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DATA BASE FOR LIGHT-WEIGHT AUTOMOTIVE DIESEL POWER PLANTS
Volume I: Executive Summary

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FINAL REPORT

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16. Abstract

The effects on fuel economy, emissions, passenger car safety and other variables due to the installation of light-weight Diesel powerplants were studied. Experimental data was obtained on naturally aspirated and turbocharged Diesel engines installed in subcompact and compact passenger vehicles. The data includes fuel economy as a function of engine type and horsepower, as a function of vehicle inertia weight and as a function of regulated emission constraints. Unregulated emissions have been characterized during the course of work. The compatibility of the Diesel engine studied with passenger car structures incorporating advanced frontal crashworthiness capabilities was also verified.

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PREFACE

In support of the National Highway Traffic Safety Administration, Office of Research and Development, Office of Vehicle Systems Research, the Department of Transportation-Transportation SystemsCenter contracted with Volkswagenwerk AG, Federal Republic of Germany to develop a data base on light-weight Diesel engines suitable for passenger cars. Volkswagen research, pre-production and production Diesel engines were used for the test portion of the work and for the 'analytical extrapolation.'

A Volkswagen research vehicle with advanced crashworthiness characteristics was provided by Volkswagen to demonstrate and document compatibility with an advanced diesel engine design (Integrated Research Vehicle). Through the effort the Diesel engines were evaluated in the context of an integrated vehicle system with the aspects of fuel economy, environment, consumer requirements and cost in mind.

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Our working team consisted of the following persons:

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1.0 INTRODUCTION

This Summary Report is Volume I of a three-volume report. The objective of the study reported herein was to obtain a data base on light-weight automobile Diesel power plants suitable for passenger cars. The power range of the engines studied was from 50 to 100 horsepower and the applicable curb weight range was from 1900 to 2900 pounds.

The characterization of the fuel economy, regulated exhaust emissions (.41/3.4/2.0 and .41/3.4/1.0 g/mi HC, CO and NOx, respectively were two specified constraint levels), several components of unregulated exhaust emissions, odor, noise, driveability, acceleration performance and other consumer related attributes of these engine/vehicle systems constituted the major effort of this program. Engine/vehicle systems tested and analyzed include:

a. A subcompact vehicle (VW-Rabbit, 2250 pounds inertia weight) equipped with a 4-cylinder Diesel engine, naturally aspirated (50 horsepower) and turbocharged (70 horsepower).

b. A subcompact vehicle (VW-Dasher, 2500 pounds inertia weight) equipped with a 4-cylinder Diesel engine, naturally aspirated (50 horsepower) and turbocharged (70 horsepower), and with a 5- cylinder Diesel engine, naturally aspirated (66 horsepower).

c. A compact vehicle (Audi 100, 3000 pounds inertia weight) equipped with a 5-cylinder Diesel engine, naturally aspirated (66 horsepower), a 6-cylinder Diesel engine, naturally aspirated (75 horsepower) and turbocharged (100 horsepower), and a V-8 Diesel engine, naturally aspirated (100 horsepower). The 6-cylinder turbocharged engine and the V-8 engine are projected, only.

d. In connection with the three engine/vehicle systems mentioned above, 12 different manual transmissions including 4 and 5 speed gearboxes were analyzed and a number of them were tested.

Throughout the study the Diesel engines considered were treated in the context of vehicle systems with the following variables paramount (the salient results for each variable are discussed in the section indicated):

1. Fuel Economy (4.1)
2. Emissions (4.2)
3. Consumer Attributes (4.3)
4. Compatibility with Advanced Crashworthiness (4.4)

Section 5 describes the results of hardware efforts: A turbocharged Diesel Rabbit and the VW Integrated Research Vehicle, in which the compatibility of one of the engines studied with an automobile of advanced crashworthiness is demonstrated.

2.0 MAJOR CONCLUSIONS

The data of vehicles and engines which were evaluated are listed in Table 1. It summarizes the major results.

2.1 FUEL ECONOMY

The composite fuel economy of vehicles in the 2000-to-3000 lb inertia weight range equipped with naturally aspirated Diesel engines varies by 24 % from 41 to 33 mpg (4.1.1).

Comparing naturally aspirated and turbocharged Diesel engines with equivalent output the composite fuel economy of turbocharged Diesel engines is higher by 20 % (4.1.2).

The composite fuel economy can be improved by 10 % using drivetrains designed for optimal fuel economy (4.1.2).

Varying the horsepower-to-weight ratio from 0.030 to 0.022 leads to an increase of the composite fuel economy by 8 % in naturally aspirated Diesel engines (4.1.3).

Changing the emission level from 0.41/3.4/2.0 to 0.41/3.4/1.0 g/mi HC/CO/NOx causes the fuel economy to drop by 5 % (4.1.4).

2.2 REGULATED EXHAUST EMISSIONS

It is possible to meet an emission level of 0.41/3.4/2.0 gram/mile HC/CO/NOx with all engine/vehicle systems under consideration. Complying with a NOx emission level of 1.0 gram/mile, requires exhaust gas recirculation (E.G.R.) which is problematic as far as smoke, particulates, odor, driveability, durability, and maintenance are concerned (4.2.1).

2.3 UNREGULATED EXHAUST EMISSIONS

During normal operation on the road, the smoke emitted by all engine/vehicle systems was invisible. Compared to current engine technology, the amount of particulates emitted is low, but it is doubled when E.G.R. is used.The odor level is in the range of modern Diesel engines,but increases when E.G.R. is used. The actual emissions of sulfates are largely dependent on the sulphur content of the fuel used. The emissions of ammonia and aldehydes compare to those of spark ignition engines. First measurements of polynuclear aromatic hydrocarbon emissions indicate lower values than those of gasoline engines (4.2.2).

2.4 NOISE

The acceleration noise of Diesel and gasoline engines (with identical HP/IW) is the same. Gasoline engines produce slightly less noise when idling or cruising (4.2.3).

2.5 PERFORMANCE, DRIVEABILITY, AND STARTABILITY

The acceleration performance (0~60 mph) of Diesel engine powered vehicles (2000-3000 lb) ranges from 11 to 20 sec, which is similar to vehicles equipped with spark ignition engines.

Under the operating conditions, fuel composition, and lubricants to be found in the U.S. driveability as well as startability present no major problems (4.3.1).

2.6 DURABILITY AND MAINTENANCE

The maintenance requirements of modern Diesel engines are lower than those of comparable gasoline engines. At the same time, the service life of Diesel engines is far longer (4.3.2).

2.7 INITIAL COST

Diesel engines are more expensive than gasoline engines. The higher cost are partly offset by the emission control measures required by gasoline engines. The price for the Rabbit Diesel is $ 170 higher than of the gasoline version.

2.8 COMPATIBILITY OF DIESEL ENGINES WITH STRUCTURES OF ADVANCED CRASHWORTHINESS

Studies performed on three typical vehicles in the inertia weight classes of 2250 lb to 3000 lb have shown, that the installation of Diesel engines comply with safety requirements, and that it does not entail significant changes in either vehicle geometry or vehicle weight (4.4).

2.9 ADVANCED ENGINE/VEHICLE SYSTEMS

The compatibility of turbocharged Diesel engines with advanced vehicle concepts is demonstrated by two vehicles. One vehicle, a VW-Rabbit (2250 lb inertia weight) equipped with a turbocharged Diesel engine, has been subjected to testing by the U.S. Environmental Protection Agency. Preliminary results are (5.1):

- 50 mpg fuel economy (composite)
- 0.42/0.93/1.01 g/mi HC/CO/NOx
- 15 seconds (0-60 mph)

To demonstrate the compatibility of a turbocharged Diesel power plant with a vehicle of advanced safety features, high performance, acceptable emissions, and good fuel economy, an Integrated Research Vehicle (IRVW) was built.
The main characteristics are (5.2):

- 2250 lb inertia weight
- 60 mpg fuel economy (composite)
- 0.41/3.4/1.5 g/mi HC/CO/NOx
- 40 mph frontal impact
- 13.5 seconds (0-60 mph)

Table 1 **Main Results of the Evaluated Engine/Vehicle Systems**

No.	Vehicle Size	No. of Passengers	Inertia Weight	Diesel Engine Type	No. of Cylinders	CID	HP	HP/IW
1	SC	4	1750	N.A.	4	90	50	0.029
2	SC	4	2000	N.A.	4	90	50	0.025
3	SC	4	2250	N.A.	4	90	50	0.022
4	SC	4	2500	N.A.	4	90	50	0.020
5	SC	4	2250	N.A.	5	130	66	0.029
6	C	5	2750	N.A.	5	130	66	0.024
7	C	5	3000	N.A.	5	130	66	0.022
8	SC	4	2250	TC	4	90	70	0.031
9	C	5	2750	TC	4	90	70	0.025
10	C	5	3000	TC	4	90	70	0.023
11	C	5	3000	N.A.*	6	146	75	0.025
12	C	5	3000	TC*	6	146	100	0.033
13	C	5	3000	N.A.*	8	180	100	0.033
14	SC	4	1750	N.A. EGR	4	90	50	0.029
15	SC	4	2000	N.A. EGR	4	90	50	0.025
16	SC	4	2250	N.A. EGR	4	90	50	0.022
17	SC	4	2250	TC EGR	4	90	70	0.031
18	C	5	2750	TC EGR	4	90	70	0.025
19	C	5	3000	TC EGR	4	90	70	0.023

*Projected Engines

Abbreviations: SC: Subcompact, C: Compact
N.A.: Naturally Aspirated, TC: Turbocharged
EGR: Exhaust Gas Recirculation Device
TIA: Total Intensity of Aroma
CID: Engine Displacement in Cubic Inch
HP/IW: Horsepower to Inertia Weight Ratio

Accel. Time 0-60	Accel. Time 30-70	Comp. Fuel Econ.	Applicable Emission Standard HC/CO/NOx	Emissions Achieved in Lab. HC/CO/NOx	Particul. Emiss-ions	Odo-rants (TIA)	Noise		
							Idle 0.5 m	Accel. 15 m	Const. 15 m
14.0	16.9	43	.41/3.4/2	.16/0.9/1.3					
16.2	19.8	42		.15/1.4/1.3					
18.3	22.9	41		.16/1.0/1.2	0.15	1.9	78	75	63
20.6	26.3	40		.15/1.2/1.3					
13.0	14.8	36		.35/1.7/1.5					
15.9	19.0	34		.40/1.7/1.7					
17.6	20.5	33		.35/1.8/1.8			75	76	63
12.7	14.5	45		.11/0.8/0.9	0.26	1.9	79	73	63
15.7	18.2	42		.15/0.7/1.1					
17.4	20.1	40		.14/0.8/1.2					
11.1	12.0	30	.41/3.4/2	.43/2.0/1.3					
14.0	16.9	41	.41/3.4/1	.45/2.5/.40					
16.2	19.8	40		.45/2.5/.46					
18.3	22.9	39		.40/2.5/.47	0.32	2.9	73	71	61
12.7	14.5	43		.20/1.2/.40	0.45	2.9	76	69	61
15.7	18.2	40		.17/1.5/.40					
17.4	20.1	38	.41/3.4/1	.17/1.6/.50					

Units: Acceleration Time in sec.
Fuel Economy in mpg
Emissions in gram/mile
Noise in dB (A)

3.0 APROACH EMPLOYED IN THE STUDY

The following tasks were performed for an assessment and evaluation of the impact of introducing Diesel-powered automobiles on the U.S. market:

- Fuel economy as a function of vehicle weight, emission level, performance, engine technology, and drivetrain.

- Feasible technologies by means of which the two emission levels of .41/3.4/2.0 and .41/3.4/1.0 gram per mile of HC/CO/NOx can be reasonably attained.

- Degree of modifications required for the concept and design of Diesel engine powered automobiles complying with safety requirements.

- Consumer Attributes.

The study is based on light-weigt passenger car Diesel engines in production, pre-production prototypes, and research engines. To cover the entire performance range from 50 to 100 horsepower at various horsepower-to-weight ratios, two engine families were established (Fig. 1) by:

- Variation of displacement (increasing number of cylinders), and

- Turbocharging, to minimize the number of basic engines.

The first engine family is made up of four engines:

- 4-cylinder naturally aspirated engine, 50 HP
- 5-cylinder naturally aspirated engine, 66 HP
- 6-cylinder naturally aspirated engine, 75 HP
- 8-cylinder (V-8) naturally aspirated engine, 100 HP (projections only)

The second family consists of two basic engines and two turbocharged versions:

- 4-cylinder naturally aspirated engine, 50 HP
- 4-cylinder turbocharged engine, 70 HP
- 6-cylinder naturally aspirated engine, 75 HP
- 6-cylinder turbocharged engine, 100 HP (projections only)

The applicability of both engine families for vehicles in the curb weight range of 1900 to 2900 lb was analyzed and all reasonable engine/vehicle combinations were simulated and evaluated. Three typical engine/vehicle systems of differing horsepower-to-inertia-weight ratios (HP/IW: 0.022; 0.025; 0.030) were tested on engine as well as on vehicle level.

Furthermore, certain drivetrain variations were analyzed and tested:

- Variation of final axle ratio,
- Variation of gear ratio,
- 4-and 5-speed transmission.

In addition, the two engine families enabled us to

- Indicate the effect of turbocharging on fuel economy, performance, and emissions;
- Compare naturally aspirated and turbocharged Diesel engines of approximately the same output; and to
- Compare the Diesel engines to spark ignition engines of equivalent output.

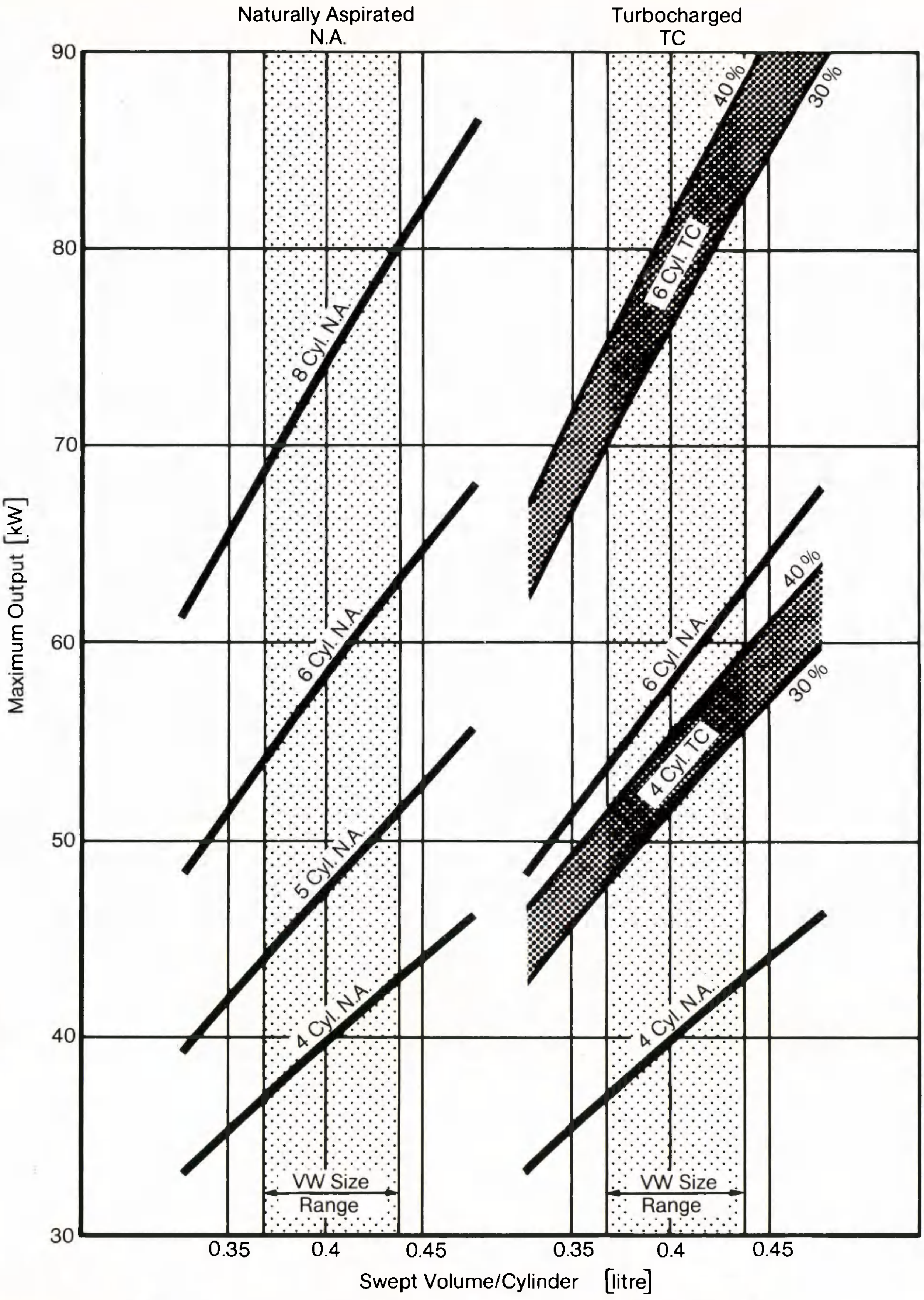

Figure 1 Performance of Engine Families.

All emissions (HC/CO/NOx) and fuel economy tests were performed in accordance with the requirements of Federal Register Part 86 and Part 600. In addition to this, unregulated emissions were measured:

- Particulates,
- Smoke,
- Odor,
- Sulfates,
- Ammonia and aldehydes.

Noise tests were run comparing the results to those obtained from equivalent vehicles powered by spark ignition engines.

The compatibility of Diesel engines and light-weight vehicle structures of current and advanced crashworthiness was evaluated by preliminary designs. The influence on weight, roominess, and vehicle geometry in front, mid, and rear-engine configurations at three safety levels (30, 40 and 45 mph frontal impact velocity) was studied.

Finally, the following consumer attributes were considered and evaluated.

- Acceleration and passing performance,
- Gradeability,
- Startability,
- Driveability,
- Operation under the range of operating environments found in the U.S.,
- Durability,
- Reliability,
- Maintenance requirements,
- Fuel grade and lubricants, and
- Cost.

Based on these evaluations, we established the intercorrelations and sensitivities to be found between the individual parameters.

For purposes of verification and demonstration, Volkswagen has provided a turbocharged Diesel Rabbit equipped with a 4-speed manual transmission and an 'Integrated Research Vehicle (IRVW)'. The IRVW demonstrates the compatibility of a turbocharged Diesel engine, a 5-speed transmission, and a structure of advanced crashworthlness.

4.0 Results

4.1 FUEL ECONOMY

To determine the interdependence between fuel economy, vehicle weight, performance described by the horsepower-to-inertia-weight ratio, engine technology, and the two emission levels (.41/3.4/2.0 and .41/3.4/1.0 gram/mile HC/CO/NOx), the engine/vehicle systems shown in Table 1 were tested on engine and vehicle level in the 1750 to 3000 lb inertia weight range.

4.1.1 Vehicle Weight

The 50 HP naturally-aspirated 4-cylinder Diesel was tested in the 1750-to-2500 lb inertia weight classes. Its fuel economy was found to range from 43 to 40 mpg in the Composite Driving Cycle (Figure 2).

The 66 HP naturally-aspirated 5-cylinder research Diesel engine was tested in the 2250-to-3000 lb inertia weight classes, the resultant fuel economy ranges from 36 to 33 mpg (Figure 2). Following our experience with the 4-cylinder engine now in production we project for this engine a potential improvement of 2 mpg.

The 70 HP turbocharged 4-cylinder research Diesel engine was tested in the 2250-to-3000 lb inertia weight classes. Compared to the naturally-aspirated 5-cylinder engine, its fuel economy is better, ranging between 45 and 40 mpg (Figure 2).

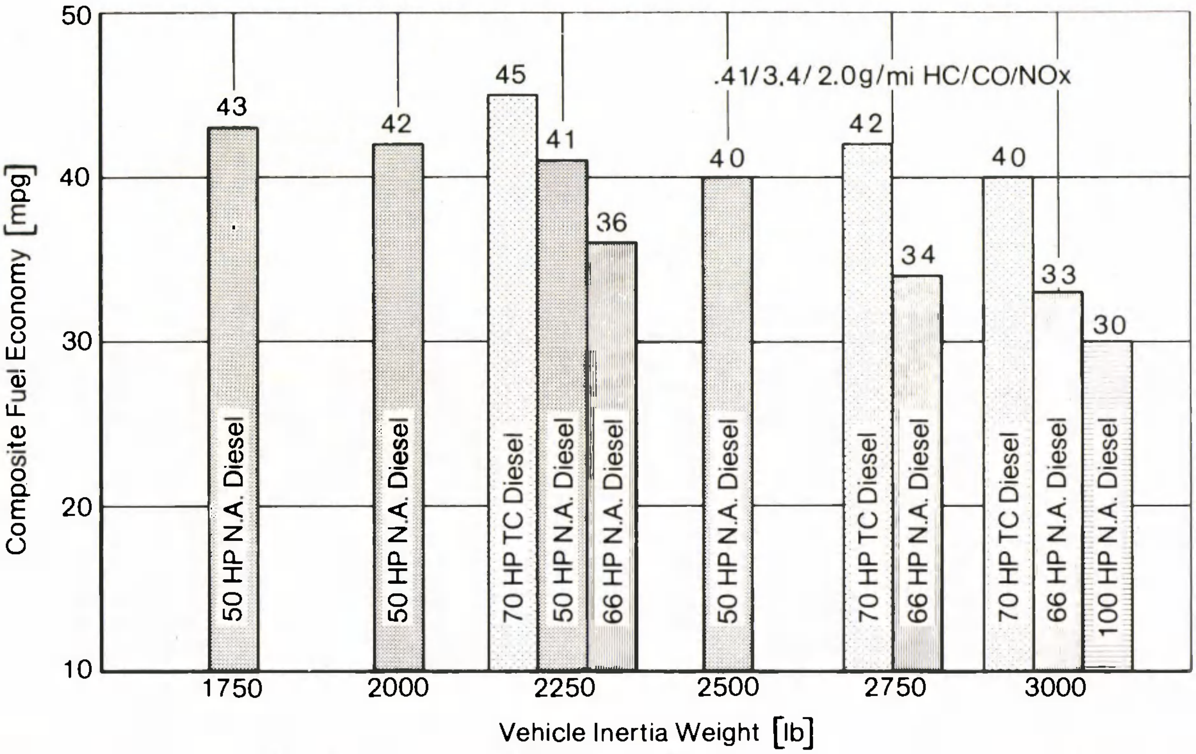

Figure 2 Composite Fuel Economy of Various Diesel Engines Averaged over the City and Highway Driving Cycles.

The fuel economy is given in terms of No.2 Diesel fuel. The figures given may vary by ± 2 mpg.

4.1.2 Engine Technology and Drivetrain

A comparison between the equivalent HP/iW ratios of vehicles equipped with naturally aspirated and turbocharged engines shows the inherent potential of advanced technologies (Figure 3). Compared to a turbocharged engine of the same performance, the fuel economy of a naturally-aspiratet engine is worse by 18 % at an inertia weight of 2250 lb. The drop in fuel economy caused by increased HP/IW ratio is significantly smaller than the fuel economy saving attending improvements in engine technology. Fuel economy can be improved by another 10 % (Figure 9) by matching the transmission to optimum fuel economy requirements (5-speed transmission).

4.1.3 Performance

Increasing the HP/IW ratio from 0.022 to 0.030 leads to a deterioration in the fuel economy of the naturally-aspirated engines of approxemately 8 % in the 2250 lb inertia weight class (Figure 3). This may be explained by the fact that in naturally-aspirated engines any increase in the number of cylinders and in displacement entails an increase in internal friction losses. But it should be noted that this difference in fuel economy is submerged by the scatter bandwidth.

4.1.4 Emission Level of 0.41/3.4/1.0 gram/mile HC/CO/NOx

Research prototypes fitted with modulated E.G.R. to meet NOx less than 1.0 gram/mile indicated a 5 % loss in fuel economy.

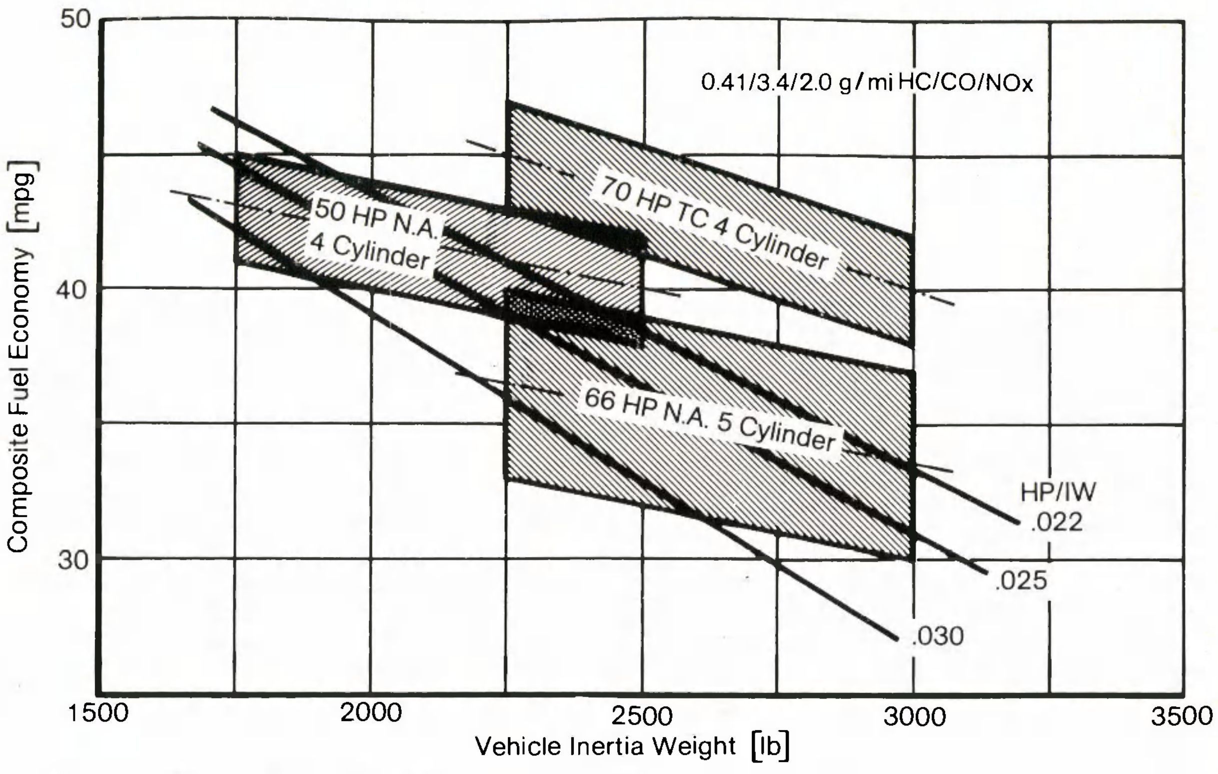

Figure 3 Comparison of Fuel Economy of 3 Different Diesel Engines.
The scatter band of the 66 HP engine Is wider because of its state of development.

4.2 EMISSIONS

As far as laboratory results are concerned it was possible to meet the emission level requirement of 0.41/3.4/2.0 gram /mile HC / CO / NOx. In order to comply with a NOx emission level of less than 1.0 gram/mile exhaust gas recirculation was required. Using E.G.R., entails some adverse effects, such as increased smoke and odor levels as well as poor driveability.

4.2.1 Regulated Exhaust Emissions

4.2.1.1 Emission level of 0.41/3.4/2.0 gram/mile HC/CO/NOx

Figures 4 and 5 show the regulated exhaust emission results for both emission levels. As far as the 4-cylinder naturally-aspirated engine and the turbocharged version are concerned, the margin necessary for manufacturing tolerances and a deterioration factor are acceptable. The results obtained from the 66 HP naturally aspirated Diesel engine and the projected 100 HP naturally aspirated Diesel engine are sufficient to meet a NOx emission level of 2.0 gram/mile.

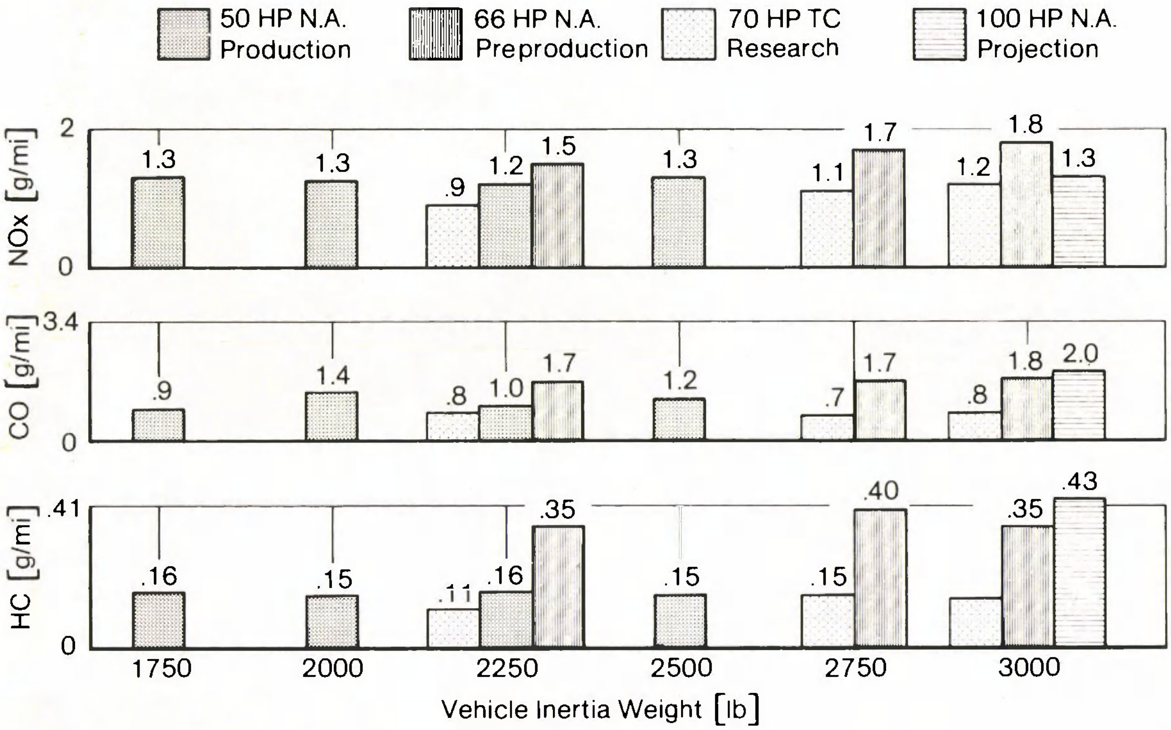

Figure 4 Regulated Exhaust Emissions from Various Diesel Engines.
Deterioration factors and variances due to manufacturing (30% of the figures indicated) are not taken into account.

4.2.1.2 Emission Level of 0.41/3.4/1.0 gram/mile HC/CO/NOx

Using laboratory engines, we were able to lower the emission of NOx to 0.85 gram/mile at an inertia weight of 2250 lb by engine internal measures (swirl chamber geometry, injection profile).This caused the fuel economy to drop by 4 %.

In order to comply with the stringent emission level of .41/3.4/1.0 (HC/CO/NOx) in production engines we were striving to reach engineering goals (50 % of the given emission level) approximately. Research prototypes fitted with modulated E.G.R. reached this goal but the HC emissions deteriored much more significantly, increasing to twice the original amount, which means that the naturally-aspirated engine went beyond the 0.41 gram/mile limit. The emission of CO also rose significantly. In order to overcome the most adverse effects of E.G.R., such as

- increased smoke level,
- increased odor level,
- reduced durability,
- increased maintenance requirements, and
- poor driveability,

even turbocharged engines will have to wait for a technological breakthrough.

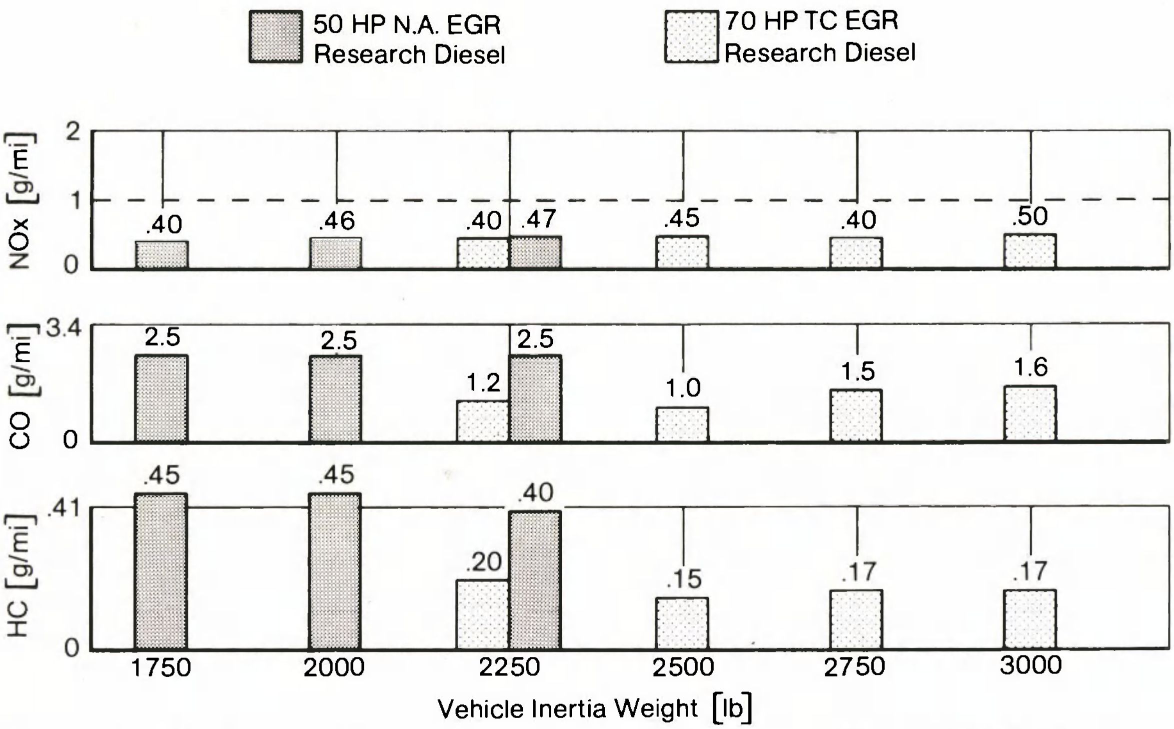

Figure 5 Regulated Exhaust Emissions of Two Diesel Engines with Controlled Exhaust Gas Recirculation (Preliminary Data).

The trade-off between low NOx, and acceptable HC and CO is a function of the amount of exhaust gas recirculated (EGR). Note the increased smoke and odor levels which are due to EGR.

4.2.2 Unregulated Exhaust Emissions

For the two emission levels of .41/3.4/2.0 and .41/3.4/1.0 gram/mile HC/CO/NOx, unregulated emission data have been generated according to the FTP-75 test procedure for both the 50 HP naturally-aspirated and the 70 HP turbocharged engine. We expect unregulated emissions of the 5-cylinder engine to be the same as those of the 4-cylinder naturally-aspirated engine.

4.2.2.1 Smoke

Smoke is assessed visually, i.e. according to its opacity, which should be below the limit of visibility if the engine is adjusted properly, especially if it is a swirl-chamber engine (Bosch Number: Less than 3.5 at full load). While cruising, the smoke emissions of all engine/vehicle systems were found to be invisible.

4.2.2.2 Particulates

Fig. 6 shows the emission of particulates at the two emission levels. The emission of the 50 HP naturally aspirated engine (0. 5 gram/mile) and of the 70 HP turbocharged engine(0.26 gram/mile) are the lowest values known of current Diesel engines. Turbocharging produces higher particulate emissions, but the exhaust gas is less opaque due to the increased throughput of air. If E.G.R. is applied the emission of particulates increases by a factor of two.

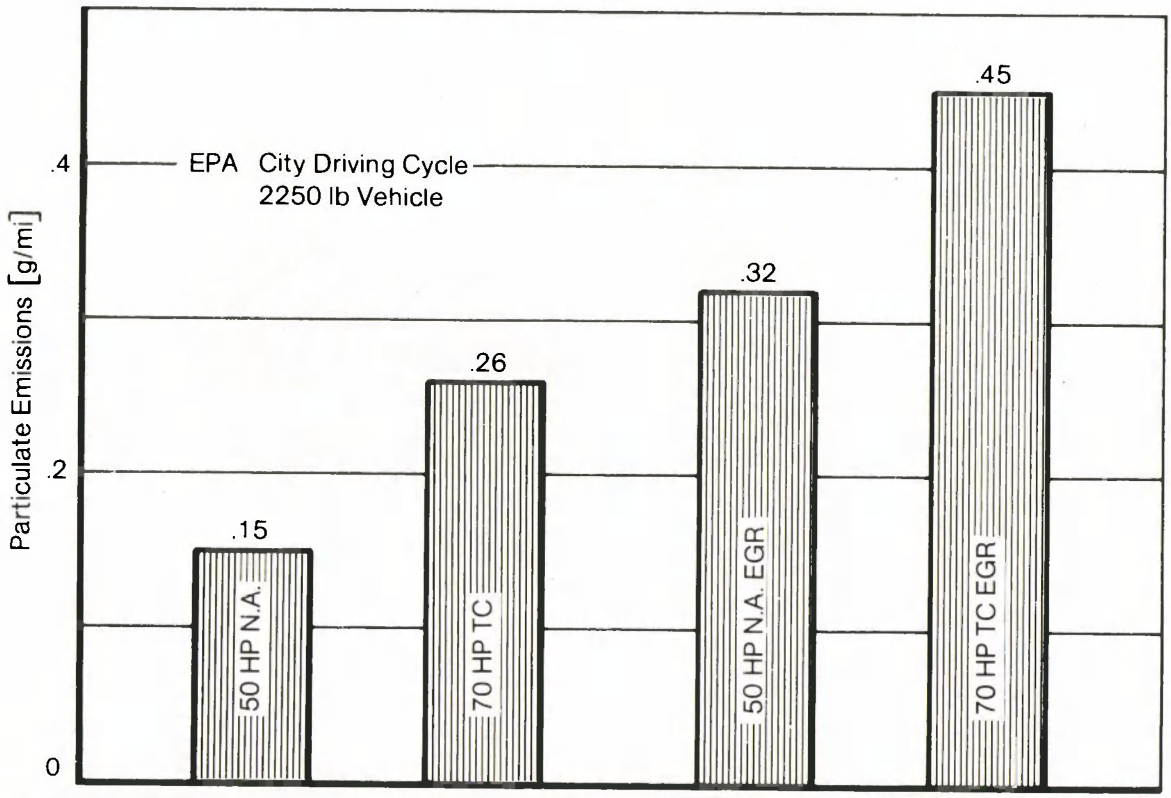

Figure 6 Particulate Emissions.
Test results for current Diesel engines measured by EPA: .30 to .62 g/mi.

4.2.2.3 Odor

The odor emission was calculated mainly from the mass emissions of two odorants, aromatic hydrocarbons and partially oxygenated hydrocarbons. When combined on a logarithmic scale indicating the so-called total intensity of aroma (TIA) their indication seems to agree with the response of the average human nose. Fig. 7 shows the influence of E.G.R. and of fuel composition on odor. There is no difference between naturally-aspirated and turbocharged engines in this respect. If E.G.R. is applied, the odor level rises by one unit. Fluctuations amounting to half a unit are caused by the differences in the composition of the two fuels used. Consequently, there seems to be a connection between a low odor level and HC emissions.

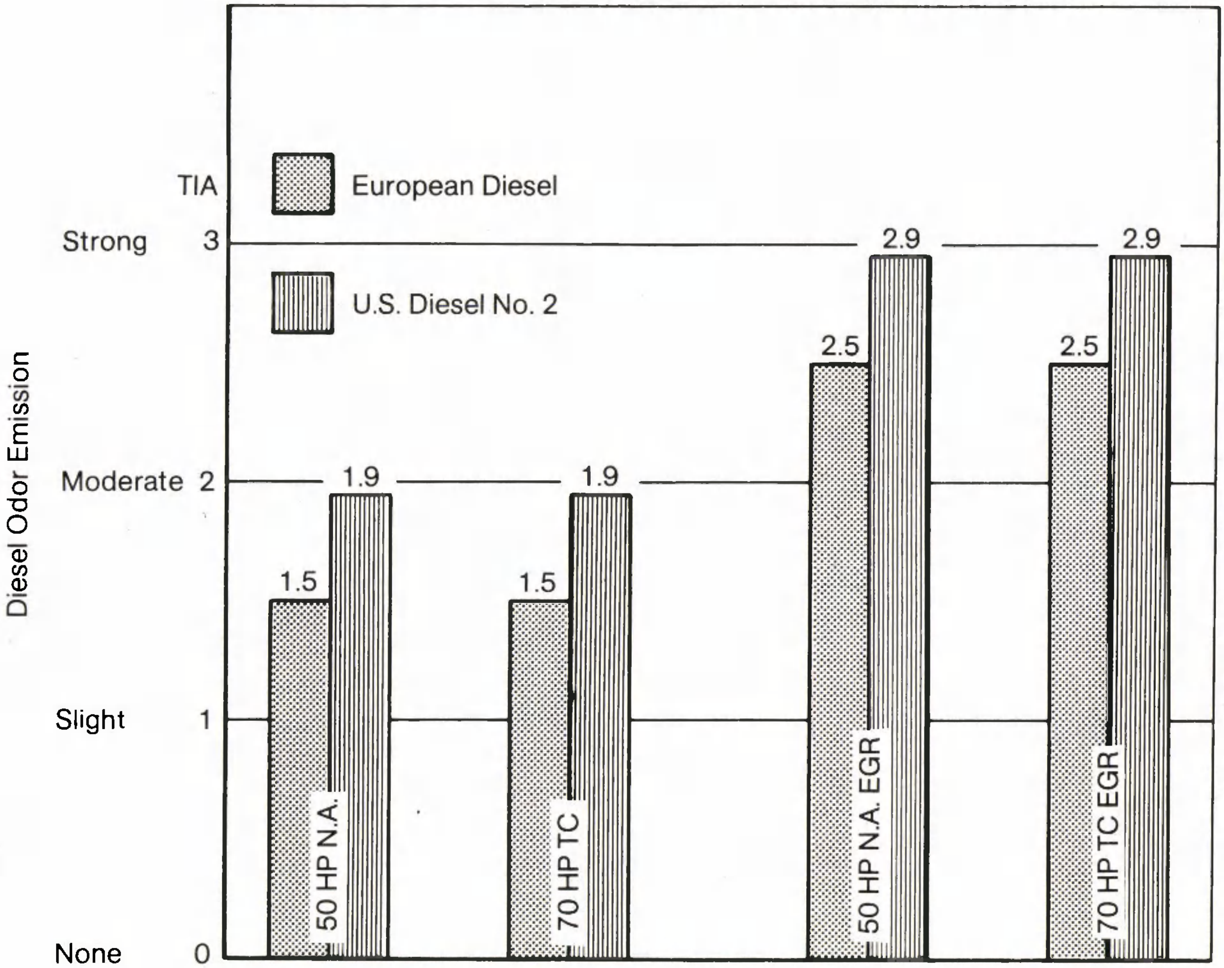

Figure 7 Diesel Odor Emission Averaged over a City Driving Cycle Influenced by Fuel Composition and Exhaust Gas Recirculation (EGR).
Odor values may vary by ± 0.25 units.

4.2.2.4 Sulfates

Of the total amount of sulphur contained in Diesel fuel, a fraction ranging from 1 to 2 % is converted into sulfates, which is equivalent to the conversion rate of spark ignition engines (2 %). Mainly, the differences between the emissions of Diesel and gasoline engines are due to the unequal sulphur content of the fuels, which in Diesel fuels ranges from 0.1 to 0.5 % by weight, and in gasoline corresponds to 0.03 % by weight. About 80 to 90 % of the sulphur is burned into sulphur dioxide (SO_2), whereas the remaining 10 to 20 % are shared by several other sulphur compounds.

4.2.2.5 Ammonia

Ammonia is emitted at the same rate as by spark ignition engines (from 3 to 6 mg/mile).

4.2.2.6 Aldehydes

Diesel engines emit aldehydes at a rate of 20 to 30 mg/mile, as compared to 30 to 100 mg/mile produced by gasoline engines.

4.2.2.7 Polynuclear Aromatic Hydrocarbons

Based on findings of earlier studies made by VW on gasoline engines, the emissions of polynuclear aromatic hydrocarbons were found to be lower for Diesel engines. There are no secure data concerning the impact of these hydrocarbons on health.

4.2.3 Noise Emission

The noise emitted by the engines was measured according to the following requirements:

- measuring the noise of a full-load acceleration from 30 mph according to SAE J 986a, and
- measuring the noise of a 30 mph constant speed drive by at a distance of 30 ft,
- measuring the idle noise at a distance of 0.5 m from the vehicle front.

For various engine/vehicle systems, the results of these tests include:

- the interior noise level at constant speed,and
- the interior noise level at full-load acceleration (Fig. 8.).

When comparing Diesel and gasoline engines of the same output installed in the same vehicle

- the noise level at full-load acceleration is the same, and
- the noise level at constant speed is lower in gasoline engines.

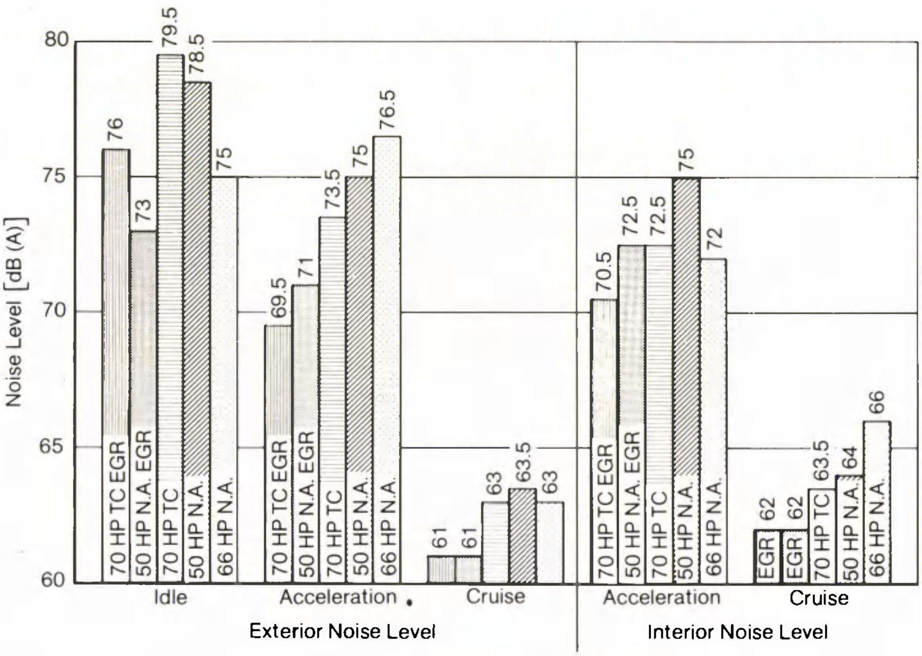

Figure 8 Noise Emission by Various Engine/Vehicie Systems Measured at a Speed of 30 mph and at a Distance of 15 m (50 ft) according to SAE J 986 a.
(Idle noise measured at 0 5 m=1.65 ft).
The noise tolerance is ± 1 dB (A).

4.3 CONSUMER ACCEPTABILITY AND COSTS

4.3.1 Performance, Driveability, and Startability

All engine/vehicle systems have been tested under the range of operating environments found in the U.S. in order to establish their performance, driveability, and startability.

4.3.1.1 Performance

The performance of a vehicle is indicated by the following parameters:

- Acceleration time from 0 to 60 mph (less than 20 seconds);
- Time for performing a passing maneouver between 30 and 70 mph (less than 25 seconds);
- Top speed (not less than 75 mph);
- Maximum gradeability (not less than 30 %).

The actual performance of a vehicle mainly depends on its horsepower-to-weight ratio. The extent of this influence may be lessened by adjusting the transmission accordingly.

Fig. 9 shows the relationship existing between fuel economy, acceleration time from 0 to 60 mph, inertia weight, and transmission ratio.

Fig. 10 shows the relationship existing between passing performance, gradeability, inertia weight, and transmission ratio in the case of a 70 HP turbocharged Diesel engine. The gradeability is limited by the traction of the tires.

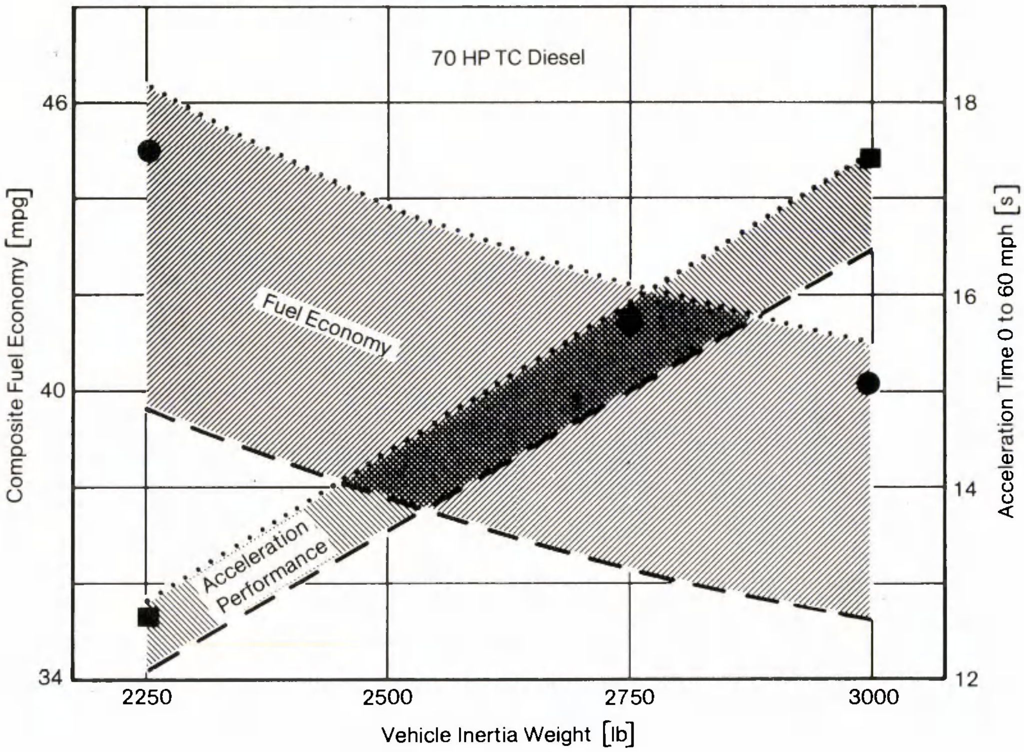

Figure 9 Fuel Economy and Acceleration Performance as a Function of Drivetrain Ratio and Weight.
70 HP Turbocharged Research Diesel; Manual Transmission.
—— Limit for max. performance, top speed 75 mph, n/v = 66 rpm/mph.
• • • • Limit for max. fuel economy, acceptable performance, n/v = 38 rpm/mph.
● Fuel economy for recommended n/v = 50 rpm/mph.
■ Acceleration performance for recommended n/v = 50 rpm/mph.
The figures may vary by ± 2 mpg and ± 0.5 sec.

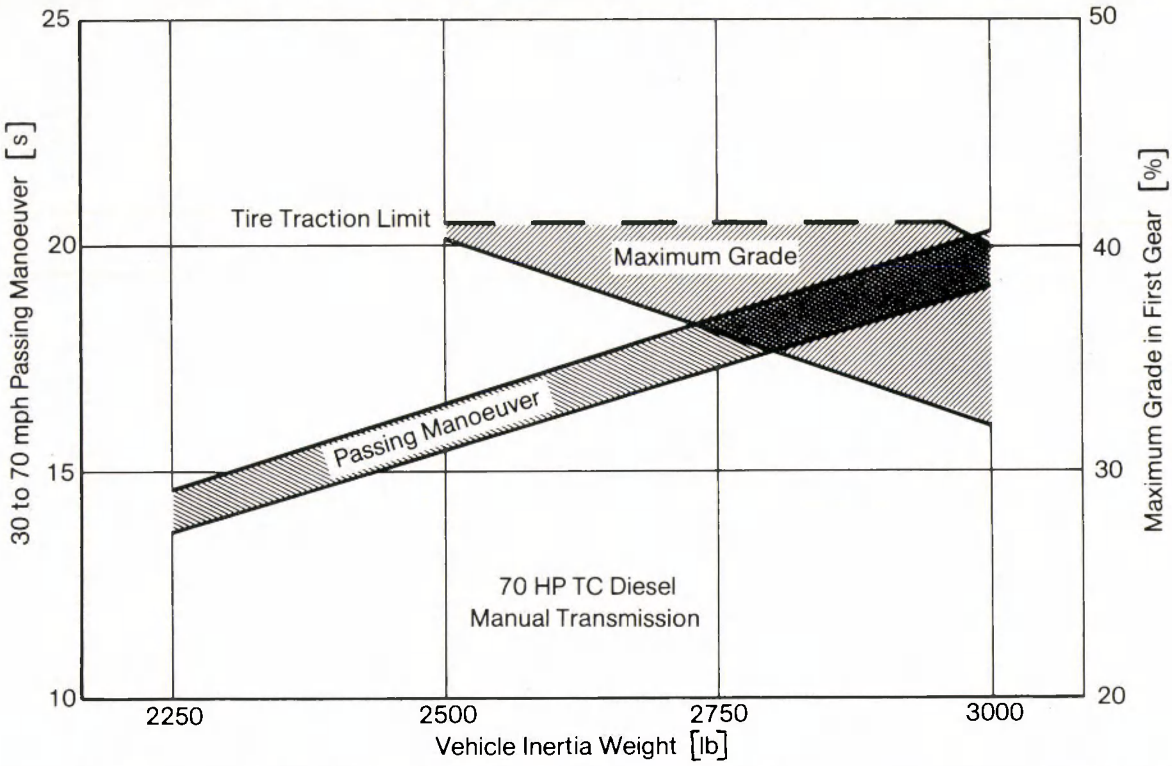

Figure 10 Time Range for a 30 to 70 mph Passing Manoeuver and Maximum Grade as a Function of Driveline Ratio and Inertia Weight.
70 HP turbocharged Diesel engine; manual transmission; front-wheel drive.

4.3.1.2 Driveability

Driveability was tested in accordance with a Volkswagen test procedure. Each vehicle was tested by a panel of expert drivers who awarded merit points for properties such as,

- Startability: Number of successful cold starts/total number of trials;
- Idling quality: Assessment of the smoothness of the engine run as judged from the driver's seat;
- Noise: Judged from the driver's seat;
- Surge: Short abrupt power fluctuations at any speed or load;
- Hesitation: A temporary lack of initial engine response to accelerator action;
- Pick-up Performance: Judged from the driver's seat;
- Acceleration jolt: Jerks felt in the driver's seat which are caused by exessively fast engine response.

Awards ranged from 0 to 10 merit points, no less than 5 being required to indicate customer acceptance.

When plotted chronologically, the merit points awarded for each property form a 'subjective driveability profile'. As the weight of each property and the interconnections existing between them are ambiguous we did not evaluate any sums of all merit points awarded.

In the following figures, driveability profiles are shown which were obtained from tests performed in the Alps at an altitude of 2200 m (7200 ft) and a temperature of approximately 0°C (32° F).

Fig. 11 is a comparison of driveability profiles obtained from a Diesel and a gasoline engine of the same output. Disregarding its idle noise, the cold-start performance of the Diesel engine is more acceptable. No difference was found in the warm-up and warm running phases.

Fig. 12 is a comparison between the driveability profiles obtained from a turbocharged 70 HP research Diesel engine and a 78 HP gasoline engine which meets the U.S. emission standards of '77. The startability of this prototype Diesel engine can be improved. The noise level of the gasoline engine was judged to be better, but the Diesel engine showed up well as far as some other properties are concerned. The comparisons mentioned above tend to favor the Diesel engine because of its better idling quality.

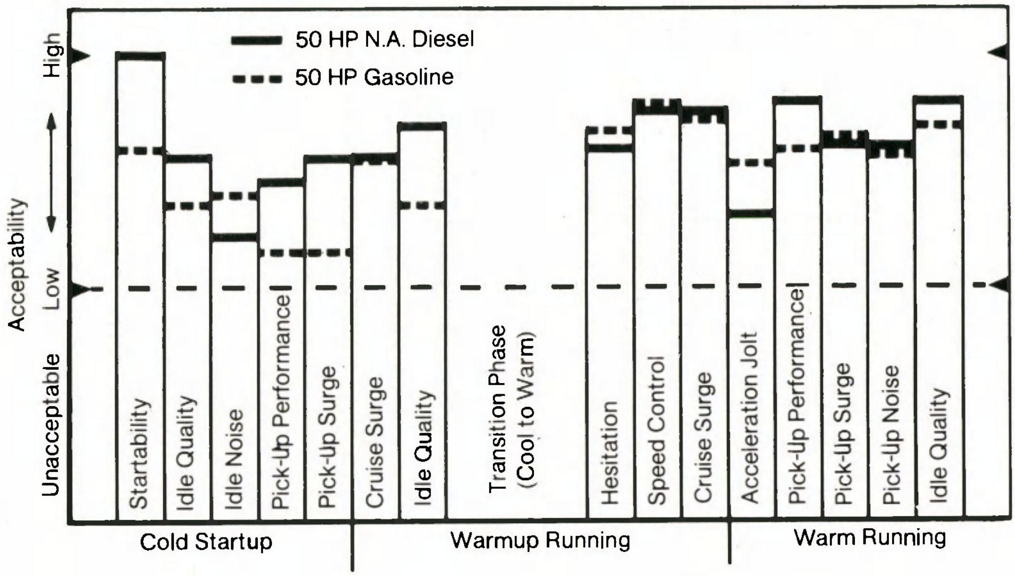

Figure 11 Subjective Driveability Profile.
50 HP Diesel versus 50 HP gasoline Rabbit.

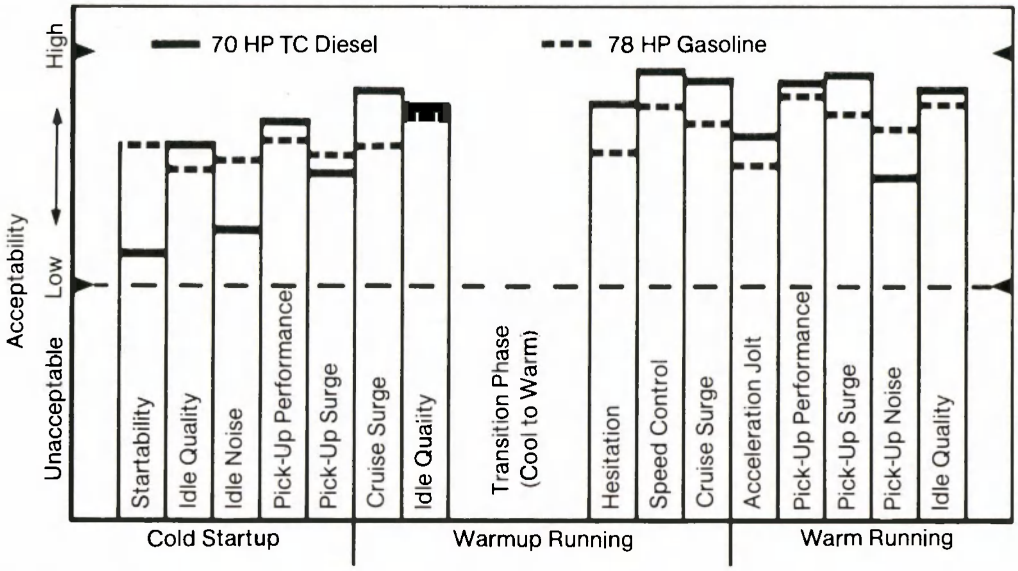

Figure 12 Subjective Driveability Profile.
70 HP turbocharged Diesel versus 78 HP gasoline Rabbit.

Fig. 13 shows the deterioration of a driveability profile caused by introducing exhaust gas recirculation in order to meet stringent emission standards. Although startability may be improved, surge and pick-up performance still cause severe problems.

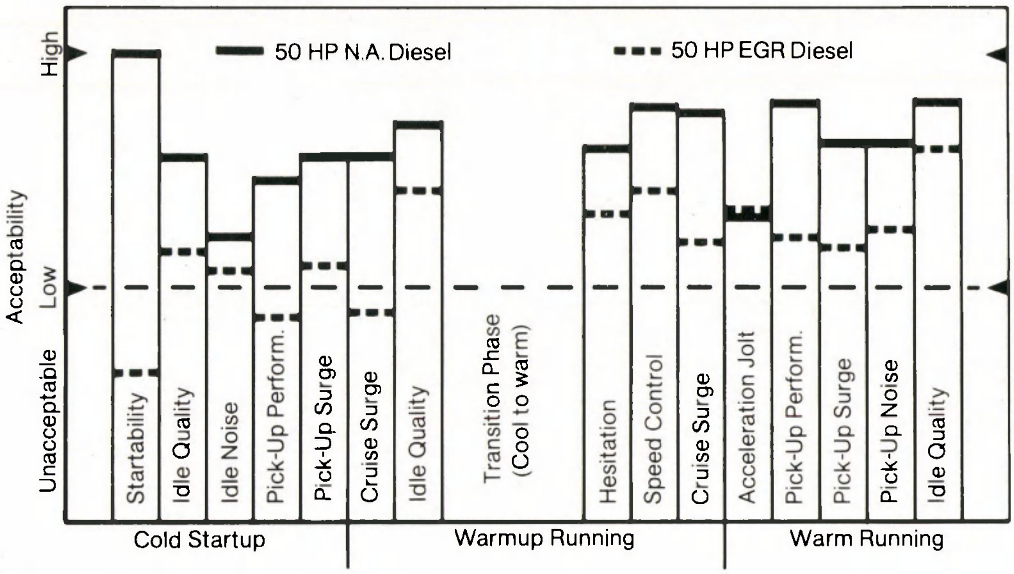

Figure 13 Subjective Driveability Profile.
Comparison of a Rabbit with 50 HP production Diesel engine versus a Rabbit with the same engine equipped with a research EGR device.

4.3.1.3 Startability

Our assessement of the start-up behavior was based on the range of environmental conditions found in the U.S..At extremely low temperature, the startability of Diesel engines is limited by the thermodynamics of the process of self-ignition. Preheating ensures good starting at low temperatures and minimum blue-smoke emissions. The engines have shown themselves capable of starting at any temperature above $-25°$ C($-11°$F) provided that adequate fuel is used. The so-called Cold Filter Plugging Point (CFPP) indicates the low-temperature properties of Diesel fuels. The properties of winter-grade fuels have to be adapted to the prevailing geographical requirements. At temperatures below $-25°$ C, it may be necessary to use auxiliary devices like starting fluids.

4.3.1.4 Tests at High Altitudes

At high altitudes, the power output of both Diesel and spark ignition engines drops because of the low air density. However, the power output of Diesel engines drops less significantly than that of spark ignition engines.

For every 1000 m additional altitude, the power output drops by about 5 % with the fuel rate remaining constant, while the emission of smoke increases noticeable. The smoke level may be lowered by means of an atmospheric pressure correction device.

4.3.2 Durability and Maintenance Requirements

The results of experiments and of extensive durability tests performed on a fleet of 300 cars powered by Diesel engines show that Diesel engines are more durable than spark ignition engines. Endurance dynamometer tests made with the engines running at full load over 83% of the time showed that the service life of the 4-cylinder naturally-aspirated Diesel engines is twice as long as that of the spark ignition engines.

We ran EPA durability tests in order to determine emission behavior as a function of service life. They established that the fuel economy and emissions of the naturally-aspirated Diesel engines will remain stable over 50,000 miles. We do not expect commercial U.S. fuels to cause engine troubles. We tested 7 representative fuels, compositions differing in octane number, aromatics content, and end-point in cooperation with the oil industry. Using a multigrade lubricant based on SAE W15 oil guarantees satisfactory cold start behavior.

The same lubricant can be used for both Diesel and spark ignition engines. Low oil pollution enabled us to set the oil change interval at 7,500 km and the oil filter change interval at 15,000 km, which is analogous to spark ignition engines. The strain imposed on the oil through viscosity increase due to soot is relatively low, and vehicles cold-start properties have been adapted to that fact. For this reason, the oil viscosity specifications are the same as those for the spark ignition engine.

It is possible that the turbocharged engine versions may require the use of more highly sophisticated materials because their operating temperatures are higher. Compared to current Diesel practice, these maintenance requirements are less demanding because of the low quantity of soot communicated to the lubricant. The toothed-belt drive design of the VW Diesel engines facilitates economical maintenance because it is not elastic and does not need any lubrication.

4.3.3 Initial Cost and Manufacturing Impacts

Diesel engines are more expensive than gasoline engines. This higher cost is partly offset by the emission control measures in gasoline engines. Compared to the gasoline engine the additional cost of the naturally aspirated 4-cylinder Diesel engine is $ 170, which is more than balanced by the comparatively lower cost of fuel and maintenance. To this date it is impossible to estimate the additional cost of a turbocharged Diesel engine because it is a prototype and we do not yet have any production figures available.

A familiy consisting of inline engines only has distinct advantages. Besides using the same internal components such as valves, piston and connecting rods etc., the transfer line machines can be adapted to accommodate units with varying numbers of cylinders. New castings are of course necessary for the cylinder block, cylinder head, crankshaft and camshaft for each number of cylinders and seperate machines are also required for individual crankshaft and camshaft sizes.

V-engines have disadvantages in terms of production compatability, particularly when transfer machinery already exists for inline engines. V-engine configuration also requires different design at the ends of the cylinder block to allow for the stagger of the cylinder banks. Production compatability therefore favours families consisting of inline engines.

If turbocharged engines are used, a given power range is covered with a smaller number of basic engines. In some cases there could be a commonality of Diesel and spark ignition engine components.

Assuming joint production of Diesel and spark ignition engines, one should aim to make sure that both the cylinder head and the cylinder block could be machined on the same transfer line as those of the spark ignition engines.

4.4 COMPATIBILiTY OF DIESEL ENGINES WITH STRUCTURES OF ADVANCED CRASHWORTHiNESS

Three typical vehicles were analyzed to investigate the compatibility between light-weight automotive Diesel power plants and frontal impact crashworthiness at the following three safety levels:

- Current safety practice,
- Current safety practice and 40 mph frontal impact,
- Current safety practice and 45 mph frontal impact.

The typical vehicles were:

- VW Rabbit (2250 pounds inertia weight),
- VW Dasher (2500 pounds inertia weight), and
- AUDI 100 (3000 pounds inertia weight).

4.4.1 Vehicle Structure

The studies at all three safety levels were based on the assumption that the deformation characteristic of the vehicle front was rectangular and that the mean deceleration amounted to 25 g. Moreover, we presumed the configuration of the structure of all three typical vehicles to be the same. Because of these assumptions, sustaining higher impact velocities did not entail any additional reinforcements of the structure, for instance to the sides of the vehicle or to the fire wall, but necessitated lengthening the deformation zone while keeping all beam cross sections and material thickness constant.

4.4.2 Restraint system

For the study the characteristics of VW's passive restraint system of a shoulder belt and a kneebar were used. For all tests involving higher impact velocities (40 and 45 mph) pretensioners and force limlters were added to this system. Moreover, we presumed that there would be no change of the passenger compartment and thus of the room available for forward displacement. It should be noted that the reliability of the restraint system as described above is not yet proven in mass production.

4.4.3 Effects of instrumentation of the diesel engine studied in typical vehicles.

The vehicle weights and lengths shown in table 2 have been calculated on the basis of the assumptions enumerated above and reflects only the weight and length changes of the frontal vehicle structure.

Table 2 **Effects of Instrumentation of the Diesel Engines Studied in Typical Vehicles (Constant Internal Roominess)**

TYPICAL VEHICLES	ENGINES	CURRENT SAFETY PRACTICE, GASOLINE ENGINE, BASELINE		CURRENT SAFETY PRACTICE, DIESEL ENGINE		CURRENT SAFETY PRACTICE, DIESEL ENGINE AND 40 MPH FRONTAL IMPACT		CURRENT SAFETY PRACTICE, DIESEL ENGINE AND 45 MPH FRONTAL IMPACT	
		Length INCH	Weight LB KG	Length INCH	Weight LB KG	Length INCH	Weight LB KG	Length INCH	Weight LB KG
VW-RABBIT	FRONT ENGINE TRANSVERSE 4-cyl. naturally aspirated, 50 HP	154.57	825 1819	154.57	829 1828	156.54	831 1833	161.45	837 1846
	4-cyl. turbo-charged, 70 HP	154.57	825 1819	154.57	836 1843	156.54	838 1847	161.45	844 1861
VW-DASHER	FRONT ENGINE LENGTHWISE 4-cyl. turbo-charged, 50 HP	172.43	973 2145	172.43	985 2172	176.17	990 2183	182.07	998 2200
	5-cyl. naturally aspirated, 66 HP	177.75	1019 2246	177.75	1034 2280	179.72	1037 2286	185.62	1045 2304
AUDI 100	FRONT ENGINE LENGTHWISE 5-cyl. naturally aspirated, 66 HP	191.31	1173 2586	191.31	1181 2604	191.31	1181 2604	193.30	1185 2613

5.0 APPLICATIONS

Two vehicles have been supplied to the Department of Transportation - Transportation Systems Center for the purpose of demonstrating the compatibility of light-weight Diesel engines with advanced vehicle concepts, and of verifying the test results obtained by Volkswagen.

5.1 VW RABBIT EQUIPPED WITH A TURBOCHARGED DIESEL ENGINE

This vehicle is a production Rabbit made for the U.S. and equipped with a turbocharged Diesel engine.

5.1.1 General Specifications

Body type :	2 door hatchback
Curb weight :	2061 lb
Inertia weight :	2250 lb
Overall length :	155.3 in.
Overall width :	63.1 In.
Overall height :	55.5 in.
Wheelbase :	94.5 in.
Seating capacity :	4 persons

5.1.2 Engine and Drivetrain Specifications

Engine:	4 cylinder turbocharged Diesel
Bore/stroke:	3.012/3.149 in.
Displacement:	90 cu. in.
Compression ratio:	23
Transmission :	4-speed manual
Gear ratio:	3.45, 1.54, 1.32, 0.97
Axle ratio:	3.48

This vehicle has been subjected to preliminary testing by the U.S. Environmental Protection Agency.

5.1.3 Preliminary EPA Test Results

Because of the advanced VW automotive technology the road load setting is less than the nominal value given in the Federal Register.

Fuel Economy:	Urban:	44.5 mpg
	Highway:	57.0 mpg
	Composite:	50.0 mpg
Emissions:	HC :	0.42 gram/mile
	CO :	0.93 gram/mile
	NOx:	1.01 gram/mile

Acceleration time 0 to 60 mph=15 sec.

Fig. 14 VW Integrated Research Vehicle (IRVW)

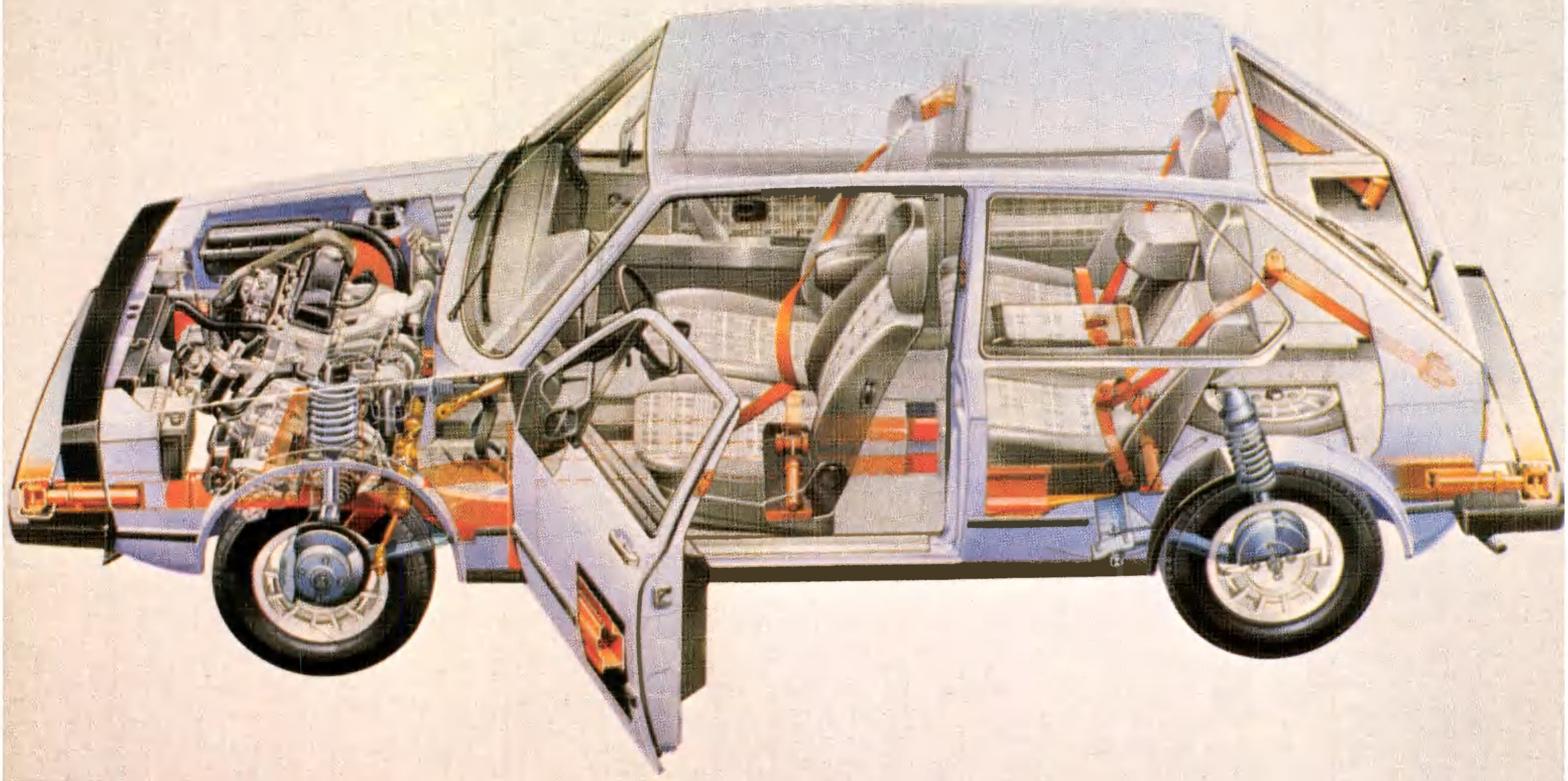

Fig. 15 Cutaway View of the VW Integrated Research Vehicle (IRVW)

5.2 INTEGRATED RESEARCH VEHICLE (IRVW)

To demonstrate the compatibility of light-weight Diesel power plants and vehicles of advanced safety features, high performance, acceptable emissions, and good fuel economy, an Integrated Research Vehicle (IRVW = Integrated Research Volkswagen, Figures 14 and 15) was designed and built from the basis of the so-called ESVW II (Experimental Safety VW No. II).

5.2.1 General Specifications

Body type:	2-door, hatchback
Overall length:	155.3 in.
Overall width:	63.4 in.
Overall height:	53.9 in.
Wheelbase:	94.5 in.
Curb weight:	2070 lb
Seating capacity:	4 persons

5.2.2 Engine and Drivetrain Specifications

Engine:	4-cylinder turbocharged Diesel
Bore/stroke:	3.012/3.149 in.
Displacement:	90 cu. in.
Compression ratio:	23
Transmission:	5-speed manual
Gear ratios:	3.45, 1.94, 1.29, 0.97, 0.75
Axle ratio:	3.7

5.2.3 Safety Features

While the ESVW II was developed, all advanced safety characteristics were incorporated in it. All major test results are shown in table 3.

5.2.4 Preliminary VW Test Results

Because of the advanced VW automotive technology the road load setting is less than the nominal values given in the Federal Register.

Fuel Economy:	Urban:	55.4 mpg
	Highway:	68.5 mpg
	Composite:	60.0 mpg

Figure 16 shows the fuel economy of the IRVW compared to the U.S. gasoline fleet 1977.
Figure 17 shows the fuel economy at steady state.

The Integrated Research Volkswagen meets the following emission standards:

HC :	0.41 gram/mile
CO :	3.4 gram/mile
NOx:	1.5 gram/mile

Noise level according to SAE J 986a: 71 dB (A).

Acceleration time 0 to 60 mph 13.5 sec.

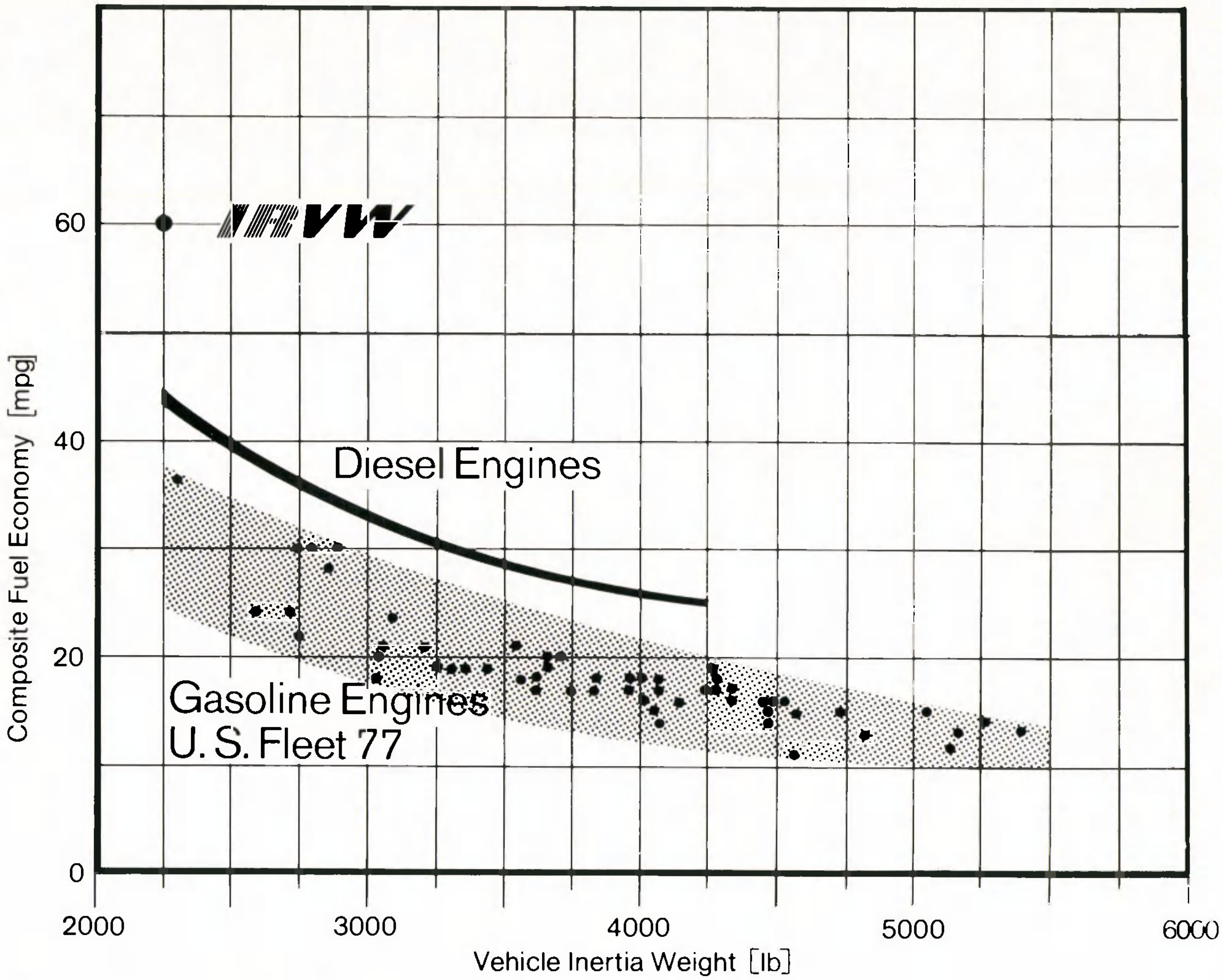

Figure 16 Comparison of Fuel Economy Results.

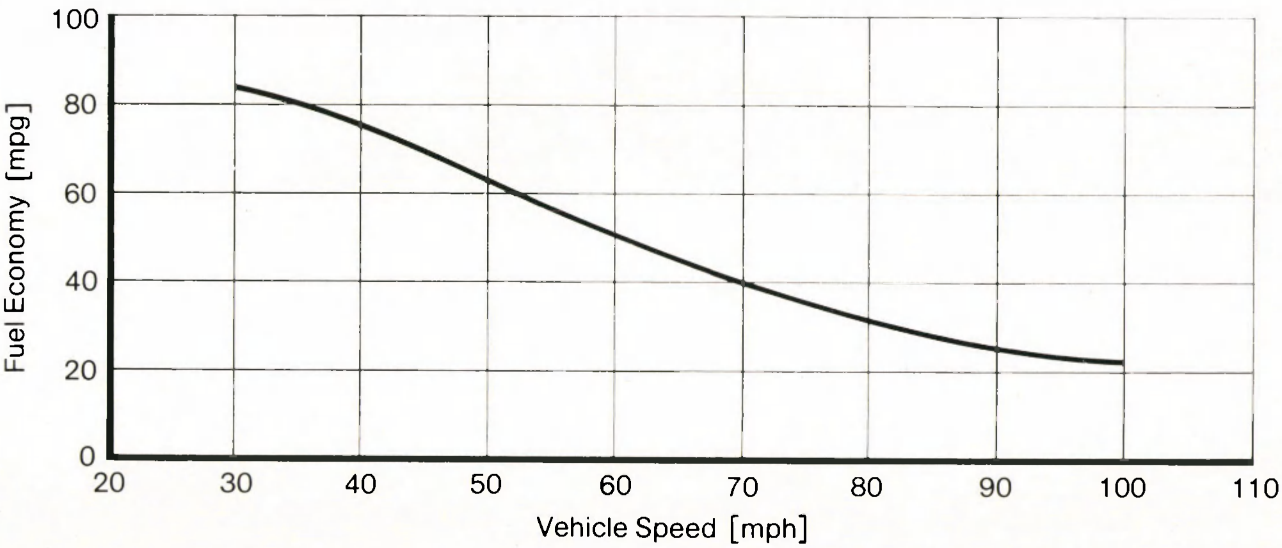

Figure 17 IRVW Fuel Economy at Steady State.

Table 3 Crash Test Results for the ESVW II.

	HIC Head			SI Chest			FEMUR LOAD			
Tolerance Level	**1000**			**1000**			**771 KP**			
	Driver	Front Passenger	Rear Passenger	Driver	Front Passenger	Rear Passenger	Driver		Front Passenger	
							Left	Right	Left	Right
40 MPH Frontal Fixed Barrier Impact	600	600	440	380	370	210	525	680	740	550
30 MPH Frontal Fixed Pole Impact	200	200	290	200	200	140	540	285	280	460
30 MPH Car-to-Car Side Collision	20	20	90	20	20	50	–	275	–	175
30 MPH Car-to-Car Rear End Collision	40	180	50	25	25	50	80	40	100	100
60 MPH Closing Speed at a Frontal Collision with a Heavy Vehicle	400	400	600	180	270	220	510	600	480	490