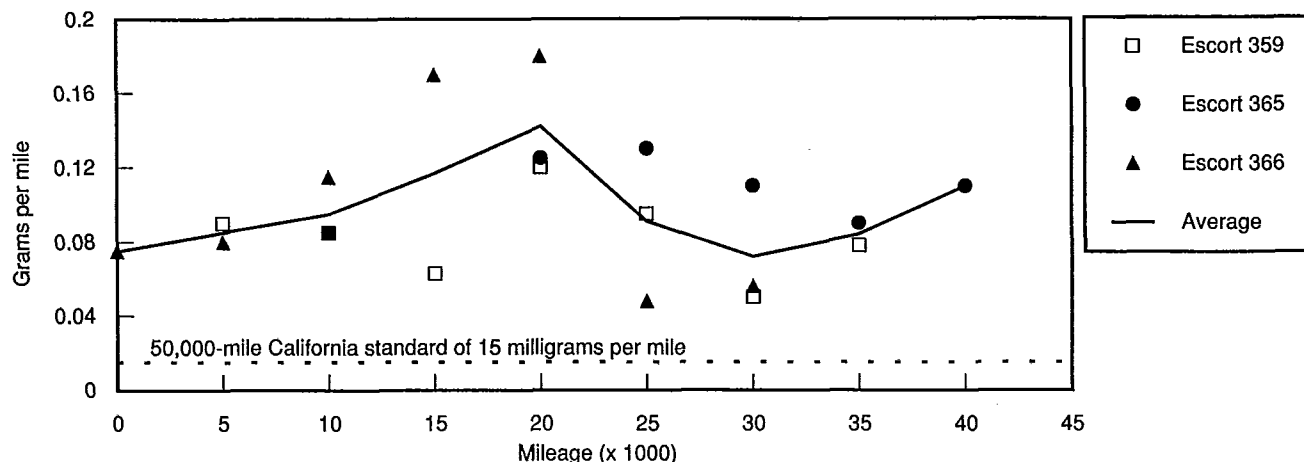
Most vehicles tested below the 50,000-mile federal NO_x standard of 1.0 gram per mile most of the time but did not meet the new 50,000-mile California standard of 0.4 gram per mile, which will be fully implemented in 1994. The more stringent standard was met infrequently by a few cars. These included carbureted and fuel-injected Ford Escorts (primarily at low mileage and with new catalytic converters), two dedicated M85 Crown Victorias, and a flexible-fuel Chevrolet Corsica that was designed to meet the standard of 0.4 gram per mile (see Figures 24, 26, and 30).

In contrast with formaldehyde emissions performance, newer cars did not perform better than older cars with respect to NO_x control. This finding is consistent with the conclusions in the earlier analysis of the larger group of vehicles. Importantly, a few cars had trouble consistently meeting even the less stringent federal NO_x standard. These included recent-technology dedicated M85 and M100 Toyotas, particularly those with lean air-fuel ratios (see Figures 27 and 28). The two 1986 Toyota Carinas that were almost alone in meeting the California formaldehyde standard (see Figures 19 and 20) were among the vehicles with unacceptable NO_x performance. This is because at lean air-fuel ratios, a reduction catalyst is not effective in controlling NO_x emissions. These data suggest that meeting tighter NO_x emissions may involve sacrificing some of the organic emissions performance described below.



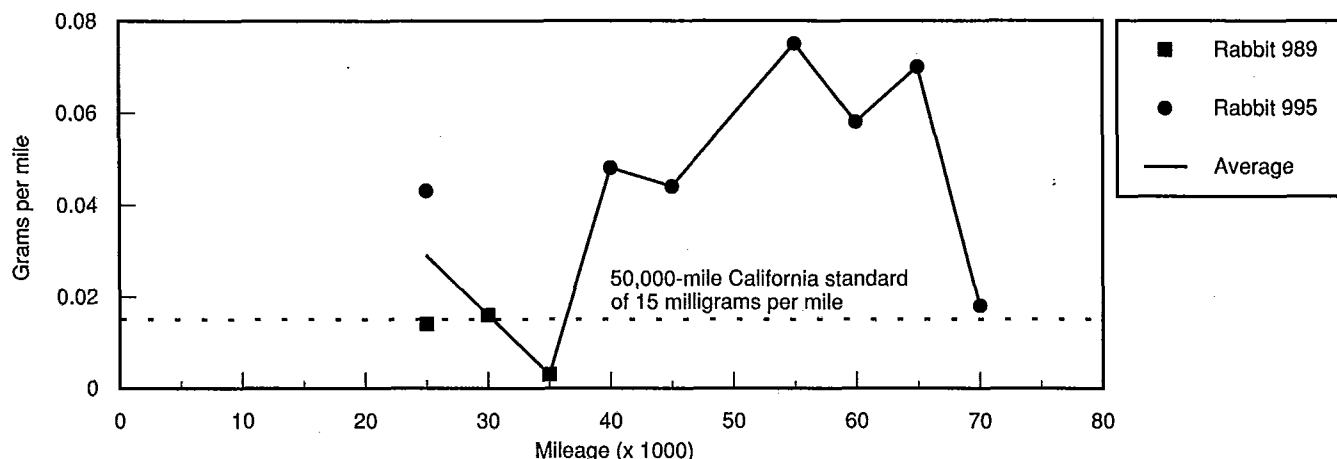
Note: Mileages are adjusted to the nearest 5000-mile interval. The catalysts were changed on Escort 484 at 19,600 miles and on Escort 485 at 18,000 miles. The data in the figure are from the California Air Resources Board (1986; 1988; "Quarterly Summary," 12/88–2/89).

Figure 15—Formaldehyde Emissions: Five 1983 Carbureted Ford Escorts (M85)



Note: Mileages are adjusted to the nearest 5000-mile interval. The catalysts were changed on Escort 359 at 27,000 miles, on Escort 365 at 27,600 miles, and on Escort 366 at 20,100 miles. (See Appendixes A and B for additional maintenance notations.) The data in the figure are from the California Air Resources Board (1988; 1989; "Quarterly Summary," 12/88-2/89).

Figure 16—Formaldehyde Emissions: Three 1983 Fuel-Injected Ford Escorts (M85)



Note: Mileages are adjusted to the nearest 5000-mile interval. The catalyst was changed on Rabbit 995 at 68,000 miles. The data in the figure are from the California Air Resources Board (1988, 1989).

Figure 17—Formaldehyde Emissions: Two 1981 Fuel-Injected Volkswagen Rabbits (M85)

CARBON MONOXIDE EMISSIONS (SEE FIGURES 31–38)

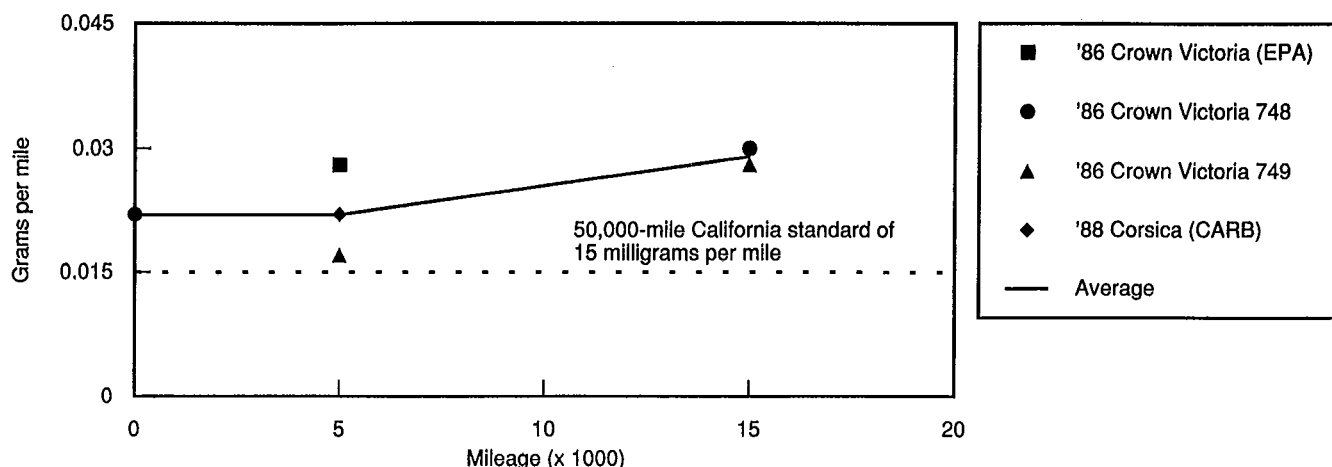
The analysis of the CO data presented graphically essentially parallels the earlier analysis of the distributional data. Average CO emission levels from the newer dedicated M85 and M100 vehicles and FFVs generally fell well below the 50,000-mile federal standard of 3.4 grams per mile (see Figures 34–38). This was a substantial improvement over the performance of the older vehicles, which often exceeded the standard (see Figures 31–33). However, some of the outliers in Figures 31–33 can be explained by equipment malfunction or maladjustment.

Among the newer vehicles, there was little difference in the performance of M100 dedicated, M85 dedicated, and flexible-fuel vehicles (see Figures 34–38).

ORGANIC EMISSIONS (SEE FIGURES 39–45)

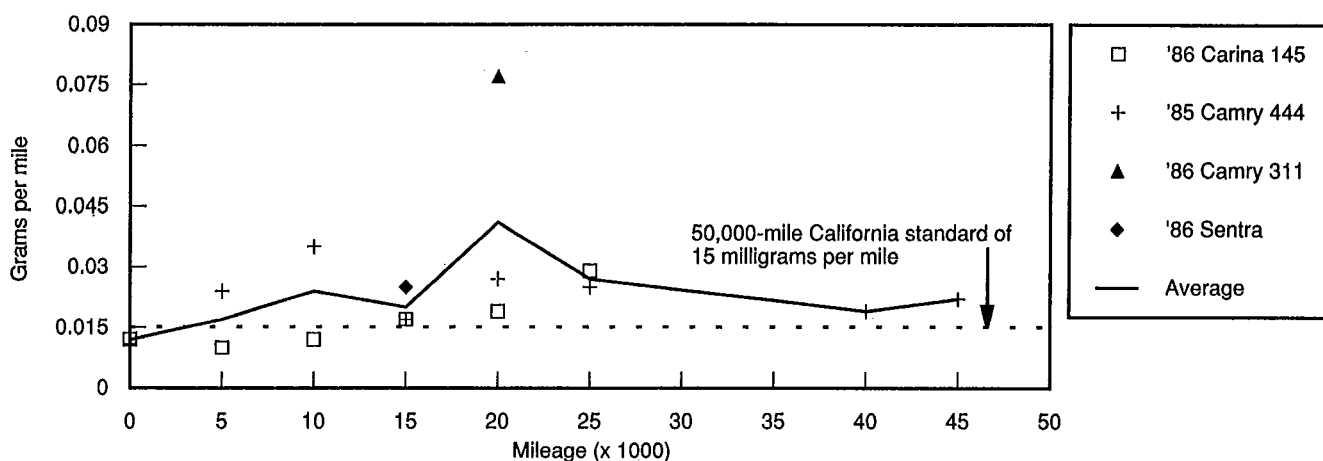
In general, the data for OMHCE emissions are more sparse, with fewer vehicles and fewer data points for a given vehicle. The newer vehicles performed well, with emissions at most mileages less than the 50,000-mile federal hydrocar-

(text continued on page 30)



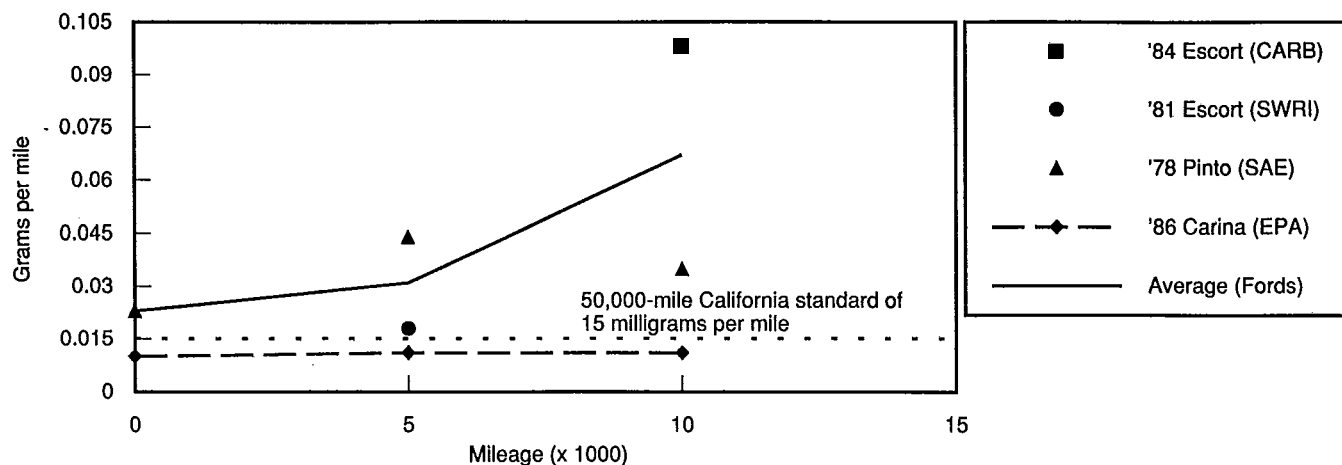
Note: Mileages are adjusted to the nearest 5000-mile interval. The data in the figure are from the California Air Resources Board (1988; 1989; "Quarterly Summary," 12/88-2/89) and Piotrowski et al. (1987).

Figure 18—Formaldehyde Emissions: Four Domestic Dedicated Vehicles (M85)



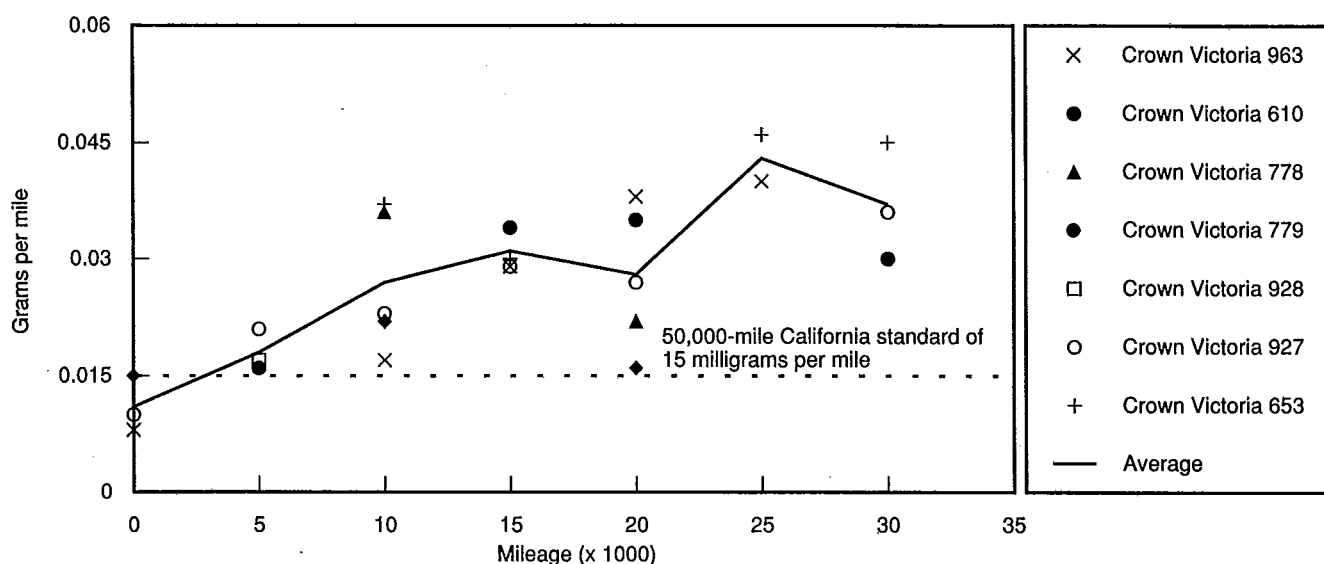
Note: Mileages are adjusted to the nearest 5000-mile interval. The data in the figure are from Blair (1988) and the California Air Resources Board (1988; 1989; "Quarterly Summary," 12/88-2/89).

Figure 19—Formaldehyde Emissions: Four Dedicated Toyotas (M85)



Note: Mileages are adjusted to the nearest 5000-mile interval. The data in the figure are from the California Air Resources Board (1986), Edwards and Baisley (1981), Piotrowski (1987), Piotrowski et al. (1987), Piotrowski and Murrell (1987), and Smith (1985).

Figure 20—Formaldehyde Emissions: Four Dedicated Vehicles (M100)



Note: Mileages are adjusted to the nearest 5000-mile interval. The data in the figure are from the California Air Resources Board (1988; 1989; "Quarterly Summary," 6/88-8/88; "Quarterly Summary," 12/88-2/89) and Horn and Hoekman (1989).

Figure 21—Formaldehyde Emissions: Seven 1987 Ford Crown Victorias (M85 Flexible-Fuel Vehicles)