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Volume III: Comparisons and Future Potential

M. W. Dowdy

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U.S. Department of Energy
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ABSTRACT

The status of five conventional automobile engine technologies is assessed and the future potential for increasing fuel economy and reducing exhaust emissions is discussed, using the 1980 EPA California emissions standards as a comparative basis. By 1986, the fuel economy of a uniform charge Otto engine with a three-way catalyst is expected to increase 10%, while vehicles with lean burn (fast burn) engines should show a 20% fuel economy increase. Although vehicles with stratified-charge engines and rotary engines are expected to improve, their fuel economy will remain inferior to the other engine types. When adequate NO_x emissions control methods are implemented to meet the EPA requirements, vehicles with prechamber diesel engines are expected to yield a fuel economy advantage of about 15%. While successful introduction of direct injection diesel engine technology will provide a fuel savings of 30 to 35%, the planned regulation of exhaust particulates could seriously hinder this technology, because it is expected that only the smallest diesel engine vehicles could meet the proposed particulate requirements.

PREFACE

This report was prepared by the Jet Propulsion Laboratory for the U.S. Department of Energy, Office of Transportation Programs, for the Vehicle Systems Program managed by Albert Chesnes. This work was done at JPL in the Energy and Control Division by the Propulsion System Section as part of Vehicle Systems Tasks managed by Eugene Baughman. Dr. M.W. Dowdy, the author of this volume, is no longer an employee of JPL. He is presently with Mechanical Technology, Incorporated, in Latham, New York.

The work was performed by the Jet Propulsion Laboratory and was sponsored by the U.S. Department of Energy under Interagency Agreements DE-AI01-76CS51011 and DE-AI01-80CS50194 through NASA Task RD 152, Amendment 165.

The purpose of this vehicle systems task was to perform a technical assessment of conventional automotive engine status and report the results. The status of the technology reported is that which was available through April 1981. This volume is part of the final report consisting of three volumes.

Volume I presents the status of Otto cycle engine technologies; Volume II presents the status of Diesel engine technology and Volume III compares these conventional engine types and discusses their future potential.

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SECTION 1

INTRODUCTION

The purpose of this volume of the report is to provide an assessment of the status of conventional engine technology as currently used in the automobile application and to indicate the future potential for increasing fuel economy and reducing exhaust emissions by advancing this technology. This evaluation covers uniform charge Otto engines using three-way catalyst emission control systems, lean burn (fast burn) uniform charge engines using other emissions control technology, stratified charge engines, diesel engines and rotary engines. Current production engines and advanced development activities for each engine type are covered in detail in Volumes I and II of this report. This volume is devoted mainly to a comparison of these five types of conventional engines.

During the last decade, many factors have helped shape the automotive product which is being produced in 1980-81. Among these factors are government regulations to help maintain air quality and encourage energy conservation, fuel availability concerns, and rapidly escalating fuel prices. The general trends in exhaust emissions and fuel economy regulations which have led to changes in automotive technology in recent years are given in Figure 1-1, which shows that significant reductions in gaseous emissions have been achieved, and further fuel economy increases and emissions reductions are required in future years. Of particular interest is the planned regulation of exhaust particulate matter, which could have a serious effect on the future use of diesel engines. Although government policy appears to be shifting away from further regulations of industry, it is expected that present regulations will be implemented, perhaps in a stretched-out time sequence. The fuel economy and emissions requirements in Figure 1-1 will form the basis for the comparisons and projections presented in this report.

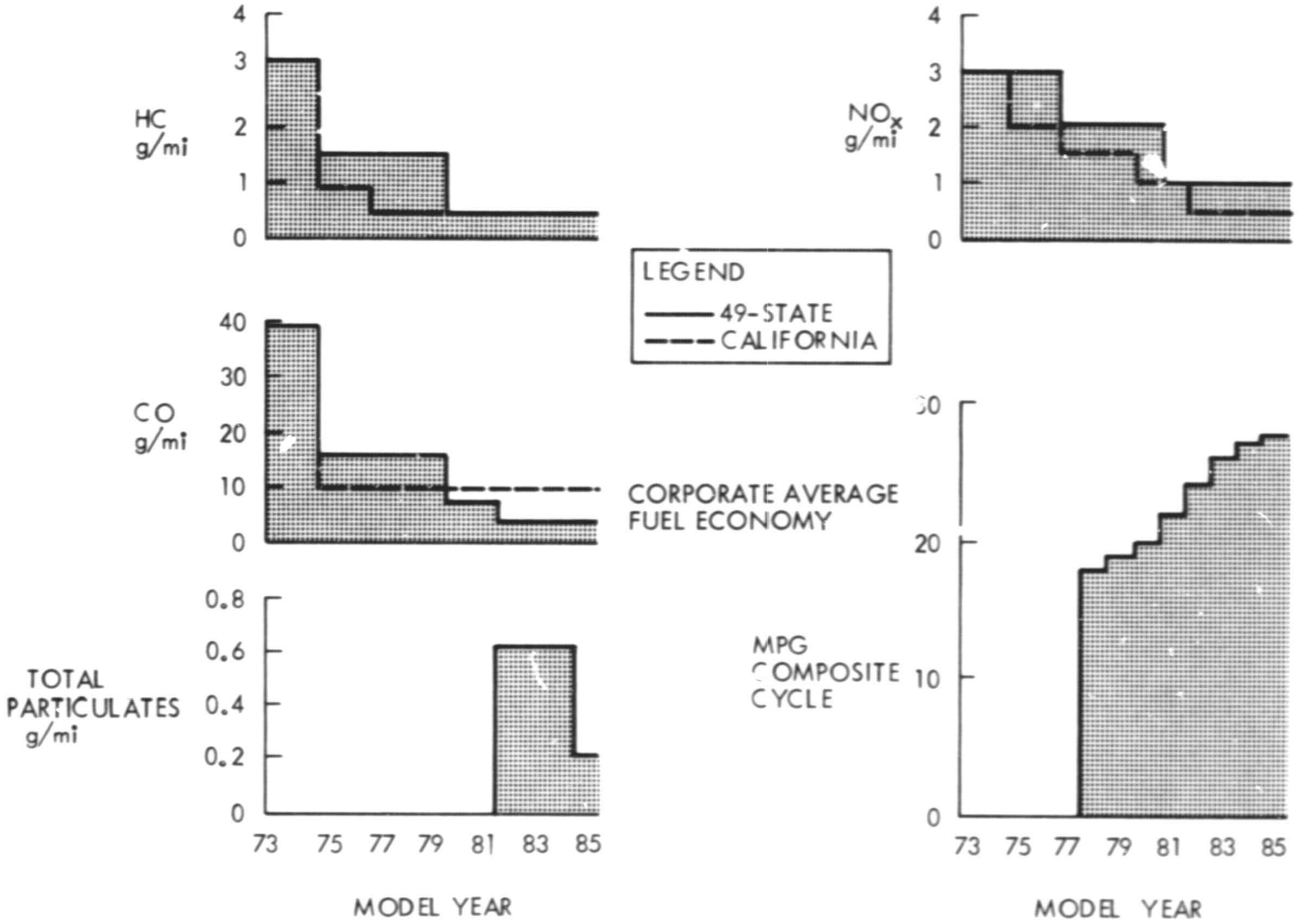


Figure 1-1. Exhaust Emissions and Fuel Economy Regulations

SECTION 2

COMPARISONS OF CURRENT ENGINE TECHNOLOGIES

This section covers the fuel economy and exhaust emissions results for current production vehicles using various engine types. The data is taken from EPA certification and fuel economy data vehicles for the 1980 model year in California. California vehicle data is used because current California emissions standards are more representative of future emissions requirements for all states.

Fuel economy over the composite driving cycle (55% urban driving and 45% highway driving) is given as a function of vehicle inertia weight in Figures 2-1 through 2-4 for the different engine types. Data scatter is partially due to the fact that the data represent vehicles with 4-speed manual, 5-speed manual, and automatic transmissions, as well as with a range of rear axle ratios. Uniform charge Otto engines with three-way catalyst emissions control and diesel engines are found in the full range of vehicle weights; however, lean burn (fast burn) and stratified charge engines are found only in lighter-weight vehicles (vehicle inertia weights less than 3,000 lb). The boundary curves around the data are used to represent the various engine types in the comparisons which follow. The fuel economy characteristic for the prechamber diesel engine is based on the use of diesel fuel, while the fuel economies for the other engine types are based on gasoline.

A comparison of the composite fuel economy for various engine types is given in Figure 2-5. Vehicles having diesel engines show significant fuel economy advantages over vehicles with other engine types for the full range of vehicle inertia weights. Part of this advantage is a result of the higher energy content of a gallon of diesel fuel. Lean burn (fast burn) engines show some fuel economy advantage over the uniform charge engines with three-way catalyst emissions control. Stratified charge engines show some fuel economy advantage in the lightest vehicles (vehicle inertia weight of 2125 lb), however, this advantage disappears in the heavier vehicles.

The previous discussions did not attempt to distinguish between vehicles having different levels of performance; however, this is an important consideration in making comparisons of different vehicles. The previous fuel economy data is shown in Figures 2-6 through 2-10 expressed as vehicle inertia weight (IW) times composite fuel economy (MPG) plotted versus horsepower divided by vehicle inertia weight. In these figures, vehicle inertia weight is expressed in tons. Fuel economy in IW(TON) X MPG is a measure of vehicle efficiency, and HP/IW(TON) provides a first-order indication of vehicle performance. The data show a significant spread in the fuel economy parameter at a given performance level.

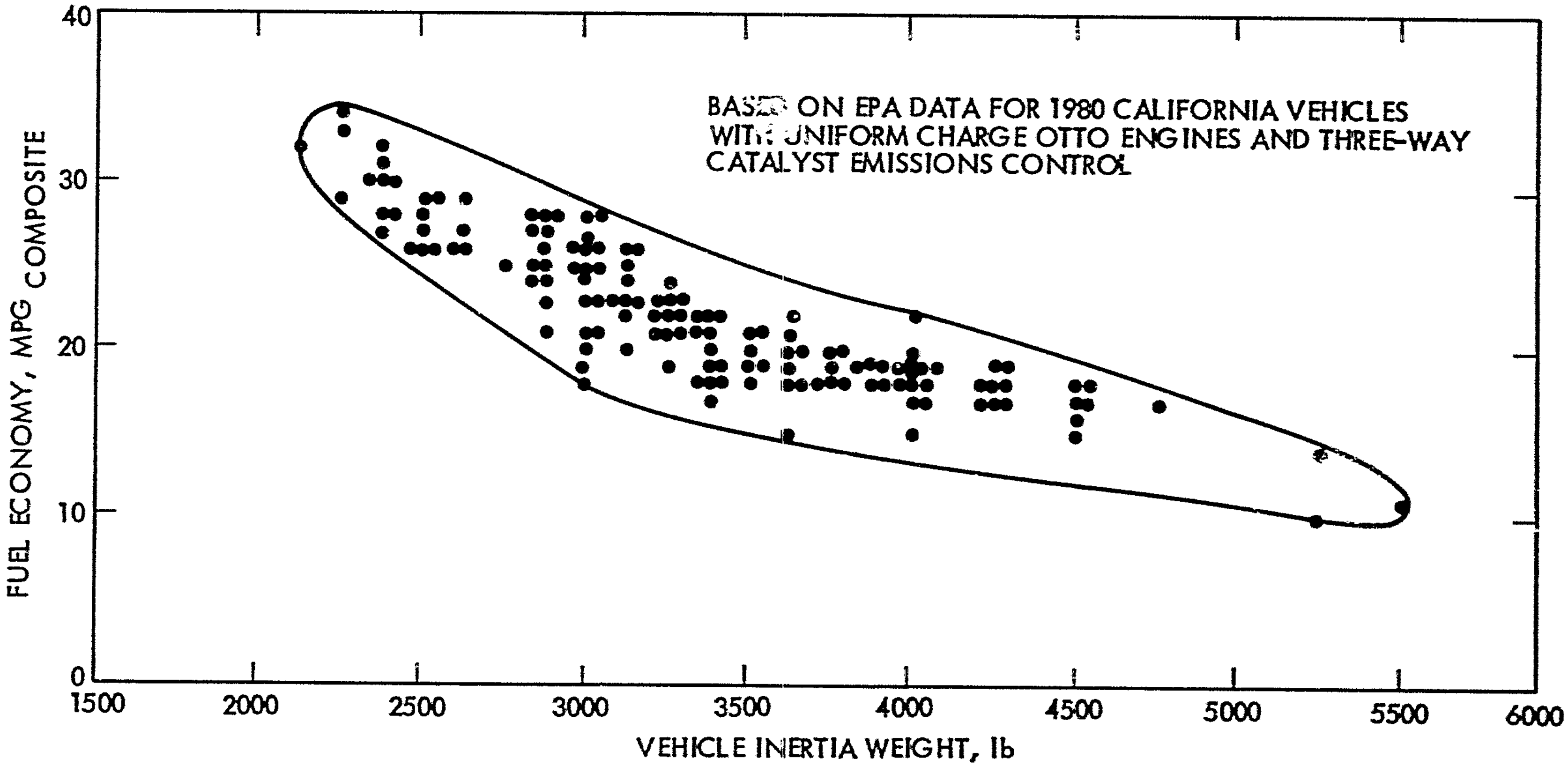


Figure 2-1. Composite Fuel Economy for 1980 California Vehicles Using Uniform Charge Otto Engines and Three-Way Catalyst Emissions Control

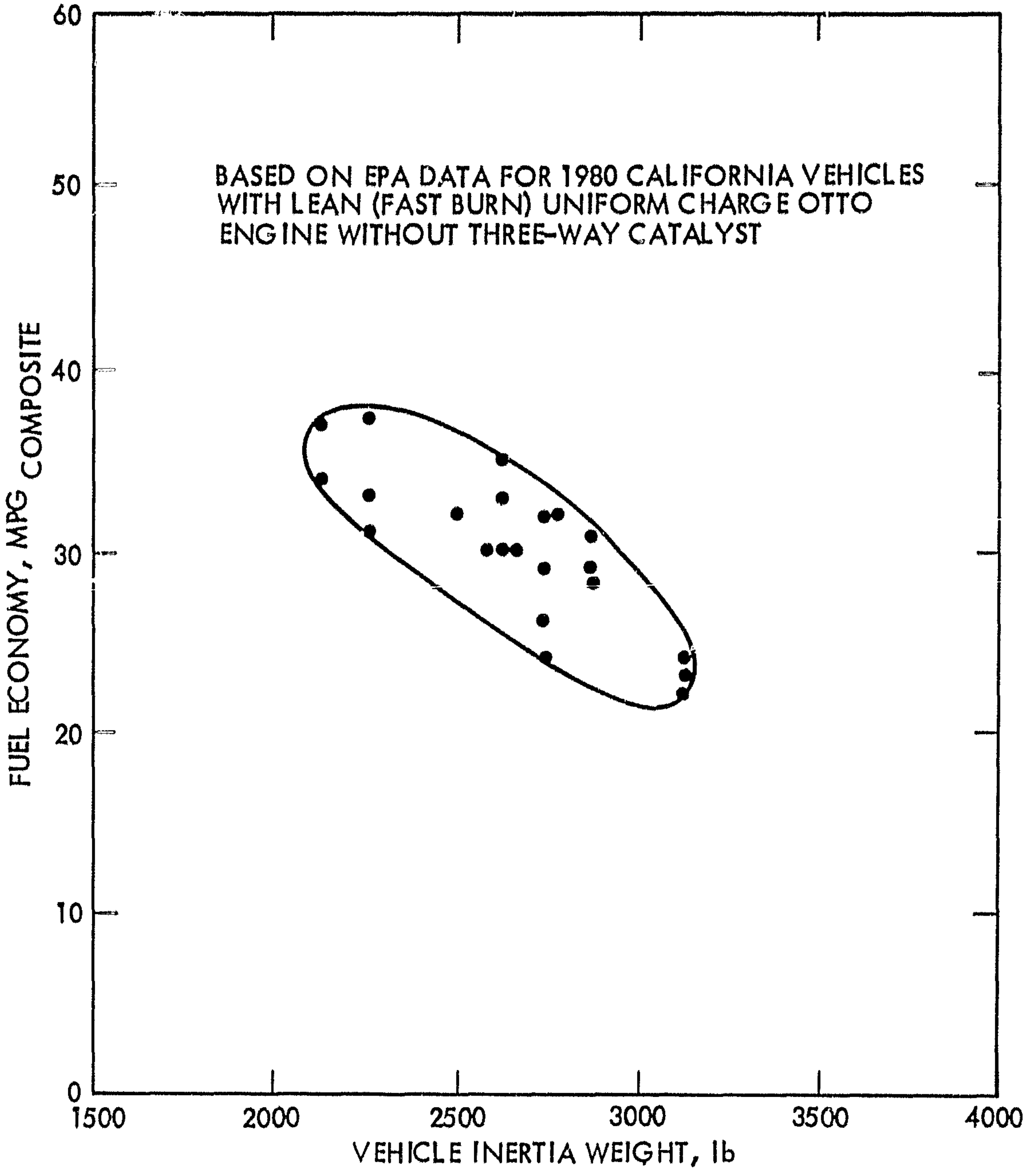


Figure 2-2. Composite Fuel Economy for 1980 California Vehicles Using Lean Burn (Fast Burn) Uniform Charge Otto Engines w/o Three-Way Catalyst

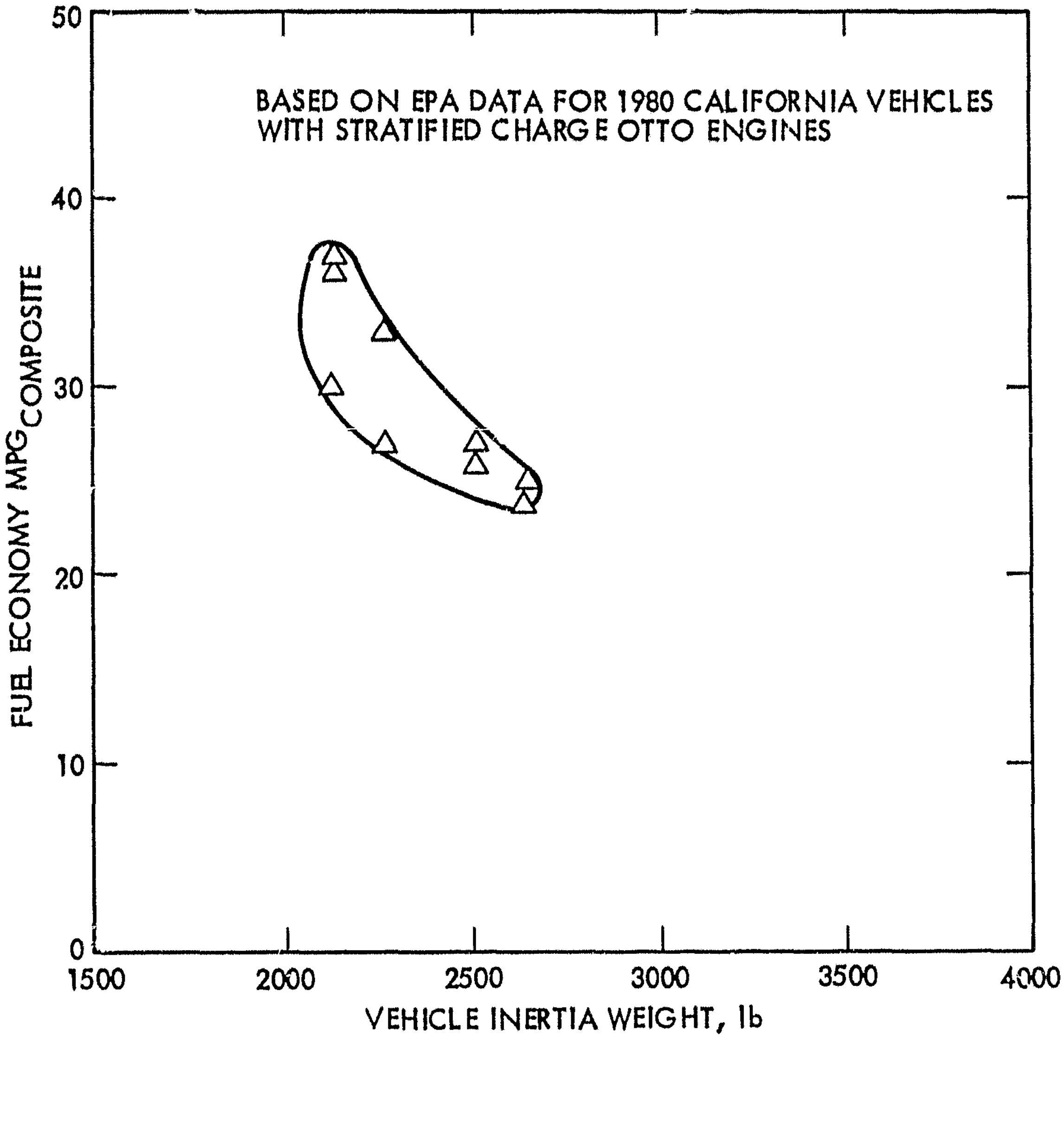


Figure 2-3. Composite Fuel Economy for 1980 California Vehicles Using Stratified Charge Otto Engines

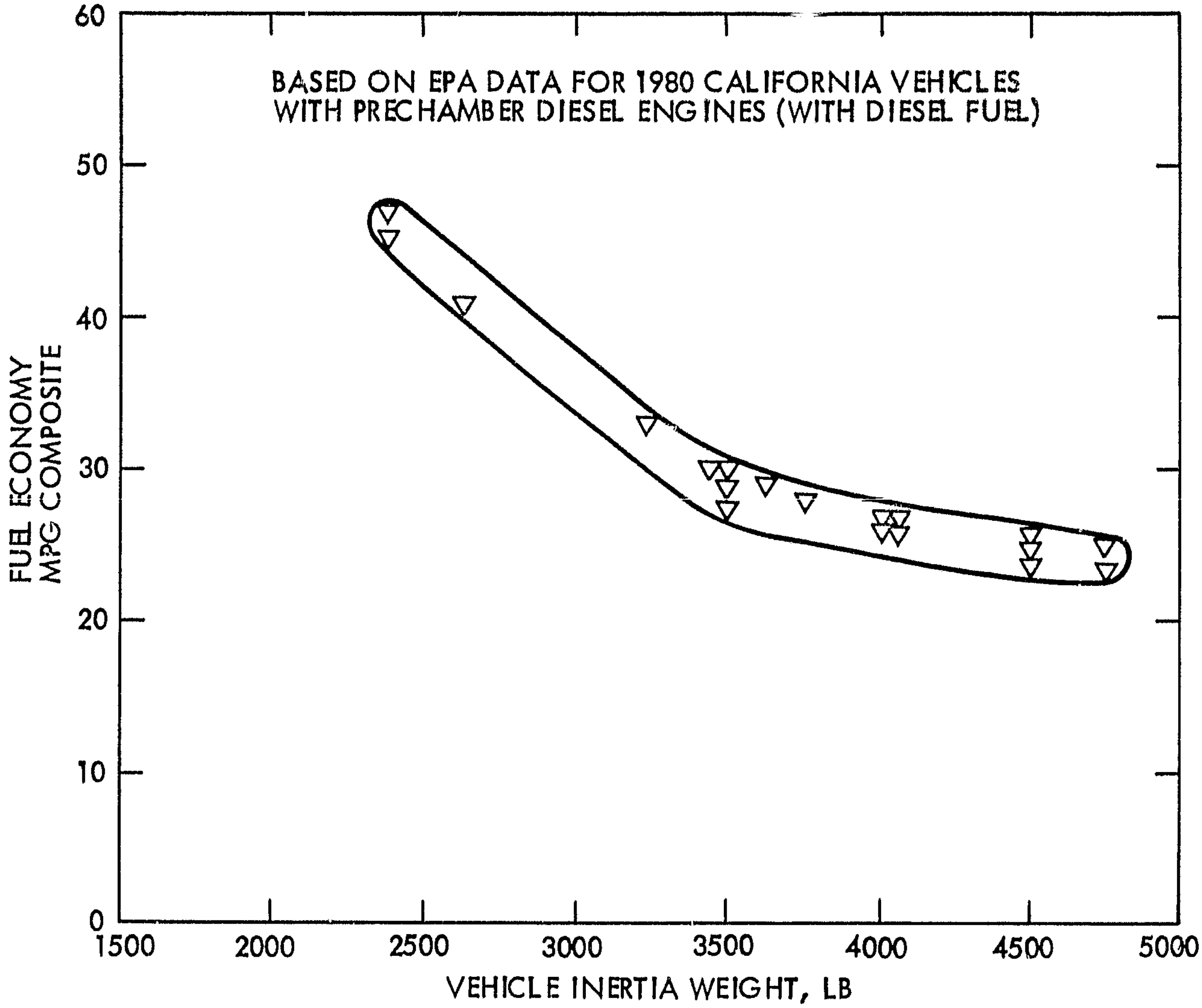


Figure 2-4. Composite Fuel Economy for 1980 California Vehicles Using Prechamber Diesel Engines

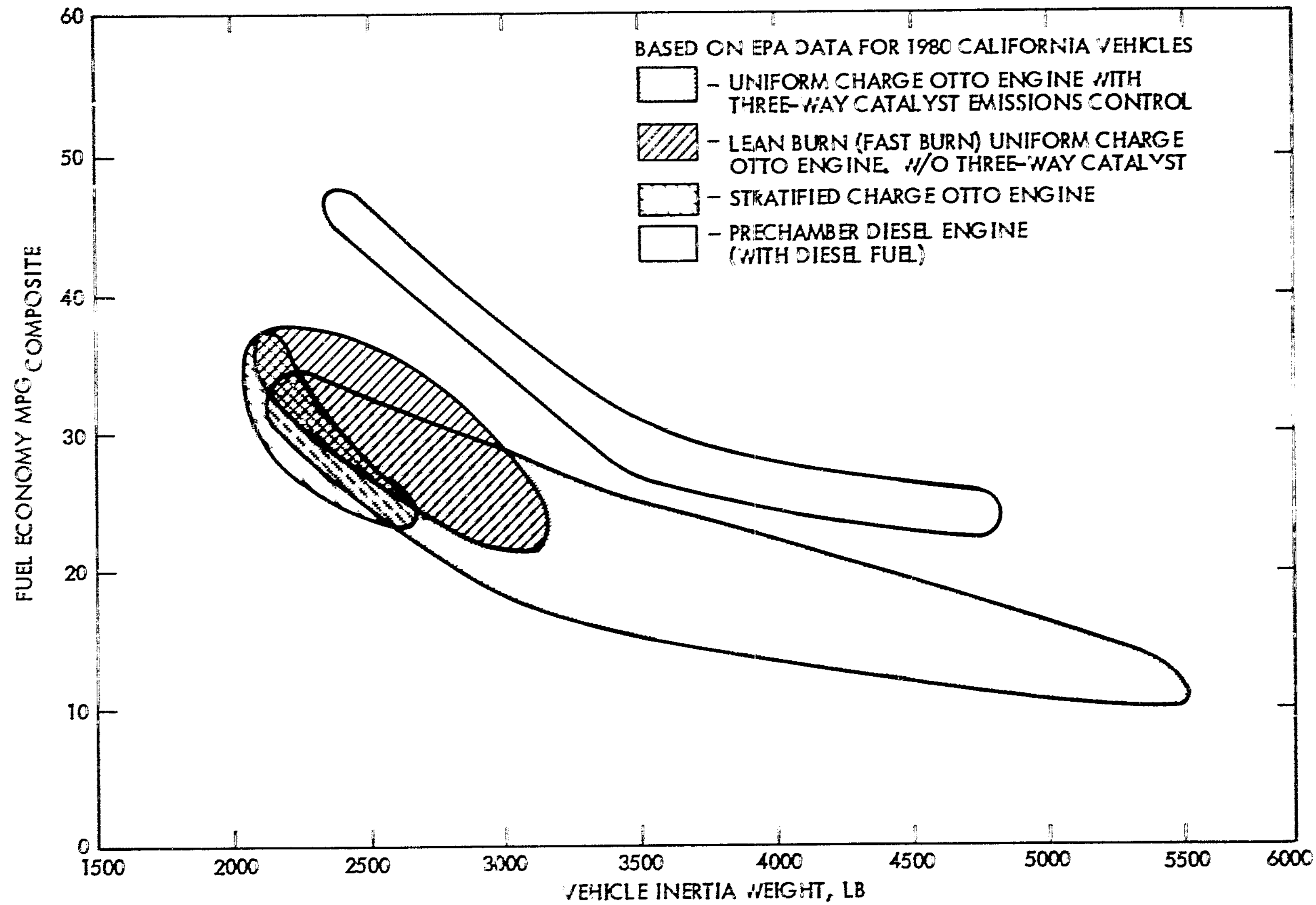


Figure 2-5. Composite Fuel Economy Comparisons for Various Engine Types

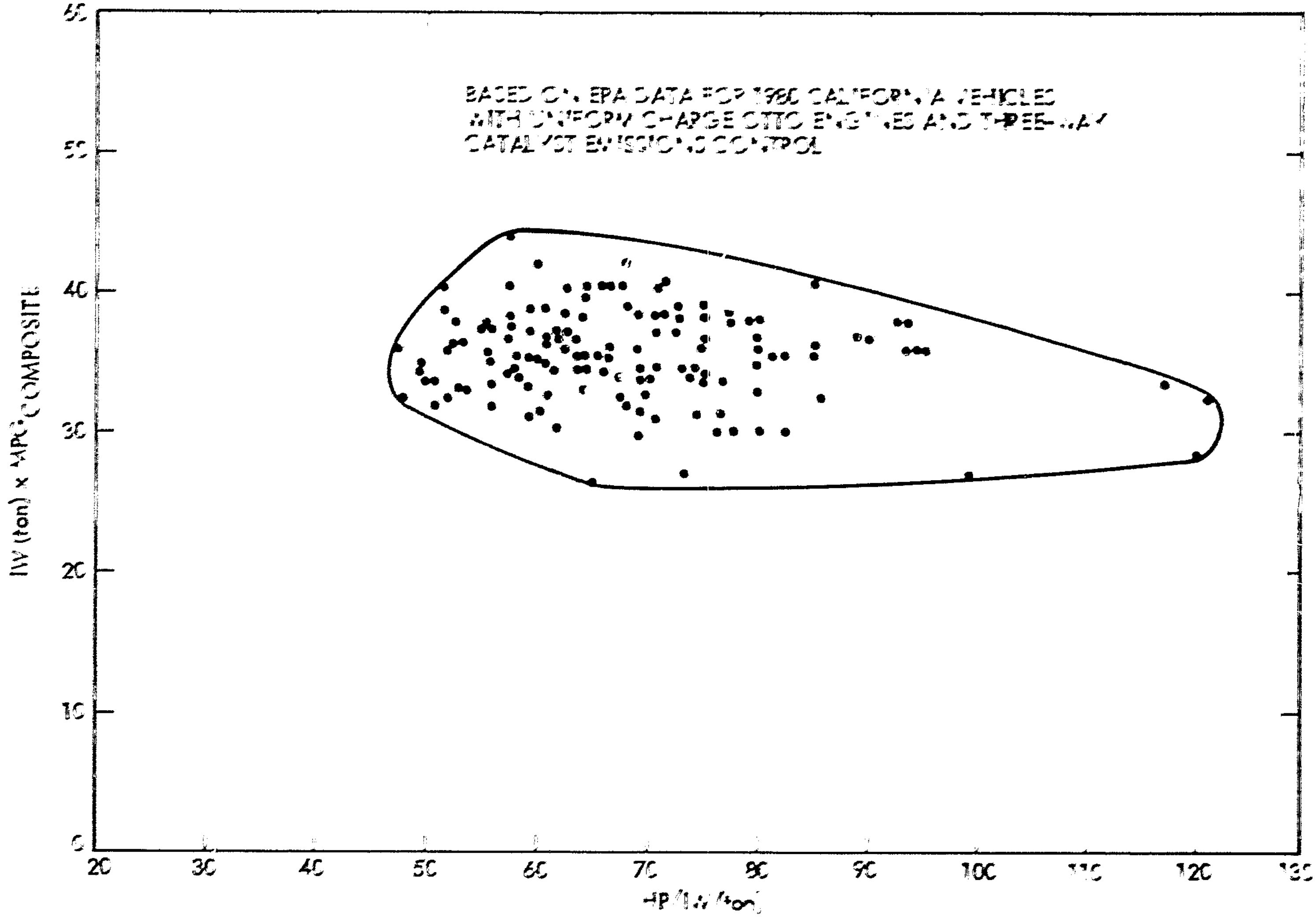


Figure 2-6. Fuel Economy Characteristics for 1980 California Vehicles Using Uniform Charge Otto Engines and Three-Way Catalyst Emissions Control

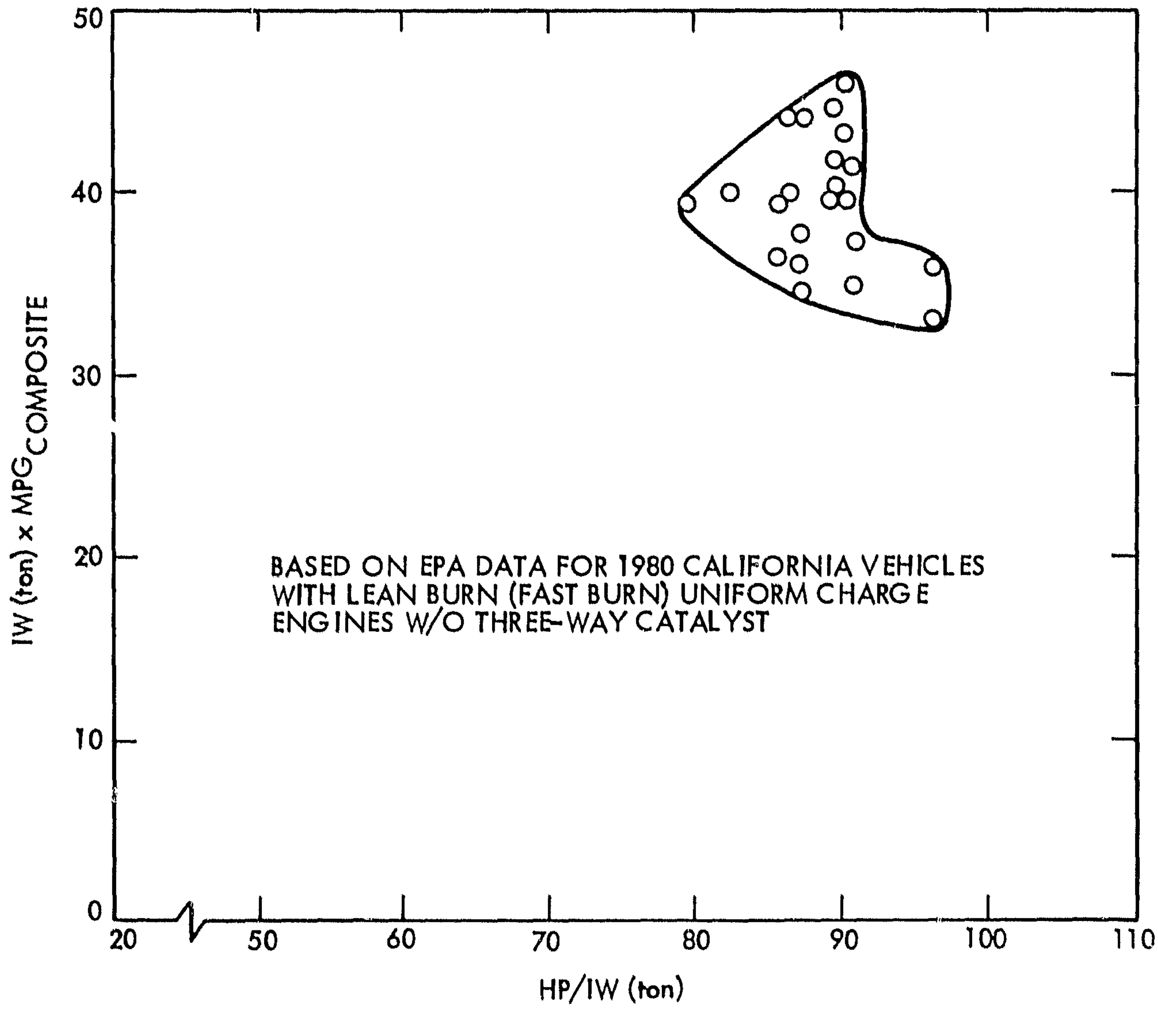


Figure 2-7. Fuel Economy Characteristics for 1980 California Vehicles Using Lean Burn (Fast Burn) Uniform Charge Engines w/o Three-Way Catalyst

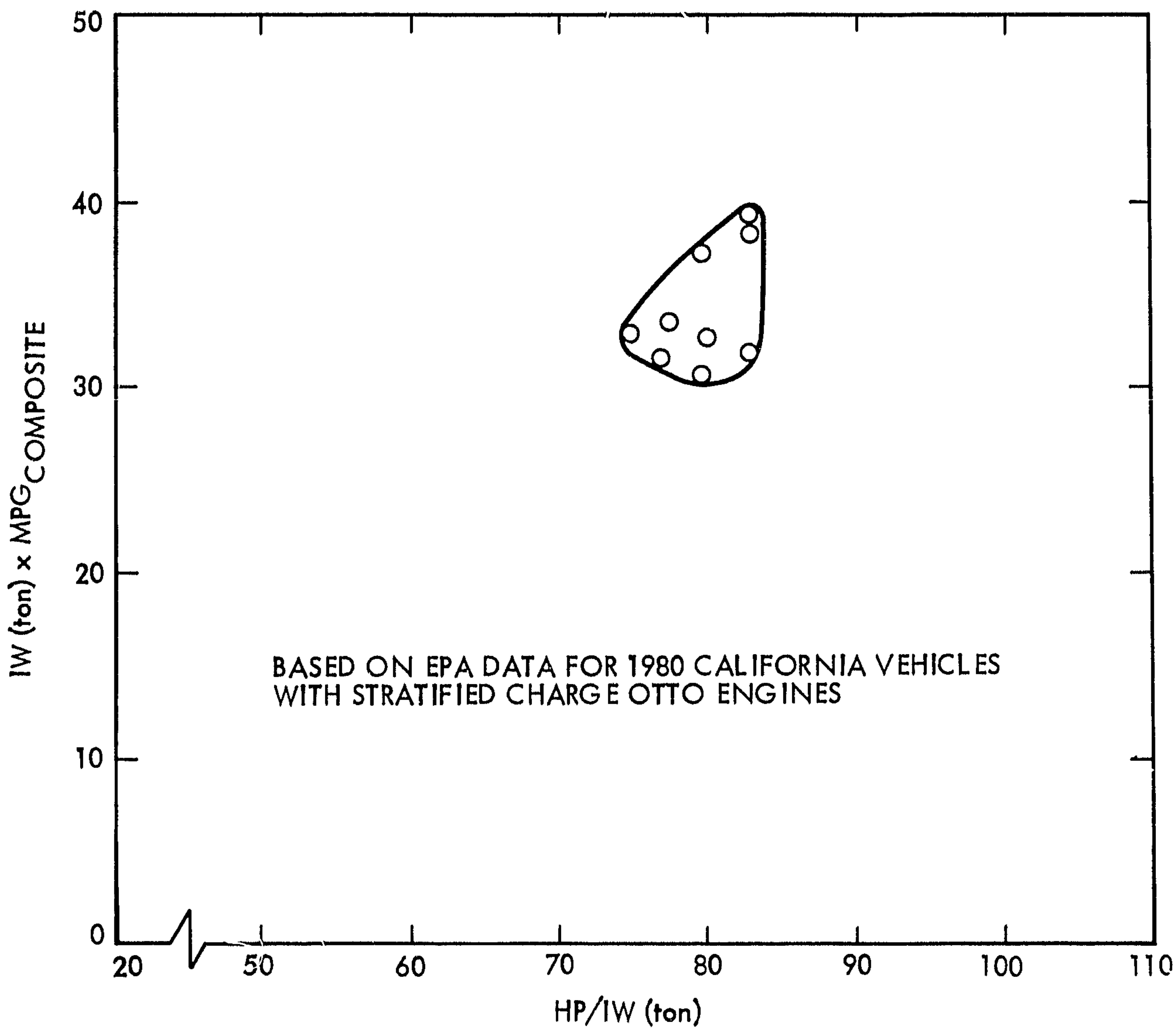


Figure 2-8. Fuel Economy Characteristics for 1980 California Vehicles Using Stratified Charge Otto Engines

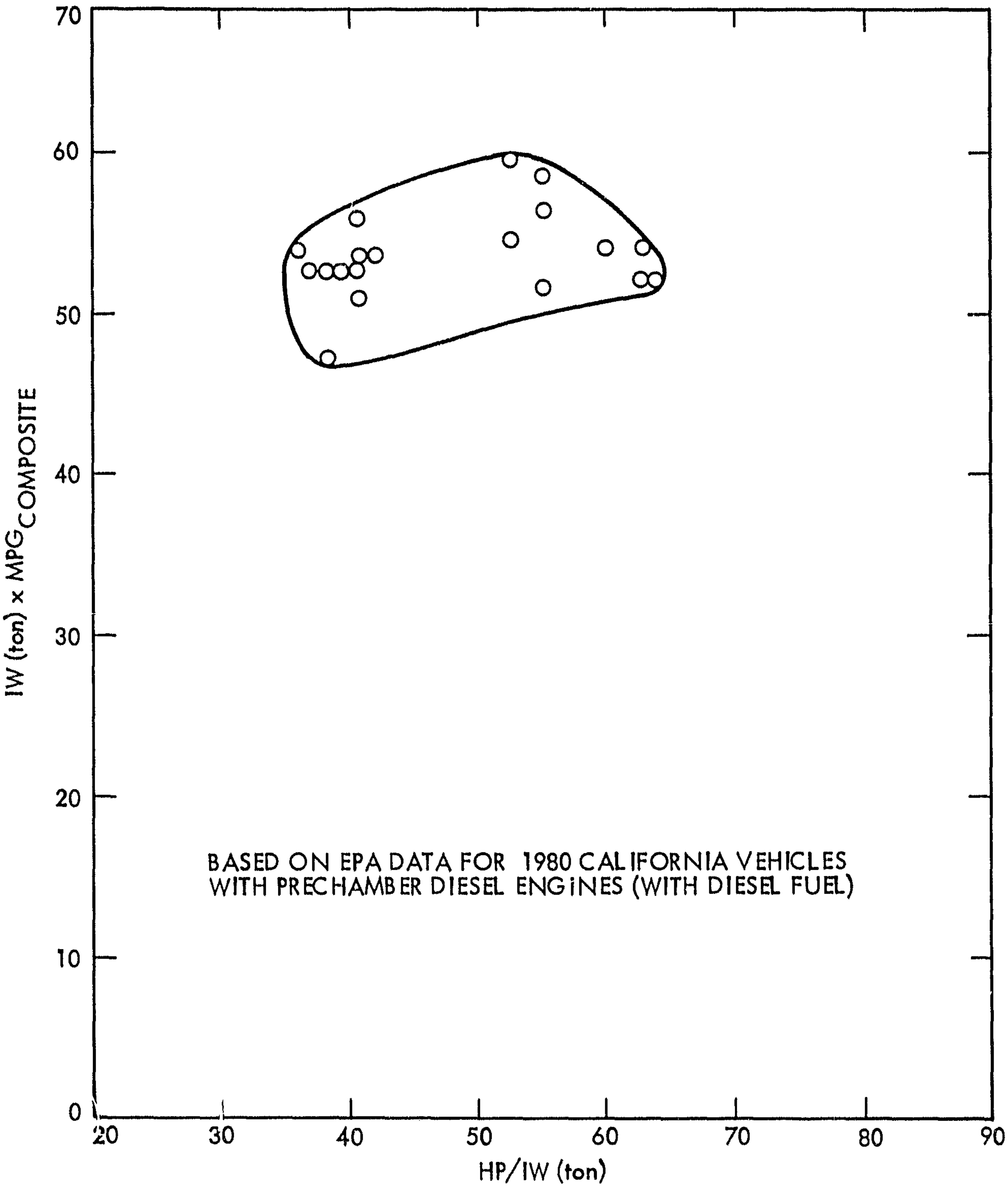


Figure 2-9. Fuel Economy Characteristics for 1980 California Vehicles Using Prechamber Diesel Engines

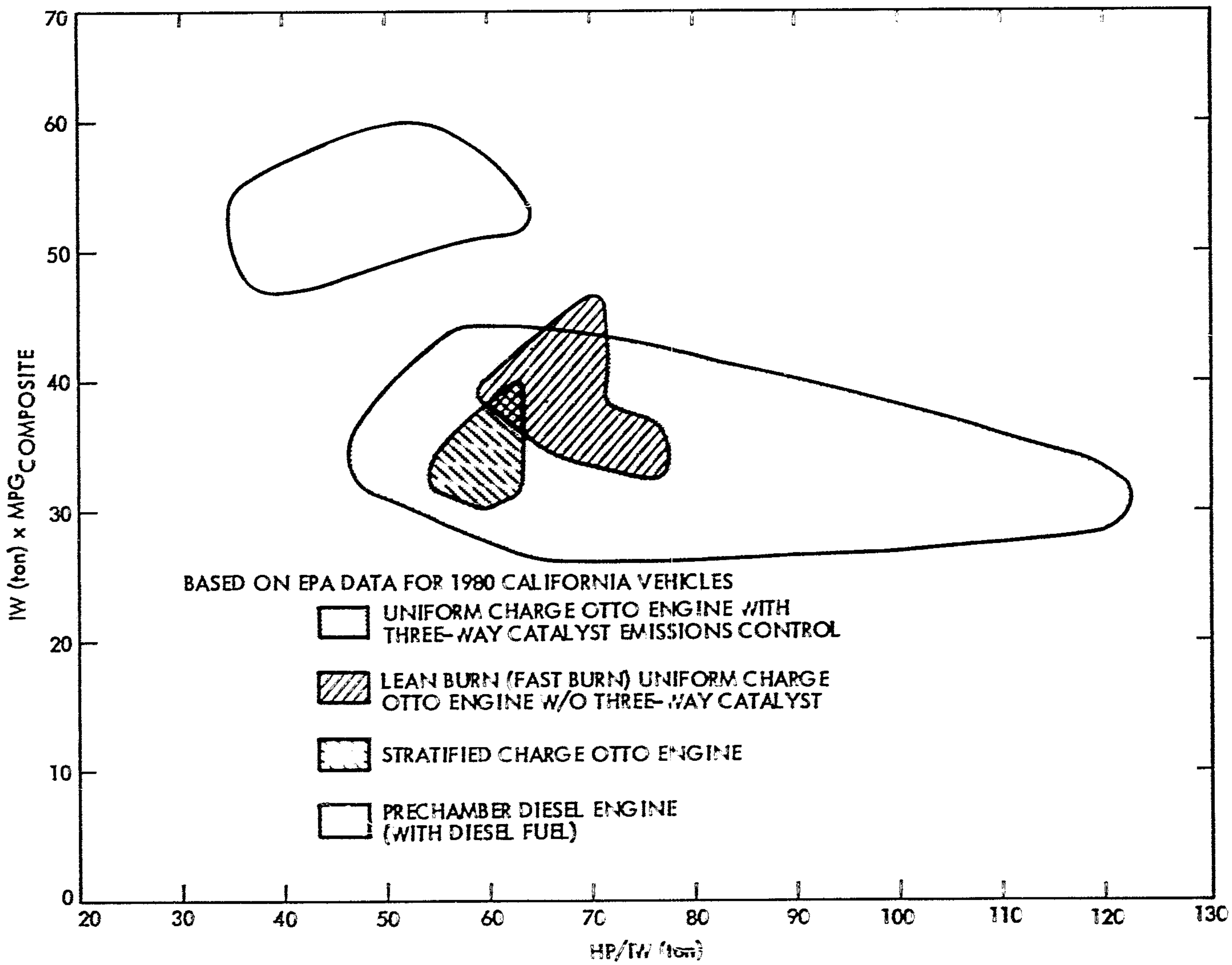


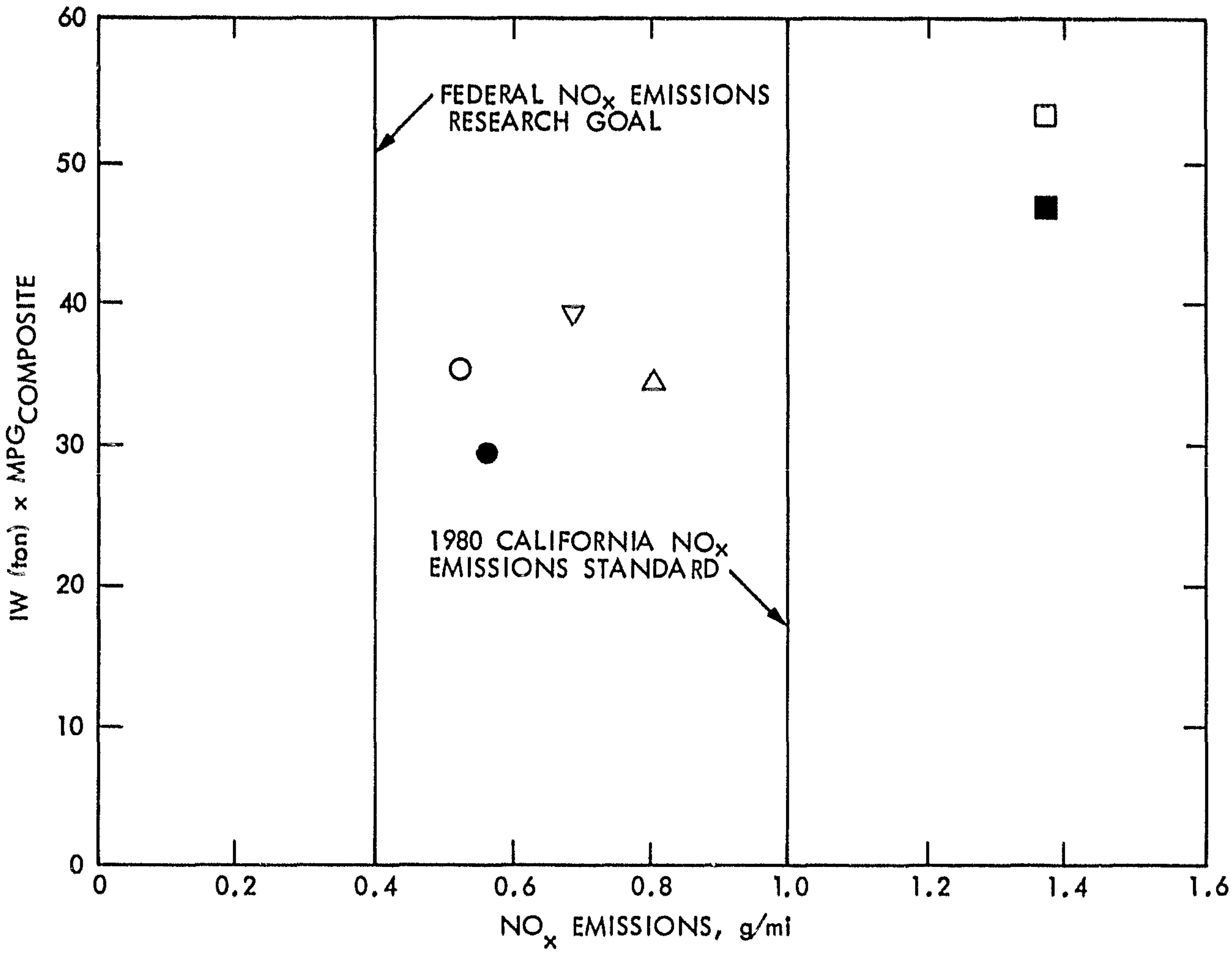
Figure 2-19. Comparison of the Fuel Economy Characteristics for Various Engine Types

The fuel economy characteristics for the various engine types are compared in Figure 2-10. Vehicles with diesel engines generally have a lower HP/IW(TON) than vehicles powered by gasoline engines. This indicates that the diesel-powered vehicles which are currently being produced and sold have lower performance than their gasoline-powered counterparts. Diesel engines still show significant fuel economy advantages in this plot, even when compared at the same vehicle performance level (as indicated by the HP/IW(TON) parameter.

A comparison of the NO_x emissions characteristics for various engine types is shown in Figure 2-11. Solid lines in the figure represent the 1980 California NO_x emissions standard and the Federal NO_x emissions research goal. All EPA data for 1980 California vehicles with a particular engine type have been averaged and plotted as a single point in this figure. The uniform charge Otto engine with three-way catalyst emissions control provides the lowest NO_x emissions of any engine type. The rotary engine data shown is from 1980 EPA test data. The rotary engine is also equipped with a three-way catalyst emissions control system. Although NO_x emissions are controlled to about the same level as for the uniform charge Otto engine (reciprocating) with three-way catalyst emissions control, the rotary engine shows significantly lower fuel economy. NO_x emissions for the lean burn (fast burn) and stratified charge engines are somewhat higher, but still well below the 1980 California standard. The prechamber diesel engine has NO_x emissions of about 1.35 g/mi, which is higher than the 1980 California standard. Diesel engine fuel economy is shown based on diesel fuel and also based on a gasoline equivalent basis so that energy efficiency comparisons can be made.

Comparisons of the HC and CO emissions characteristics for the various engine types is shown in Figure 2-12. The solid lines represent the 1980 California emissions standards. All engine types meet these requirements with margin. Diesel engines tend to have lower CO emissions and higher HC emissions than the gasoline engine types considered.

As previously mentioned, prechamber diesel engines currently in production have difficulty meeting the 1.0 g/mi NO_x emissions requirement. The ability of diesel engines to meet the proposed 0.2 g/mi particulate emissions regulation (in 1985) is also a major open issue. The general trends of particulate and NO_x emissions for prechamber diesel engines are shown in Figure 2-13. The emissions characteristics for current production vehicles are represented by the right-hand termination points of the curves. Both NO_x and particulate emissions increase significantly with increasing vehicle inertia weight. This figure shows the relationship between particulates and NO_x emissions, which are reduced through the use of exhaust gas recirculation (EGR) and modified injection timing. In this case, reductions in NO_x emissions are accompanied by increases in particulate emissions. As shown in this figure, only vehicles with inertia weights less than 2000 lb can meet both the 1.0 g/mi NO_x emissions requirement and the 0.2 g/mi particulate emissions level simultaneously, using present diesel engine technology. Significant efforts are underway to develop combustion system modifications and/or fuel modifications to lower diesel engine particulate and NO_x emissions. However, in the near term, some form of exhaust treatment will probably be required for the prechamber diesel engines to meet the 0.2



PLOTTED POINTS REPRESENT AVERAGE VALUES OF EPA DATA FOR 1980 CALIFORNIA VEHICLES WITH EACH ENGINE TYPE

○ UNIFORM CHARGE OTTO ENGINE WITH THREE-WAY CATALYST

▽ LEAN BURN (FAST BURN) UNIFORM CHARGE W/O THREE-WAY CATALYST

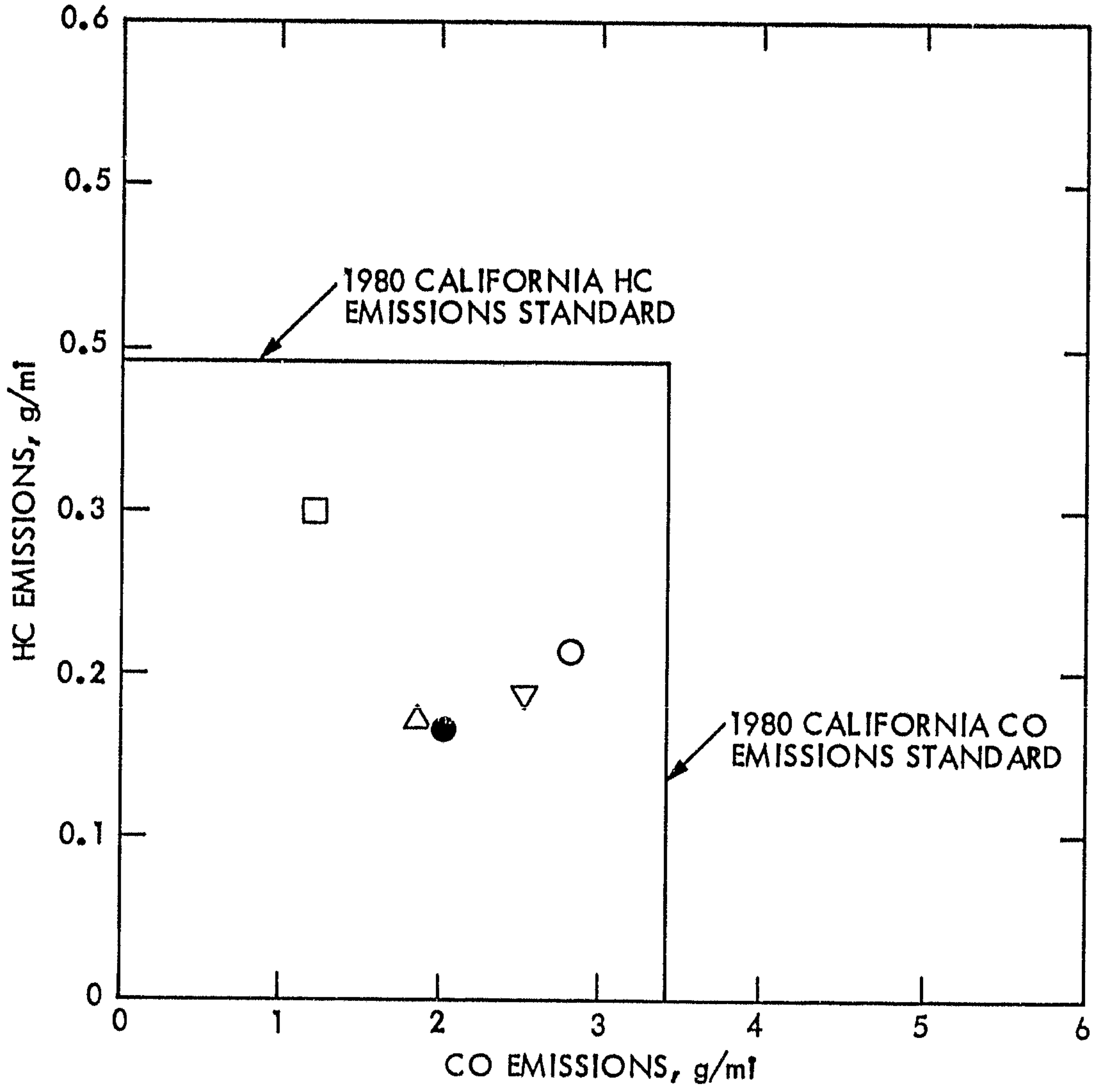
△ STRATIFIED CHARGE OTTO ENGINE

□ PRECHAMBER DIESEL ENGINE

■ PRECHAMBER DIESEL ENGINE (MPG EXPRESSED AS GASOLINE EQUIVALENT)

● ROTARY ENGINE

Figure 2-11. Comparison of the NO_x Emissions Characteristics for Various Engine Types



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● ROTARY ENGINE

Figure 2-12. Comparison of the HC and CO Emissions Characteristics for Various Engine Types

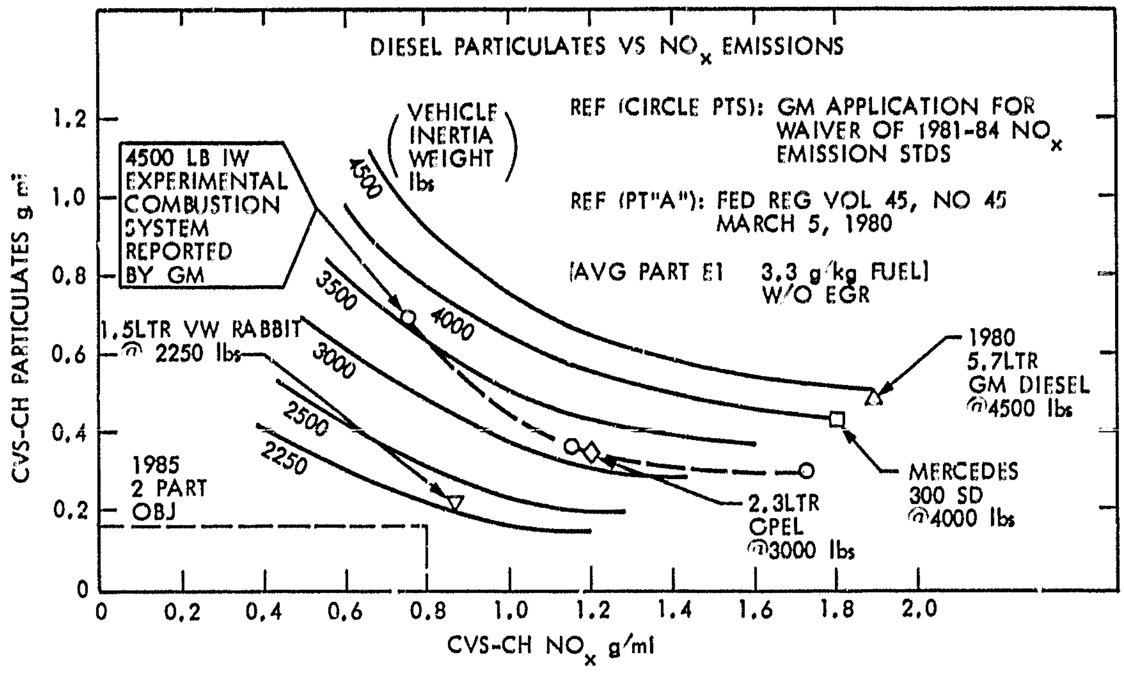

Figure 2-13. CVS-CH Particulate Emissions vs. NO_x Emissions for Light-Duty Diesel Vehicles with Inertia Weights Ranging from 2250 lb to 4500 lb

g/mi particulate emissions regulation. The most promising after-treatment device is the regenerative particulate trap.

A comparison of the average fuel economy characteristics for vehicles with various engine types is shown in Figure 2-14. Fuel economy is expressed in terms of the parameter β, which is defined as the product of vehicle inertia weight in tons and the composite fuel economy in MPG. This fuel economy parameter is plotted versus the vehicle performance parameter, HP/IW(TON). Each plotted point represents the average of all EPA data for 1980 California vehicles with a given engine type and with values of the vehicle performance parameter within a 5-unit interval (e.g., the fuel economy parameters for all vehicles with prechamber diesel engines and with HP/IW(TON) values between 55 and 60 are averaged and plotted as a single point in this figure). To provide a basis for comparison, a line is drawn to represent the average of the data points for vehicles having uniform charge Otto engines with three-way catalyst emissions control systems. The three points with the highest HP/IW(TON) values were not included in this averaging process because they represent high performance sports vehicles. Also shown are lines representing the upper and lower bounds of the data for vehicles having uniform charge Otto engines and three-way catalyst emissions control systems. A second scale is included to show the percent deviation in the parameter β, relative to the baseline average for vehicles with uniform charge Otto engines and three-way catalyst emissions control systems.

Some general conclusions regarding the relative merits of current engine technologies can be reached by comparing the average data in Figure 2-14. Vehicles with lean burn (fast burn) uniform charge engines which do not utilize three-way catalyst emissions control systems have a fuel economy parameter β which is 10% higher than the baseline system. Data for vehicles using stratified charge Otto engines give values about 5% less than the baseline system. Vehicles with diesel engines show β values about 50% higher than the baseline, when the β is calculated using diesel fuel. When the diesel vehicle fuel economy is expressed in gasoline equivalent MPG, the diesel fuel economy parameter β is 30 to 40% higher than the baseline. However, it should be recalled (see Figure 2-11) that the diesel vehicles shown here produced NO_x emissions greater than 1.0 g/mi. The NO_x emissions levels for these diesel vehicles are approximately two times as high as the NO_x emissions levels for the other engine types. The fuel economy advantage shown for the diesel vehicles in Figure 2-14 would be reduced if the diesel engines were calibrated to meet the 1.0 g/mi NO_x emissions requirement.

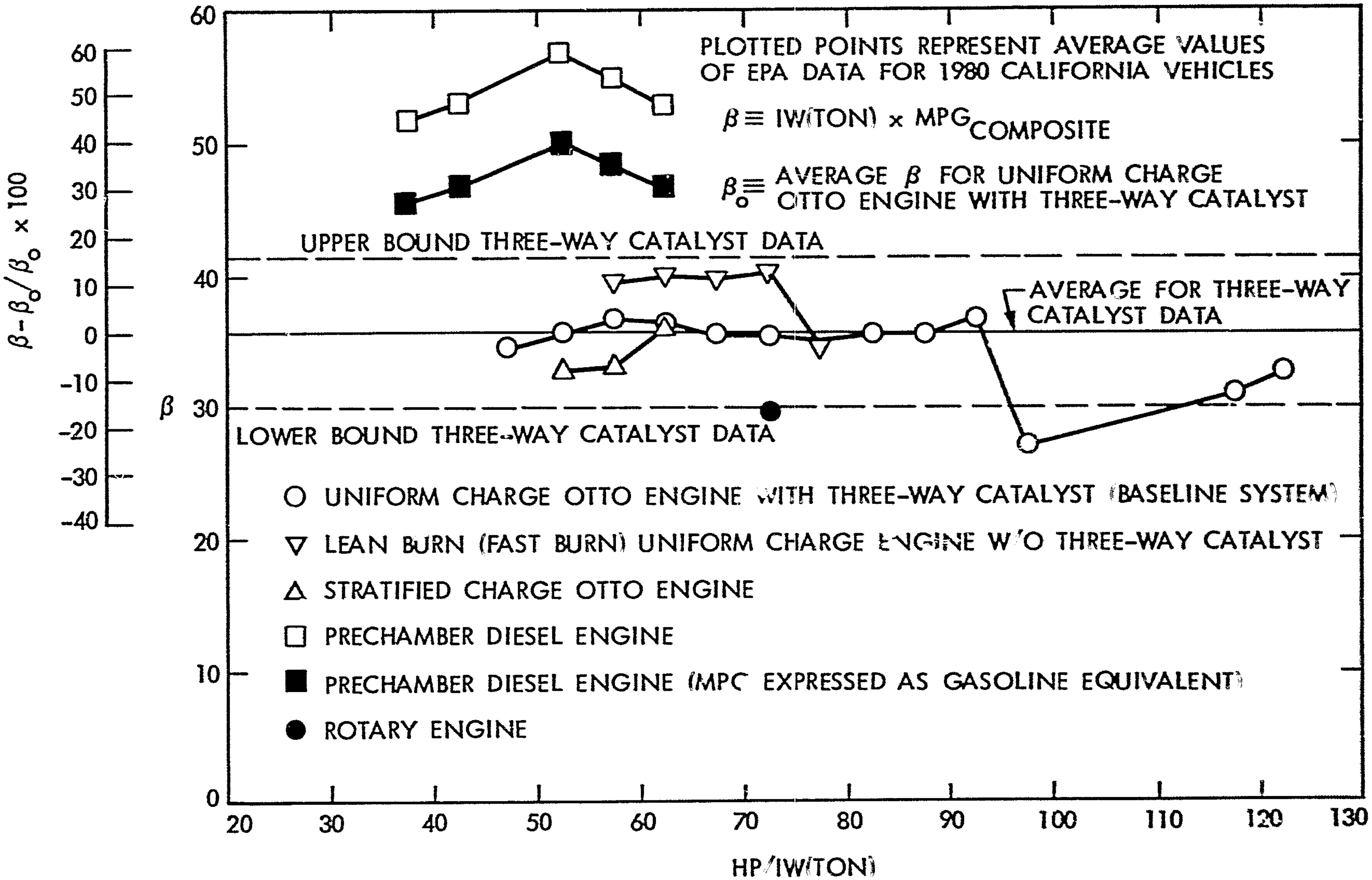

Figure 2-14. Comparison of the Average Fuel Economy Characteristics for Various Engine Types

SECTION 3

FUTURE POTENTIAL FOR VARIOUS ENGINE TECHNOLOGIES

This section will provide a comparison of the status of current conventional engine technologies and indicate the future fuel economy potential of each engine type. The comparisons are made under the assumption that the 1980 California gaseous emissions standards remain in effect and that the proposed particulate emissions standards are implemented as planned. Estimates of the future potential of each engine type are based on the use of technology which can be implemented on production vehicles by 1986.

Estimates of the fuel economy of vehicles with various engine types are shown in Figure 3-1. Fuel economy is given in terms of the fuel economy parameter β, with the vehicle inertia weight expressed in tons and the MPG being expressed in gasoline equivalent units. Fuel economy values for vehicles utilizing 1980 engine technology are taken from Figure 2-14 for vehicles with a performance parameter (HP/IW) of 57.5. This value of performance parameter was selected because it is representative of many 1980 production vehicles (see Table 3-1) including vehicles powered by each engine type considered in this study, with the exception of the rotary engine which is used in only one vehicle having a HP/IW(TON) value of about 73. As previously mentioned, the 1980 diesel vehicles did not, in general, meet the 1.0 gm/mi NO_x emissions requirements and in that sense are not equivalent to vehicles powered by the other engine types.

Fuel economy estimated for vehicles using 1986 engine technology are based on projected advances in current conventional engine technologies and the introduction of direct injection diesel engine technology. The 1980 uniform charge Otto engine with three-way catalyst emissions control is selected as the baseline system, with estimated fuel economy improvements being measured against this base.

By 1986, the fuel economy of vehicles with the advanced baseline engine system (i.e., uniform charge Otto with three-way catalyst) is expected to increase by about 10% due to dvances in the baseline engine technology. These advances will include continued development of air-fuel control systems which are more suited to closed-loop, three-way catalyst emissions control. As microprocessor-based control systems find wider use on future vehicles, more optimization of engines will be made to improve fuel economy by monitoring and controlling engine variables (e.g., spark timing, EGR, secondary air, air/fuel ratio) while at the same time maintaining low emission levels.

Continued progress in understanding lean combustion processes (e.g., flame initiation, flame propagation, and turbulence control in the combustion chamber) and practical ways of achieving a fast burn in engines is expected to result in a 15% increase in fuel economy by 1986. This estimate assumes taking advantage of the tolerance of fast burn engines to increases in compression ratio. This assumption depends on the continued availability of fuels with properties (e.g., octane rating) similar to 1980 gasoline fuels. It is expected that engine compression ratio can be increased from 8.5, which is

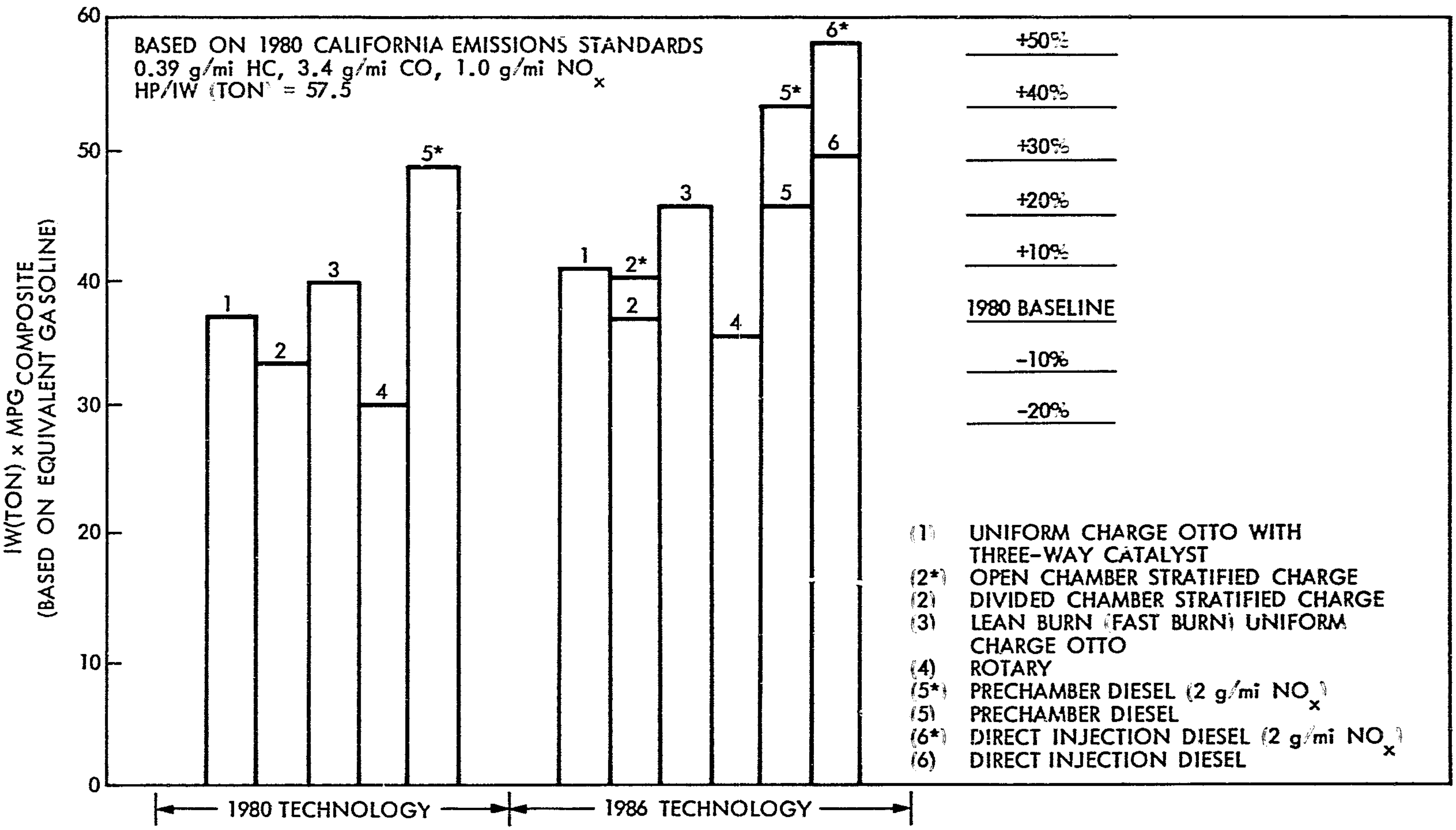

Figure 3-1. Fuel Economy Projections for Vehicles with Various Engine Types

Table 3-1. 1980 Production Vehicles with Performance Parameters of About 57.5

Vehicle	Engine Type	Displacement, cubic inches	Vehicle Inertia Weight, lb	Horsepower	HP/IW(TON)
Mazda GLC	UC Otto with 3-Way Catalyst	86	2250	65	57.8
VW Dasher	UC Otto with 3-Way Catalyst	97	2625	76	57.9
Ford Fairmont	UC Otto with 3-Way Catalyst	200	3250	94	57.9
Chevrolet Impala	UC otto with 3-Way Catalyst	231	4000	115	57.5
Honda Accord	SC Otto	107	2625	75	57.1
Mistubishi Arrow	Fast-Burn UC Otto	98	2625	78	59.4
Oldsmobile	Prechamber Diesel	350	4500	125	55.6

typical of 1980 fast burn engines, to about 12.0. A plot showing the estimated increases in engine efficiency which can be achieved by increases in compression ratio and leaner operation is given in Figure 3-2. Changing from stoichiometric operation at a compression ratio of 8.5 to operating with 50% excess air at a compression ratio of 12.0 leads to an estimated 25% increase in engine efficiency. Use of EGR rather than excess air as a diluent gas would reduce this potential gain in efficiency. Further increases in engine efficiency are possible with reductions in the combustion interval through improvements in the fast burn characteristics of this engine type. Consideration of these factors leads to the 15% estimated increase in fuel economy.

With the introduction of oxidation catalyst systems on prechamber stratified charge engines, it is expected that further optimization of engine variables (e.g., spark timing, air/fuel ratio) to achieve better fuel economy will result in a 10% improvement in fuel economy over 1980 vehicles using these engines. Although development of the open chamber stratified charge engine has slowed, another 10% gain in fuel economy would result if it is used in 1986 vehicles.

Introduction of concepts from current experimental rotary engine development activities should yield a 20% increase in the fuel economy of vehicles with rotary engines by 1986. This would make the rotary engine more competitive with conventional reciprocating engines from the fuel economy standpoint.

As previously mentioned, 1980 diesel engines were not able to meet the California emissions standards and required waivers to continue their sales in that state. If diesel engines are permitted to continue meeting the 2.0 g/mi NO_x emissions level rather than the 1.0 g/mi NO_x standard, a 10% gain in fuel economy is expected due to the introduction of more diesel engine designs (i.e., not diesels derived from gasoline engines) and an increased use of turbocharging. If diesel engines are required to control NO_x emissions to the 1.0 g/mi level through the use of EGR or injection timing retard, this will impose about a 15% penalty in fuel economy, making the prechamber diesel about equivalent to the advanced lean burn (fast burn) system.

Successful introduction of direct injection diesel engine technology will provide an additional 10% increase in fuel economy over that of prechamber diesel engines. This fuel economy advantage of direct injection diesel engines of the automotive size has been successfully demonstrated in some current experimental diesel engine programs. To meet the 1.0 g/mi NO_x emissions level would also result in a 15% fuel economy for the direct injection diesel. It is expected that only the smallest vehicles (i.e., inertia weights less than 2250 lb) with prechamber or direct injection diesel engines could meet the 0.2 g/mi particulate emissions level.

As a summary of the information contained in Figure 3-1, estimated mileages for two vehicle weights are given in Table 3-2. These results represent estimated <u>average</u> mileages for vehicles with the various engine types in the weight and power ranges indicated.

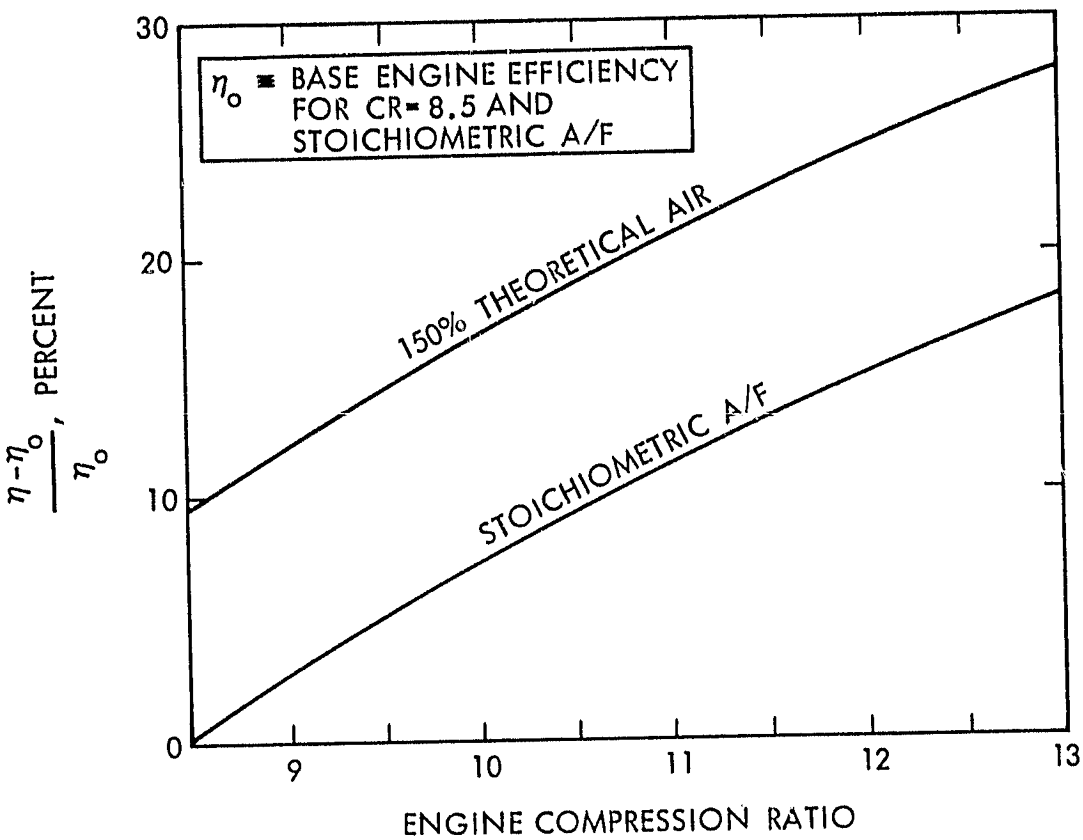

Figure 3-2. Estimated Efficiency for Lean Burn (Fast Burn) Technology

Table 3-2. Summary of Estimated Vehicle Fuel Economy

Engine Type	Vehicle Inertia Weight (lb)	Power (hp)	Composite MPG 1980 Technology	Composite MPG 1986 Technology
UC Otto (3-Way)	2000	57.5	36.6	40.3
SC Otto (Open Chamber)	2000	57.5	--	39.6
SC Otto (Divided Chamber)	2000	57.5	33.0	36.3
UC Otto (Fast Burn)	2000	57.5	39.5	45.4
UC Otto (Rotary)	2000	57.5	29.5	35.4
Diesel (Prechamber, 2 g/mi NO_x)	2000	57.5	48.5	53.4
Diesel (Prechamber, 1 g/mi NO_x)	2000	57.5	--	45.4
Diesel (Direct Injection, 2 g/mi NO_x)	2000	57.5	--	58.2
Diesel (Direct Injection, 1 g/mi NO_x)	2000	57.5	--	49.5
UC Otto (3-Way)	3000	86.3	24.4	26.9
SC Otto (Open Chamber)	3000	86.3	--	26.4
SC Otto (Divided Chamber)	3000	86.3	22.0	24.2
UC Otto (Fast Burn)	3000	86.3	26.3	30.3
UC Otto (Rotary)	3000	86.3	19.7	23.6
Diesel (Prechamber, 2 g/mi NO_x)	3000	86.3	32.3	35.6
Diesel (Prechamber, 1 g/mi NO_x)	3000	86.3	--	30.3
Diesel (Direct Injection, 2 g/mi NO_x)	3000	86.3	--	38.8
Diesel (Direct Injection, 1 g/mi NO_x	3000	86.3	--	33.0

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