T NO. DOT-TSC-NHTSA-79-62.I

DOT-HS-805 276

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

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Federal Republic of Germany

1979
FINAL REPORT

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VIRGINIA 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
Office of Passenger Vehicle Research
Washington DC 20590

Technical Report Documentation Page

1. Report No. DOT-HS-805 276	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DATA BASE FOR LIGHT-WEIGHT AUTOMOTIVE DIESEL POWER PLANTS, Volume I: Executive Summary		5. Report Date December 1979
		6. Performing Organization Code
7. Author(s) B. Wiedemann, R. Schmidt, et al.		8. Performing Organization Report No. DOT-TSC-NHTSA-79-62.I
9. Performing Organization Name and Address Volkswagenwerk* Research Division 1180 Wolfsburg Federal Republic of Germany		10. Work Unit No. (TRAIS) HS017/R0411
		11. Contract or Grant No. DOT/TSC-1193
12. Sponsoring Agency Name and Address U.S. Department of Transportation National Highway Traffic Safety Administration Office of Passenger Vehicle Research Washington DC 20590		13. Type of Report and Period Covered Final Report June 30 '76-July 30 '77
		14. Sponsoring Agency Code

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge MA 02142

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 the work. The compatibility of the Diesel engine studied with passenger car structures incorporating advanced frontal crashworthiness capabilities was also verified.

The report consists of three volumes. Volume I, the Executive Summary, presents a summary of the data obtained and a review of the important conclusions. Volume II, the main body of the report, provides a discussion of the fuel economy and emissions obtained, a description of the engine/vehicle systems tested and the results of factory driveability tests. Volume III, the appendixes, presents miscellaneous data used during the program.

17. Key Words Diesels, CI-Engines, Passenger cars, Fuel economy, Safety, Emissions, Automobiles,	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	47	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

In support of the National Highway Traffic Safety Administration, Office of Passenger Vehicle Research, the Department of Transportation-Transportation Systems Center 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.

The authors wish to acknowledge the guidance provided by Mr. H.Gould and Dr.R.John of the Department of Transportation-Transportation Systems Center and Dr. K. Digges of the Department of Transportation-National Highway Traffic Safety Administration.

Our working team consisted of the following persons:
Miss C. Schwarz, Messrs. R. Graupmann, W. Lange, K.-J. Lemke, H. Leptien, Dr. G. W. Schweimer and M. Willmann.

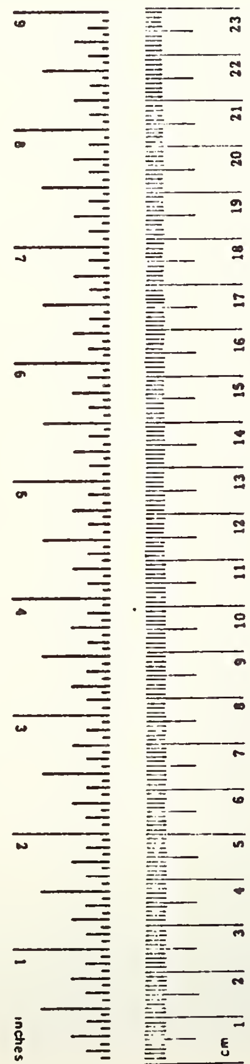
They were supported by:
Miss J. Dommschack and Messrs. H.-D. Beckmann, P. M. Deja, P. Jirousek, W. Kiegeland, W. Kurpiers, Dr. K.-H. Lies, J. Nitz, E. Pommer, K.-H. Schneider and P. Seifert together with members of the staff from the VW prototype shop, the VW transmission development department and the VW measuring and testing department.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

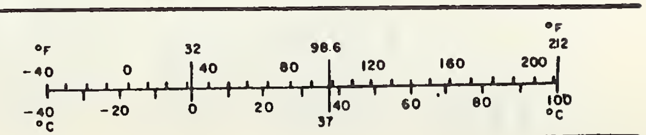
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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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). Data on the 6-cylinder turbocharged engine and the V-8 engine are projections only.

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

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

f. A systems analysis computer programm previously developed by Volkswagen was updated. The main variables are: Engine Function, Installation Suitability, Material and Fuel Conservation, Environmental Requirements.

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 2250-to-3000lb inertia weight (IW) range equipped with naturally aspirated Diesel engines with nominal EPA road load setting varies by 24%, 41 to 33 mpg at constant performance level (4.1.1). The fuel economy value at 2250 lb IW with an EPA road load setting that reflects the actual road load is 44 mpg.

Comparing the naturally aspirated and turbocharged Diesel engines under study and yielding equivalent vehicle performance the composite fuel economy of turbocharged Diesel engines is higher by about 20% (4.1.2).

Comparung 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% with some other adverse effects (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 (EGR) which is problematic as far as smoke, particulates, odor, driveability, durability and maintenance are concerned. In the presence of EGR additional work for the reduction of HC is required (4.2.1).

2.3 UNREGULATED EXHAUST EMISSIONS

During normal road operation 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 increased when EGR is used. The odor level of the engines studied is in the range of modern designed passenger car Diesel engines, but increases when EGR 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 indentical 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 lubriants to be found in the U.S. driveability as well as startability present no major problems (4.3.1). All engines studied exhibited no startability problems above minus 11° F (-25°C).

2.6 DURABILITY AND MAINTENANCE

The maintenance requirements of modern Diesel engines are lower than those of comparable gasoline engines.

Based on test data and engineering analysis the service life of the Diesel engines studied exceeds the service life of equivalent gasoline engines.

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 naturally aspirated (NA) 4 cylinder Rabbit Diesel is $ 170 higher than of an equivalent 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 test data obtained on the engine families show that the more advanced Diesel engine (turbocharged Diesel as compared to the naturally aspirated engine) offer definite advantages in terms of engine performance (efficiency, emissions and noise) and vehicle packaging, namely, the lower volume requirements for the engine allows for greater flexibility in the design for passenger comfort and safety at constant fuel economy and power.

To demonstrate the compatibility of a turbocharged Diesel power plant, 4 cylinder 70 HP, five speed manual transmission 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, 4 passengers
- 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)

Another equivalent 4 cylinder turbocharged Diesel engine installed in a standard '77 Rabbit vehicle (2250 lb IW) with a four speed manual transmission has yielded approximately 50 mpg (composite EPA cycle) and has also met the above emission standard. The same '77 Rabbit with the above five speed transmission and the same calibration of the IRVW would also yield 60 mpg. Those values are based on road-load settings that correspond to the actual road-load consistent with EPA procedures.

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

No.	Vehicle Size	No. of Passengers	Inertia Weight (IW)	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
TIA: Total Intensity of Aroma (ADL-Method)
CID: Engine Displacement in Cubic Inch
HP/IW: Horsepower to Inertia Weight Ratio, HP/lb

Accel. Time		Comp. Fuel Econ.	Applicable Emission Standard	Emissions Achieved in Lab.	Particul. Emiss-ions *	Odo-rants (TIA)	Noise		
0-60	30-70		HC/CO/NOx	HC/CO/NOx			Idle 0.5 m (19.7')	Accel. 15 m (59.1')	Const. 15 m (59.1')
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		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		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		2.9	73	71	61
12.7	14.5	43		.20/1.2/.40		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
Weight in lb
Noise in dB (A)

*Refer to Figure 14 for Values

3.0 APPROACH

The objective of this program was to obtain a data base on the performance of light-weight automotive diesel power plants at the engine and vehicle level in sufficient detail to permit projections of the potential associated with the introduction of a significant number of Diesel powered automobiles into the U.S. auto fleet.

Production prototype light-weight diesel power plants in the power range from 50 to 100 BHP were considered. The power plants were applied to automotive vehicles in the 2000 to 3000 pound inertia weight classes with a horsepower to test weight ratio of HP/IW = 0.022 – 0.033 HP/lb.

The data base ist based on analytical and experimental efforts as shown in Fig. 1. Main emphasis was given to the following items:

- 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.

An analytical evaluation was performed to define the engines to be tested. To cover the entire performance range from 50 to 100 horsepowers, two engine families were established (Figure 2) 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 (Figure 3)
- 5-cylinder naturally aspirated engine, 66 HP (Figure 7)
- 6-cylinder naturally aspirated engine, 75 HP (Figure 5)
- 8-cylinder (V-8) naturally aspirated engine, 100 HP (projections only) (Figure 8)

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

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. Figure 9 shows the vehicles used for analytical and experimental work.

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.

Furthermore, certain drivetrain variations were analyzed and tested:

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

In the course of work a recently developed objective system for systems analytical evaluation of automotive power plants was updated.

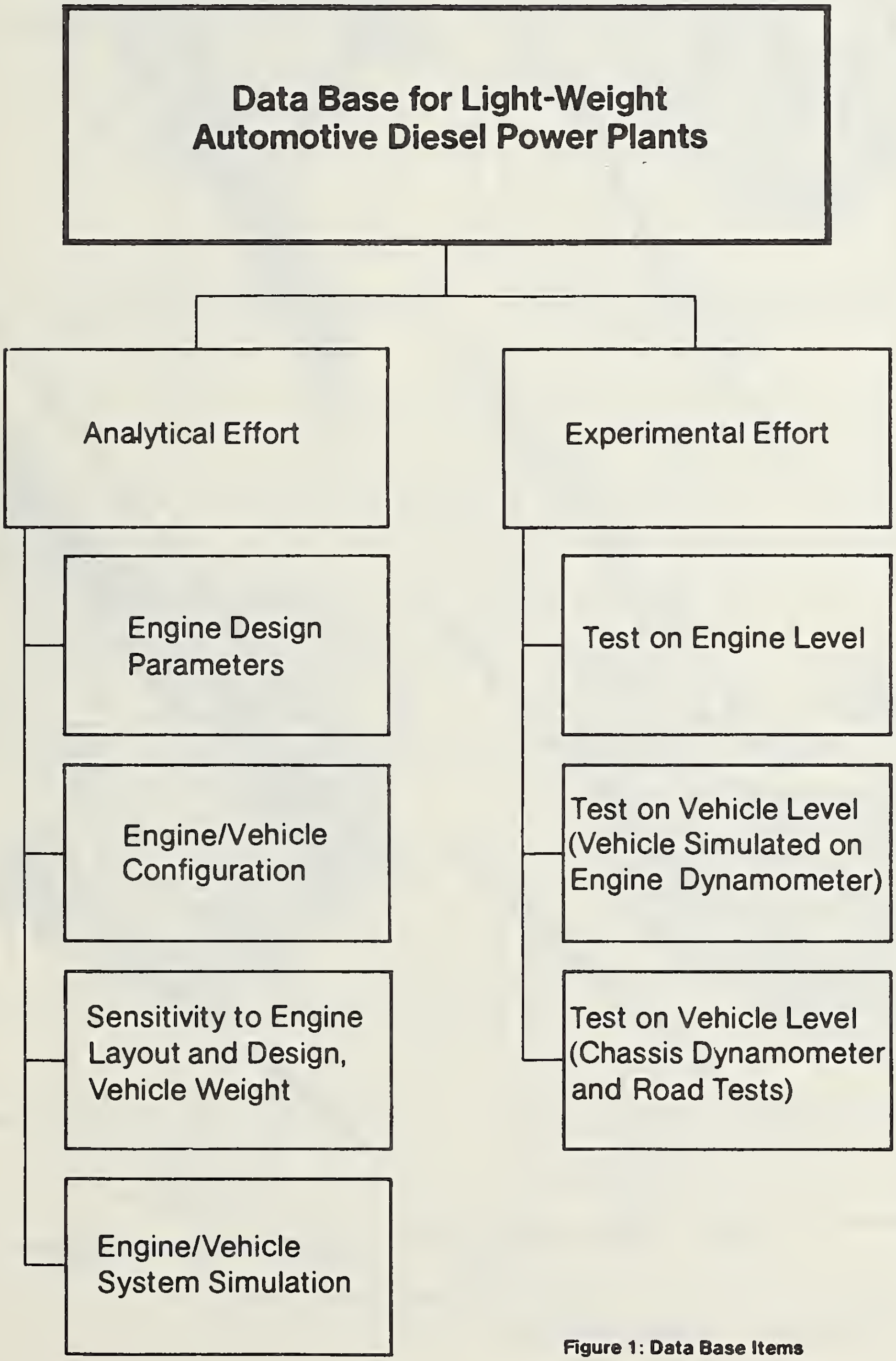


Figure 1: Data Base Items

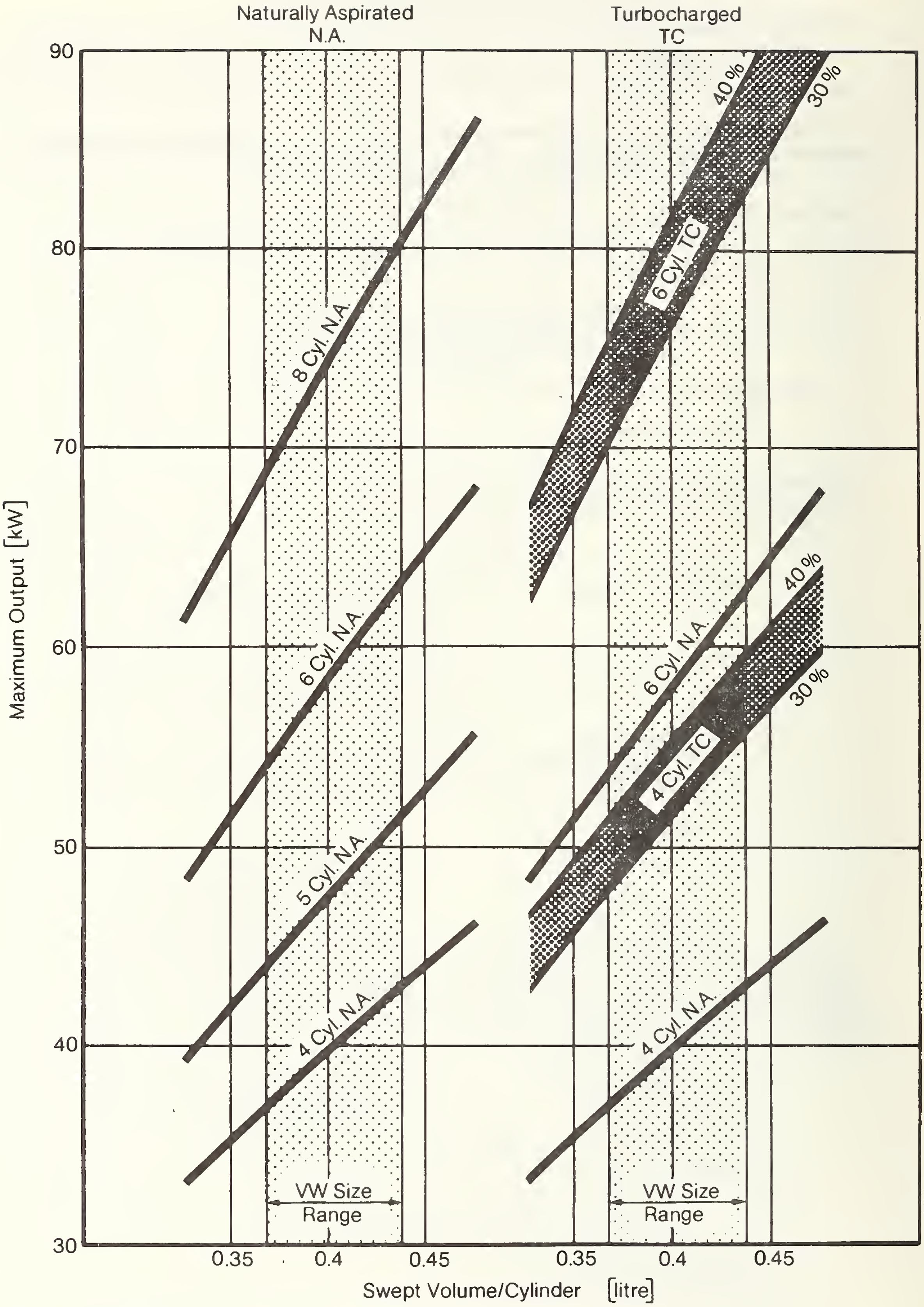


Figure 2 Performance of Engine Families.

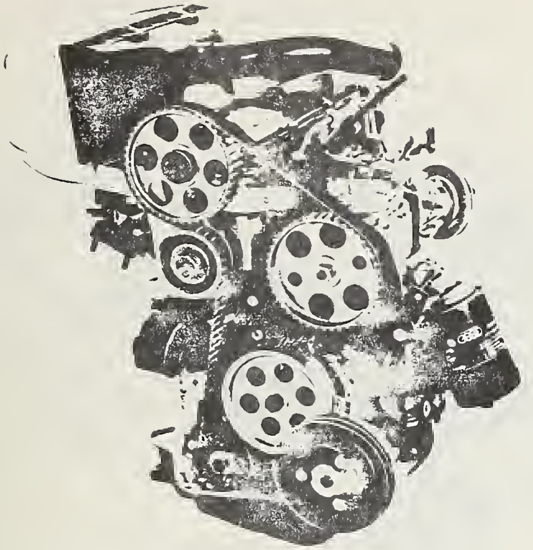


Figure 3: 4-Cylinder Naturally Aspirated
Diesel Engine 50 HP

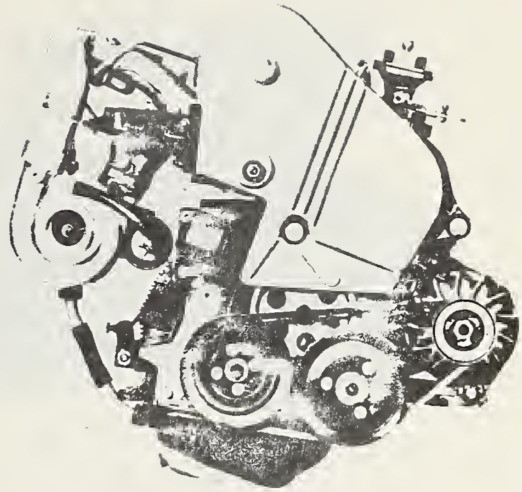


Figure 4: 4-Cylinder Turbocharged Diesel
Engine 70 HP

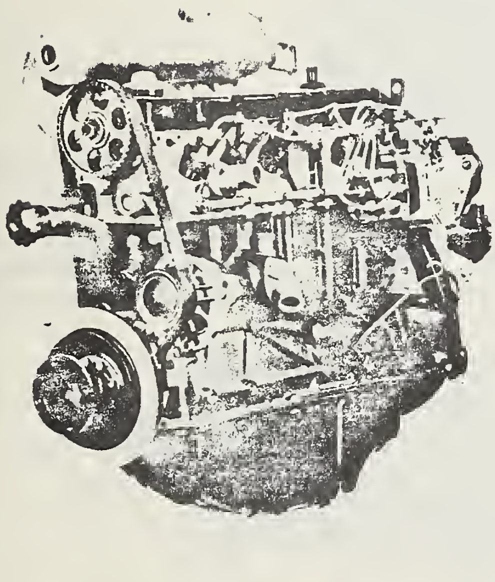


Figure 5: 6-Cylinder Naturally Aspirated
Diesel Engine 75 HP

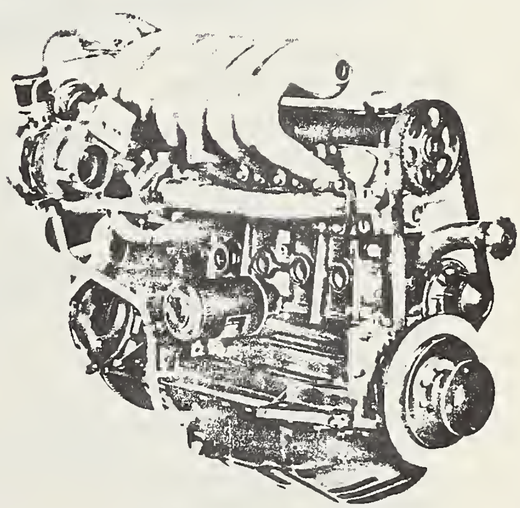


Figure 6: 6-Cylinder Turbocharged
Diesel Engine 100 HP

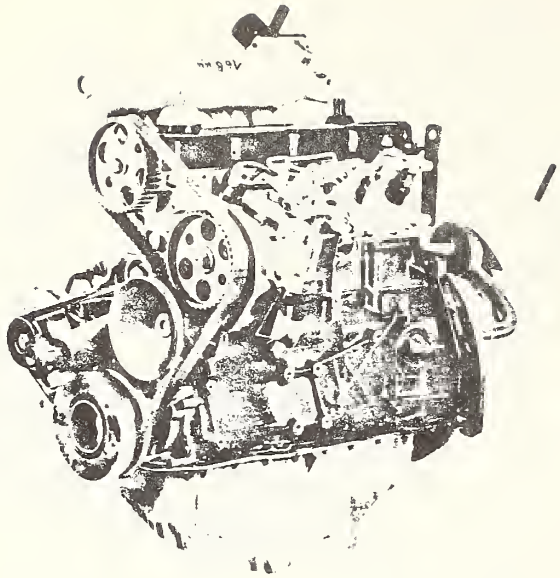


Figure 7: 5-Cylinder Naturally Aspirated Diesel Engine 66 HP

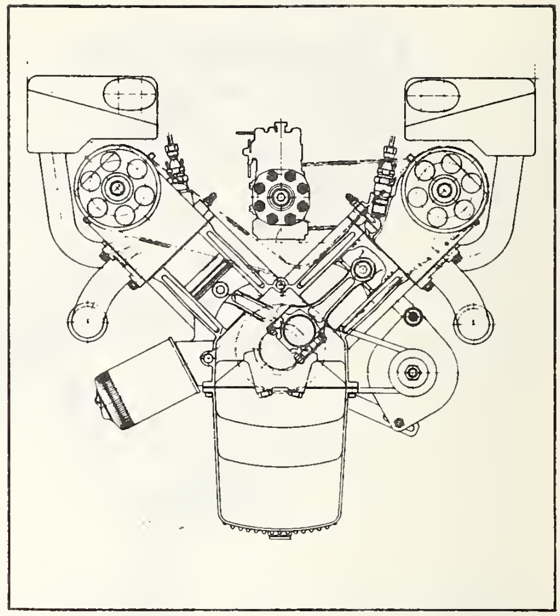


Figure 8: V8 Naturally Aspirated Diesel Engine 100 HP

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.

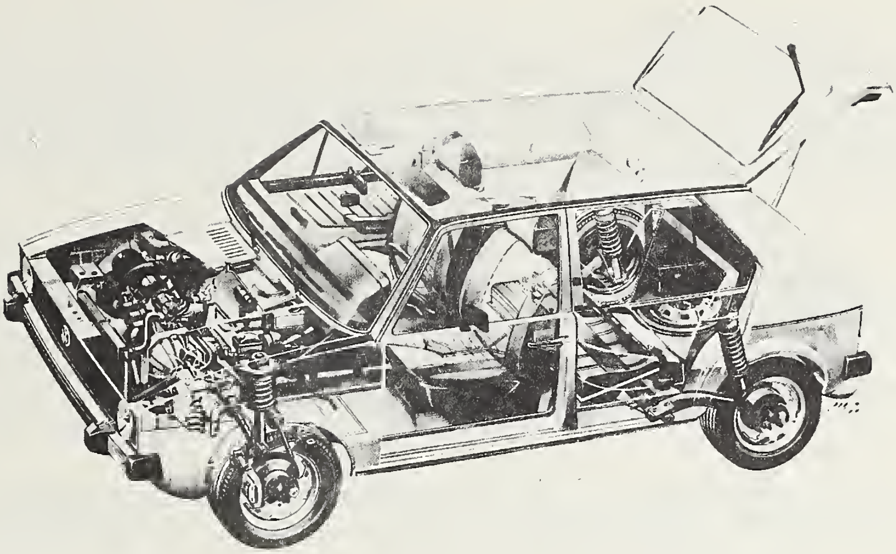
The compatibility of Diesel engines and light-weight vehicle structures of current and advanced crashworthiness was evaluated by preliminary designs. The influence on weight, roominess, and vehicle geometry in front, mid, and rear-engine configurations at three safety levels (30, 40 and 45 mph frontal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

Finally, the following consumer attributes were considered and evaluated.

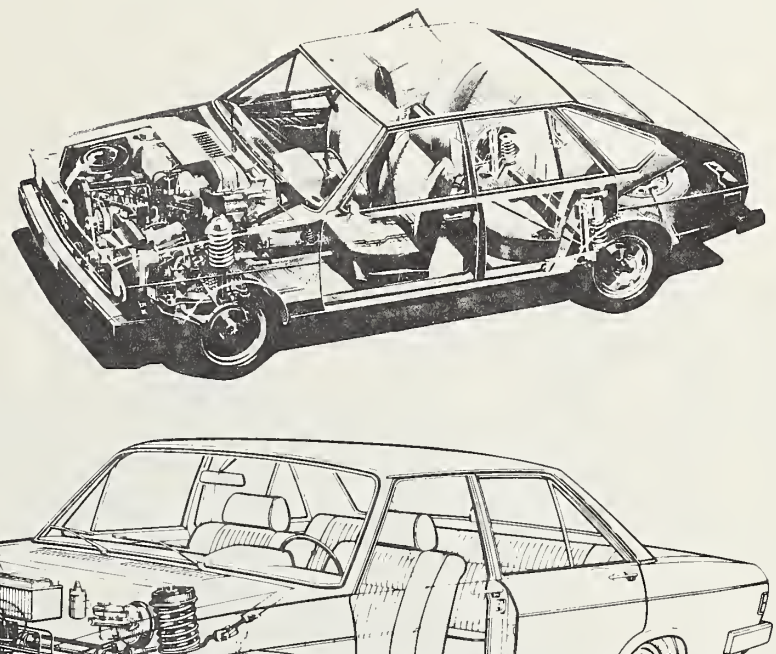
- Acceleration and passing performance,
- Gradeability,
- Startability,
- Driveability,
- Operation under the range of operating environments found in the U.S.,
- Durability,
- Reliability,
- Maintenance requirements,
- Fuel grade and lubricants, and
- Cost.

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

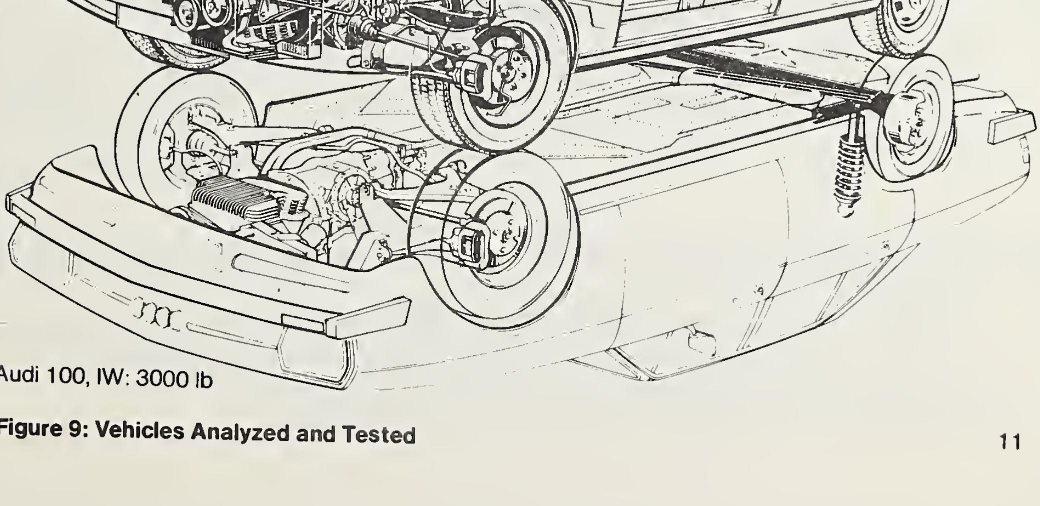
For purposes of verification and demonstration, Volkswagen has provided a turbocharged Diesel Rabbit equipped with a 4-speed manual transmission and an 'Integrated Research Vehicle (IRVW)'. The IRVW demonstrates the compatibility of a turbocharged Diesel engine, a 5-speed transmission, and a structure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



VW Golf (Rabbit), IW: 2250 lb



VW Dasher, IW: 2500 lb



Audi 100, IW: 3000 lb

Figure 9: Vehicles Analyzed and Tested

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 10).

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 10). 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.10).

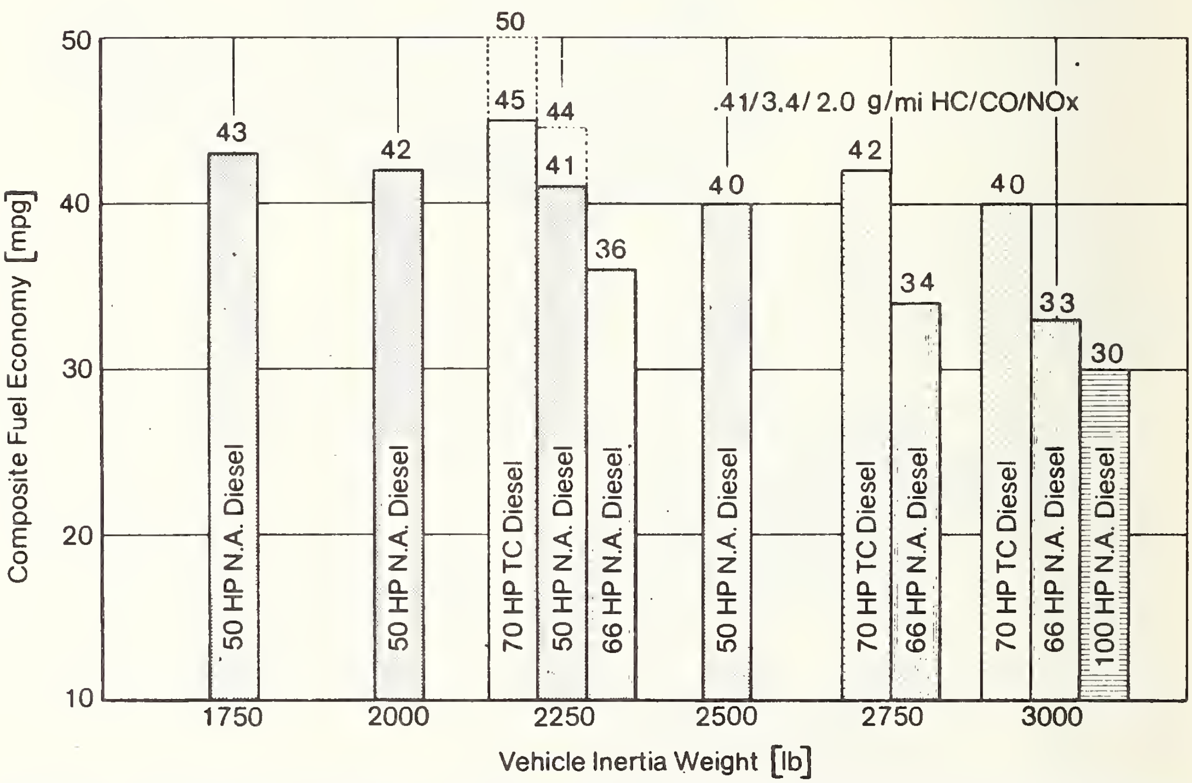


Figure 10 Composite Fuel Economy of Various Diesel Engines Averaged over the City and Highway Driving Cycles.

The fuel economy is given in terms of No. 2 Diesel fuel based on nominal EPA road load setting. The figures given may vary by ± 2 mpg.

----- recently by EPA obtained results at actual road load setting.

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 (Fig. 11). Compared to a turbocharged engine of the same performance, the fuel economy of a naturally aspirated 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 19) 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 approximately 8% in the 2250 lb inertia weight class (Figure 11). 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 EGR to meet NOx less than 1.0 gram/mile indicated a 5% loss in fuel economy with some adverse effects.

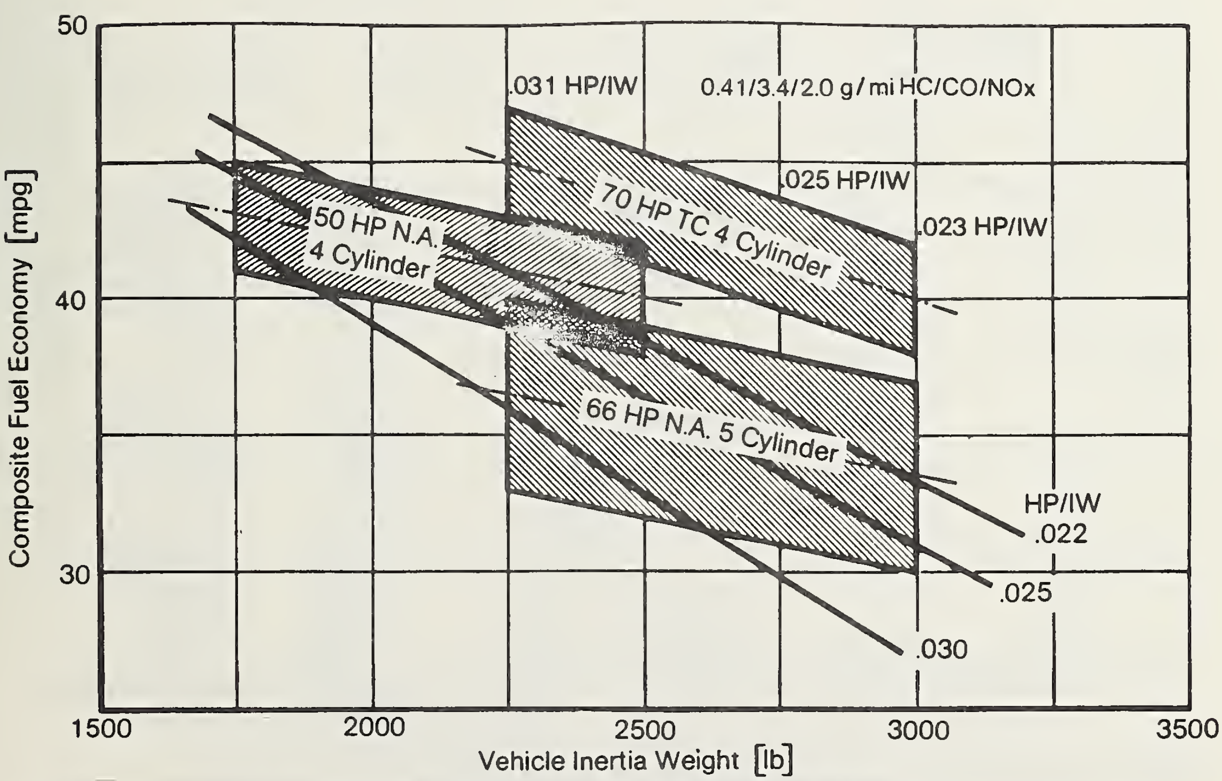


Figure 11 Comparison of Fuel Economy of 3 Different Diesel Engines.
The scatter band of the 66 HP engine is wider because of its state of development.

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 EGR, 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 12 and 13 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.

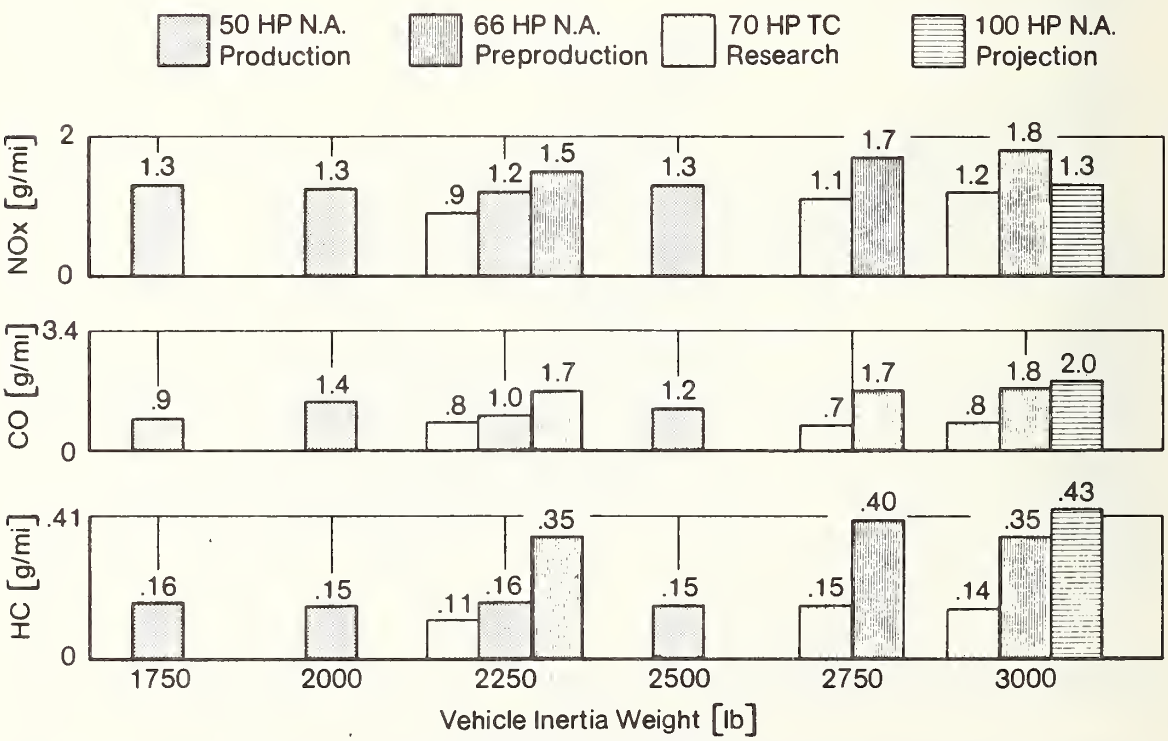


Figure 12 Regulated Exhaust Emissions from Various Diesel Engines.
Deterioration factors and variances due to manufacturing (30 % of the figures indicated) are not taken into account.

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 achieve NOx = 0.85, HC = .39, CO = 1.4 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 7%.

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 EGR 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 EGR, such as

- increased smoke level, (smoke was visible during transients and tests performed at altitudes, see also Fig. 14)
- increased odor level. (Figure 15)
- reduced durability,
- increased maintenance requirements, and
- poor driveability, (Figure 23)

It appears that major technological advancements are required to sucessfully implement EGR in production engines.

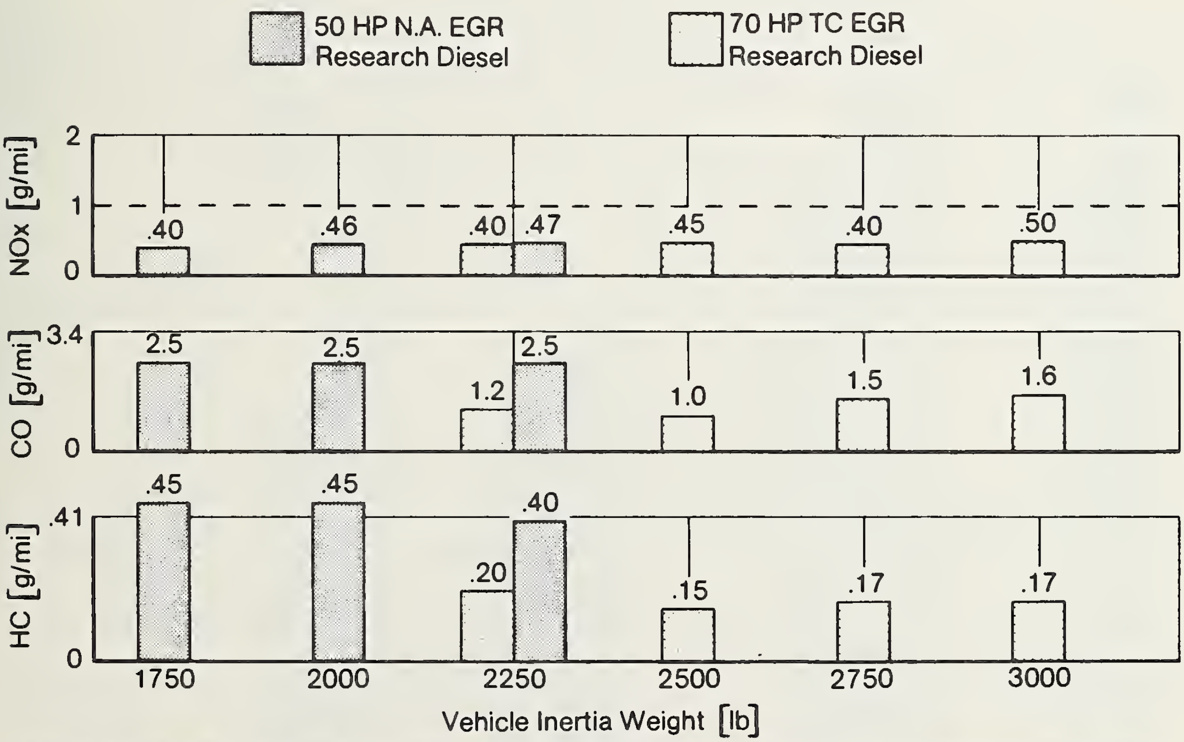


Figure 13 Regulated Exhaust Emissions of Two Diesel Engines with Controlled Exhaust Gas Recirculation (Preliminary Data).

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 using the FTP-75 drive cycle for both the 50 HP naturally-aspirated and the 70 HP turbocharged engine.

It is judged that the unregulated emissions obtained on the 4-cylinder engines may be used, in the absence of experimental data, to predict some of the unregulated emissions for the remaining engines of both engine families.

4.2.2.1 Smoke

While cruising the smoke emissions of all engine/vehicle systems without EGR were found to be invisible (Bosch Number: Less than 3.5). Introducing EGR caused smoke during transients and especially when altitude tests were performed (Bosch Number: higher than 8.0).

4.2.2.2 Particulates

Figure 14 shows the emission of particulates at the two emission levels. The emission of the 50 HP naturally aspirated engine (0.35 gram/mile) and of the 70 HP turbocharged engine (0.25 gram/mile) indicate low values within the range of current Diesel engines (see Summary Report on the Evaluation of Light Duty Diesel Vehicles, EPA, March 1975, 75-21 JJM). If EGR is introduced the emission of particulates increases significantly.

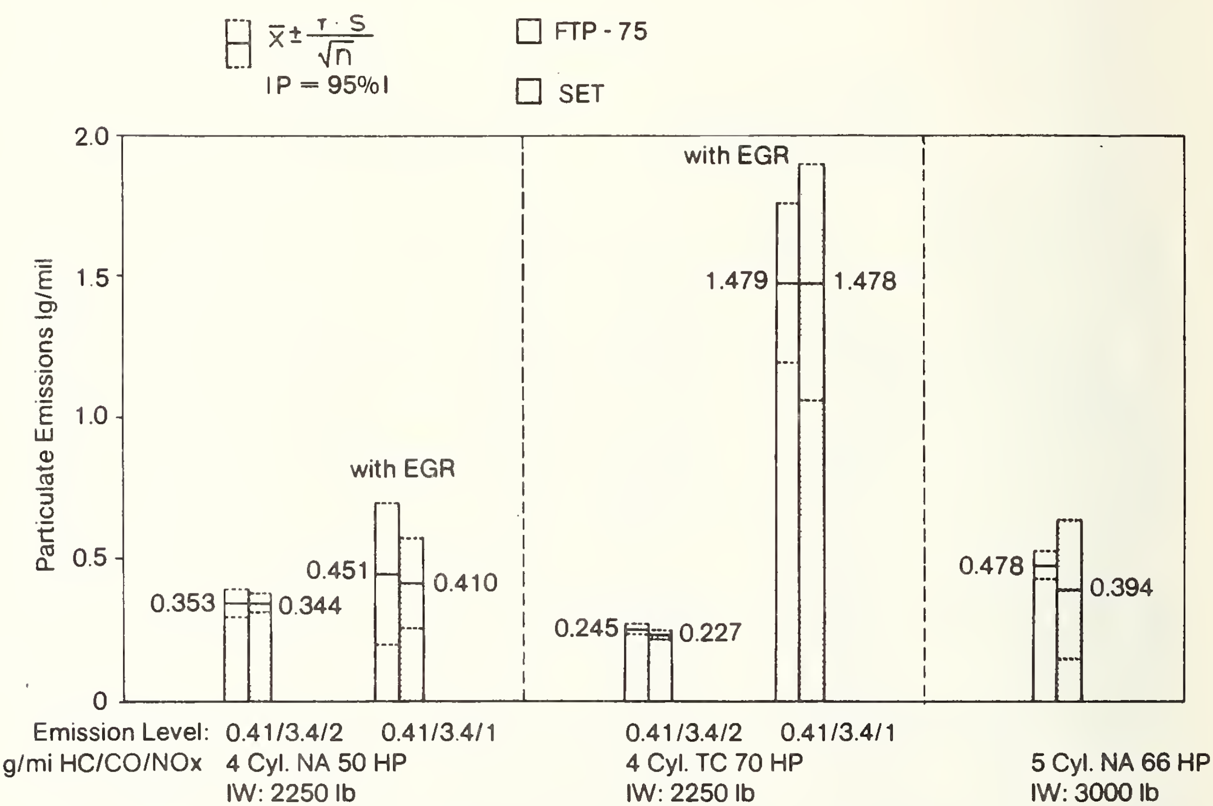


Figure 14: Particulate Emissions.
Test results for current Diesel engines as measured by EPA ranges from .30 to .62 g/mi. (Summary Report on the Evaluation of Light Duty Diesel Vehicles, EPA, March 1975, 75-21, JJM).

4.2.2.3 Odor

The odor level was determined mainly from the mass emissions of two odorants, aromatic hydrocarbons and partially oxygenated hydrocarbons (A. D. Little method). 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. Figure 15 shows the influence of EGR and of fuel composition on odor. There is no difference between naturally aspirated and turbocharged engines in this respect. If EGR 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.

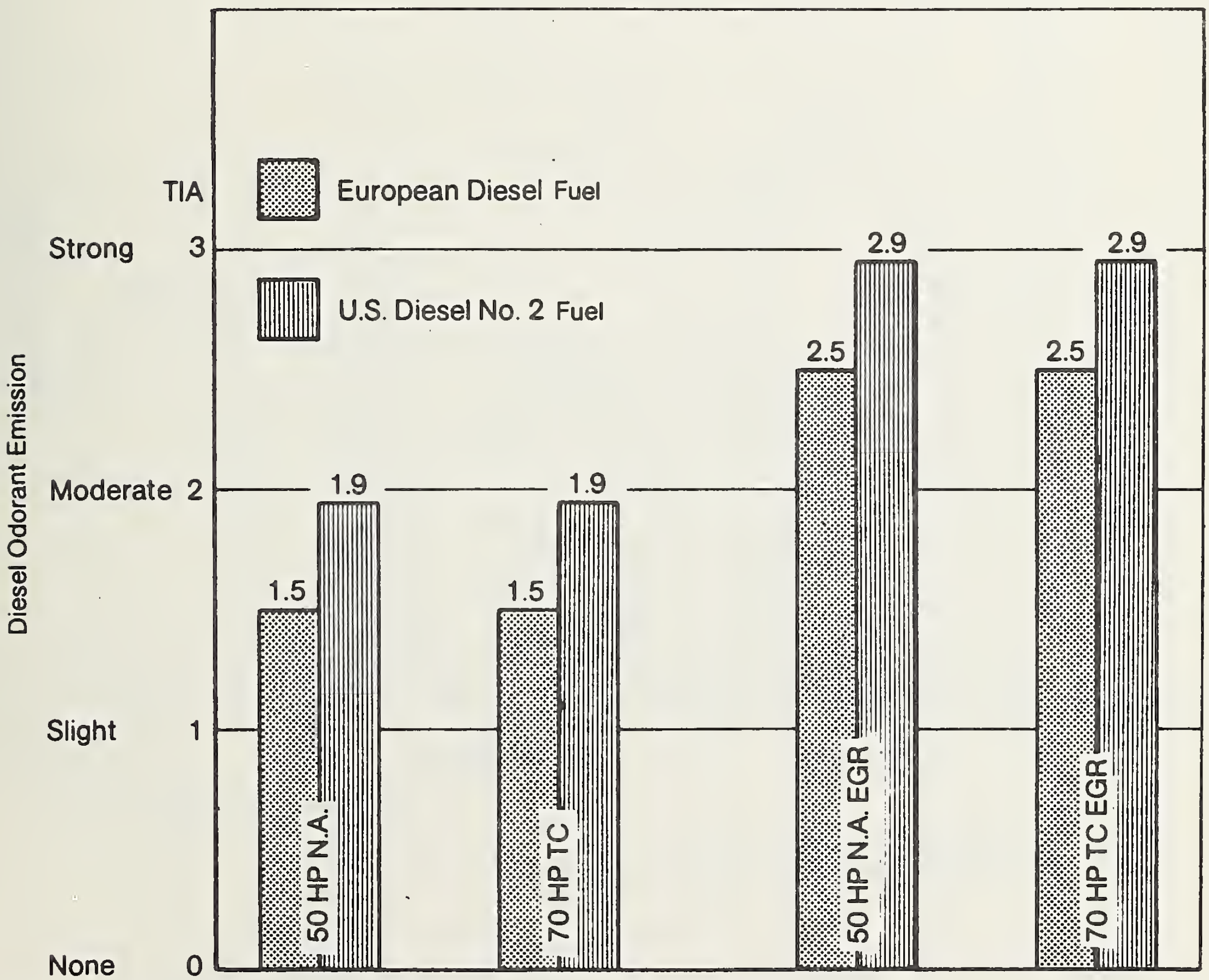


Figure 15: Diesel Odor Emission Averaged over a City Driving Cycle Influenced by Fuel Composition and Exhaust Gas Recirculation (EGR).
Odor values may vary by ± 0.25 units.

4.2.2.4 Sulfates

Figure 16 shows the emission of sulfates at the two emission levels. 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 without catalytic converters. 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.

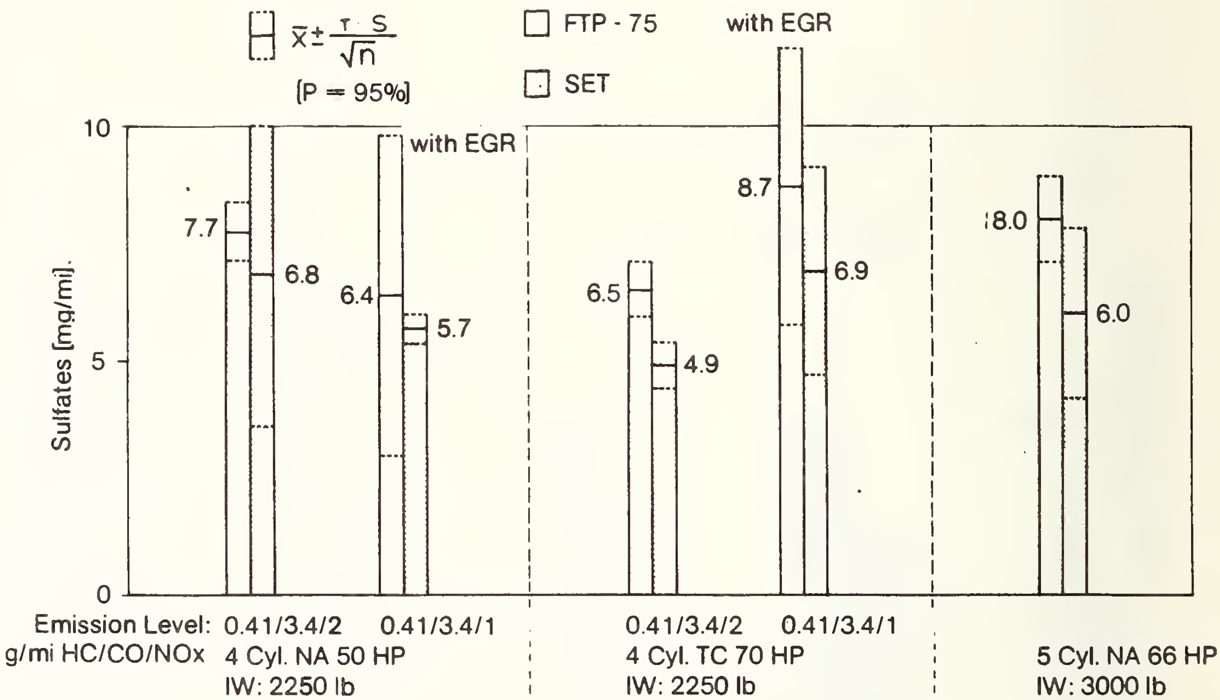


Figure 16: Sulfate Emissions
The Diesel Fuel Contained 0.225 wt % S

4.2.2.5 Ammonia

Ammonia emissions in the FTP-75 and SET driving cycle range from 2.5 to 4 mg/mile at both gaseous emission levels.

4.2.2.6 Aldehydes

Figure 17 shows aldehyde emissions at the two emission levels. Diesel engines tested emitted aldehydes at a rate of 13-55 mg/mile. This is in the range of aldehyde emission emitted by gasoline engines.

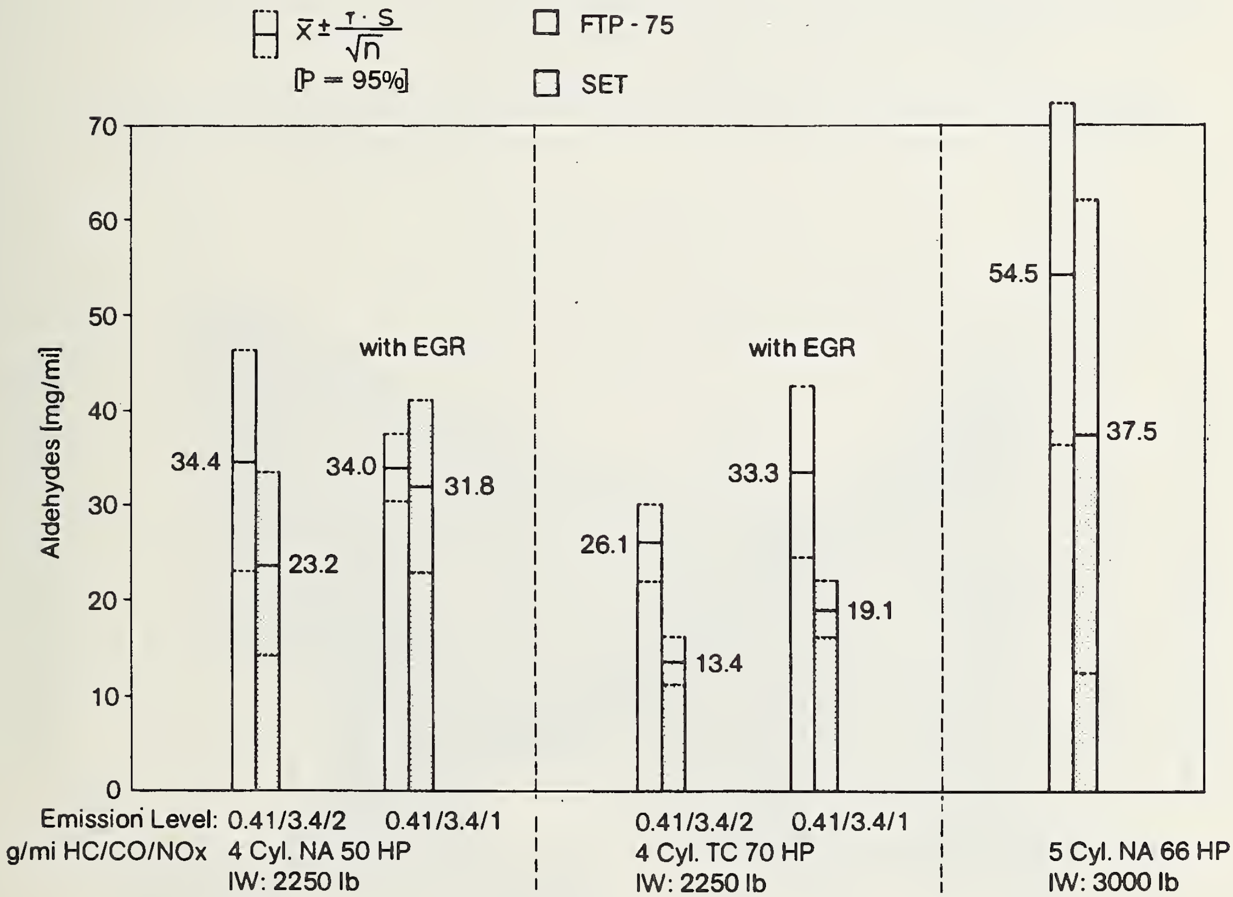


Figure 17: Aldehyde Emissions

4.2.2.7 Polynuclear Aromatic Hydrocarbons

Based on findings of earlier studies made by VW on gasoline engines (VW Report F2-76/19), the emissions of polynuclear aromatic hydrocarbons were found to be lower for Diesel engines. There are no reliable 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 procedures:
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 (1.64 ft) 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 (Figure 18).

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.

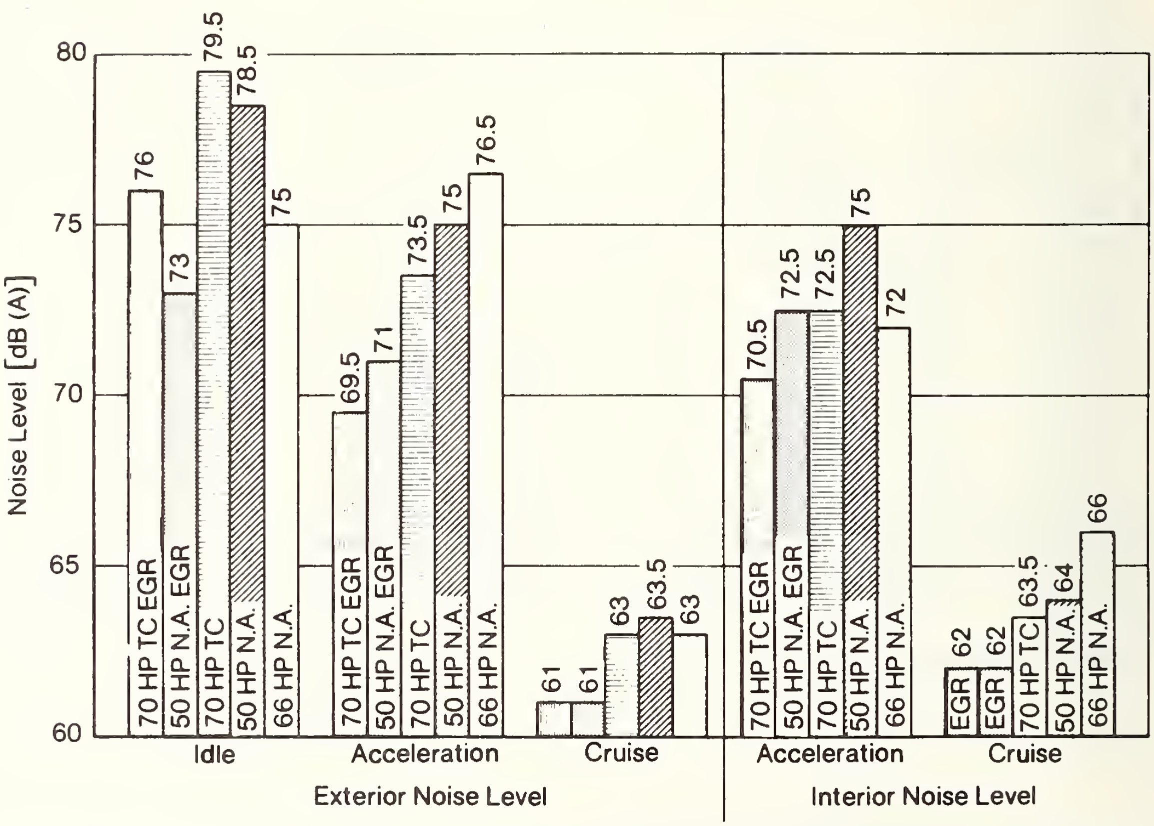


Figure 18: Noise Emission by Various Engine/Vehicle Systems Measured at a Speed of 30 mph and at a Distance of 15 m (50 ft) according to SAE J 986 a.
(Idle noise measured at 0.5 m = 1.65 ft).
The noise tolerance is ± 1 dB (A).

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 the vehicles studied were described by the following parameters: (Values in parenthesis show the assumed restrictions)

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 in first gear (not less than 30%).

In addition Figure 19 shows the relationship between fuel economy, vehicle weight, acceleration time from 0 to 60 mph, and drivelines for vehicles with the 70 HP TC Diesel engine.

Figure 20 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.

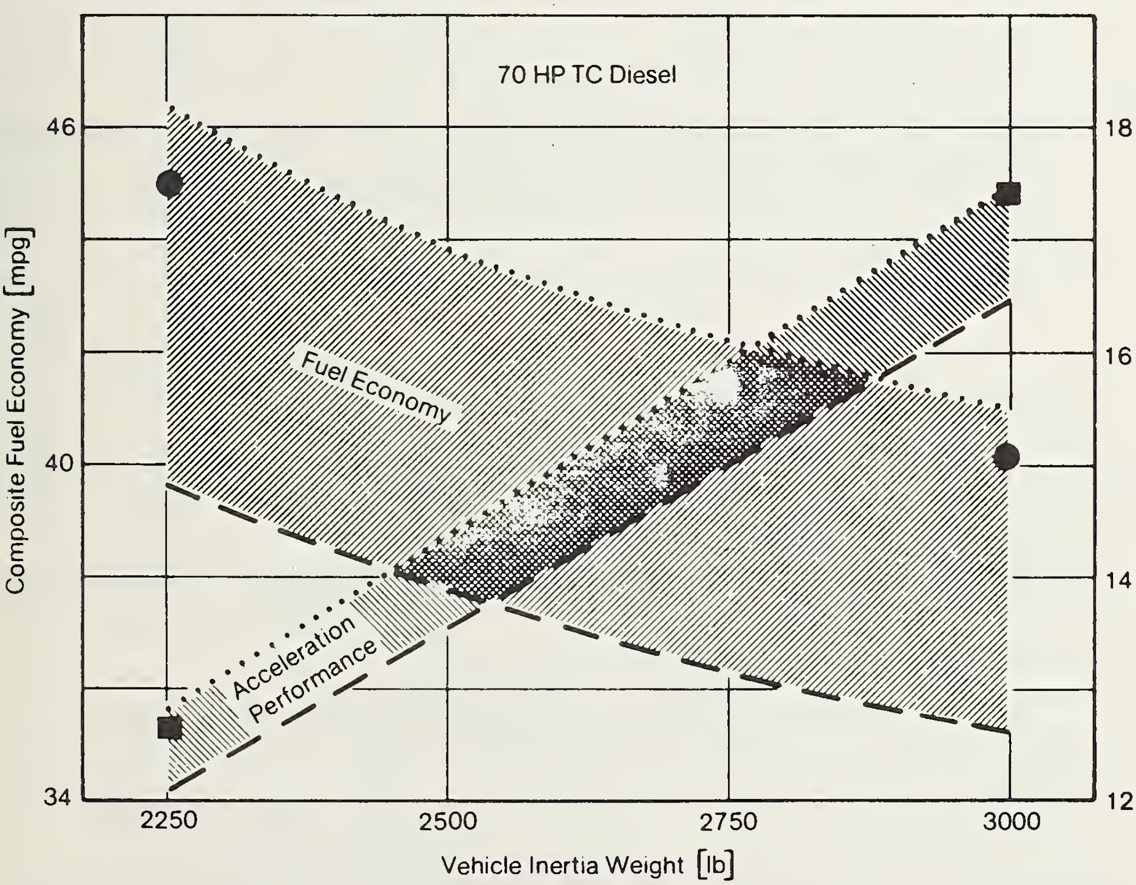


Figure 19: Fuel Economy and Acceleration Performance as a Function of Drivetrain Ratio and Weight.
70 HP Turbocharged Research Diesel; Manual Transmission.
— — Limit for max. performance, top speed 75 mph, n/v = 66 rpm/mph.
• • • • Limit for max. fuel economy, acceptable performance, n/v = 38 rpm/mph.
● 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.

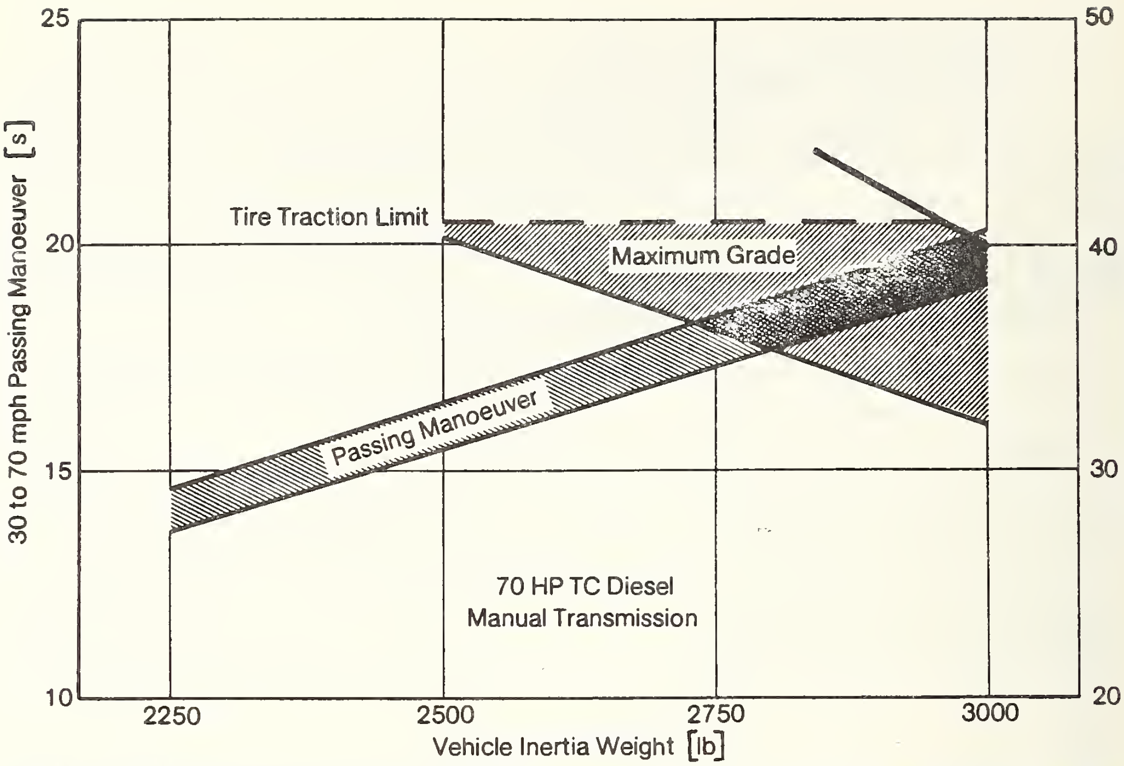


Figure 20: Time Range for a 30 to 70 mph Passing Manoeuver and Maximum Grade as a Function of Driveline Ratio and Inertia Weight.
70 HP turbocharged Diesel engine; manual transmission; front-wheel drive.

4.3.1.2 Driveability

Subjective 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: Subjective evaluation by driver
- Surge: Short abrupt power fluctuations at any speed or load,
- Hesitation: A temporary lack of initial engine response to accelerator action,
- Pick-up Performance: Subjective evaluation by driver,
- Acceleration jolt: Jerks felt in the driver's seat which are caused by exessively fast engine response.

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

When plotted in order of operating modes, the merit points for each property form a subjective driveability profile. As the weight of each property and the interrelationship existing between these are ambiguous, sums were not taken.

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).

Figure 21 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.

Figure 22 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.

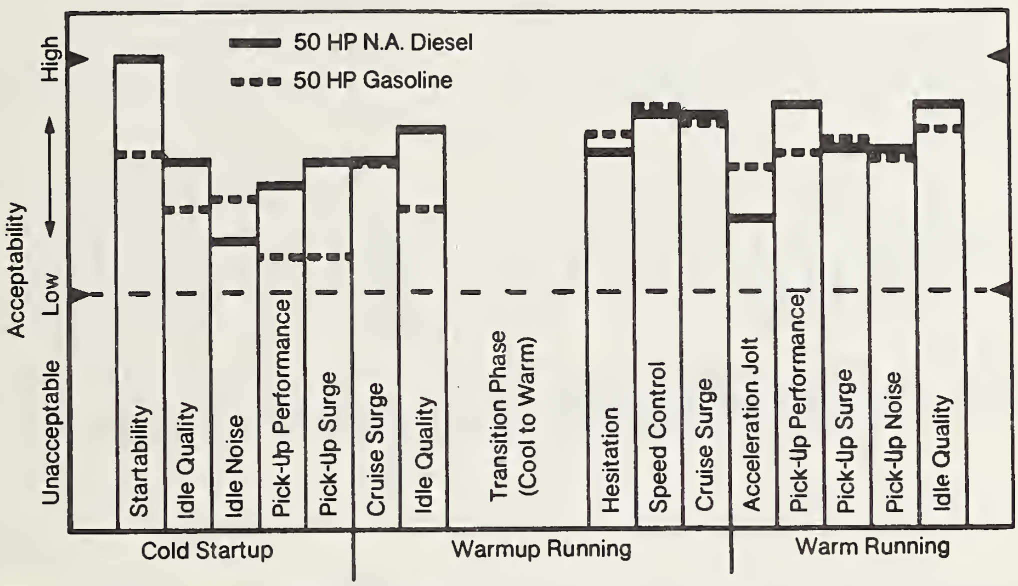


Figure 21: Subjective Driveability Profile.
50 HP Diesel versus 50 HP gasoline Rabbit. (Carburated, not marketed in the U.S.)

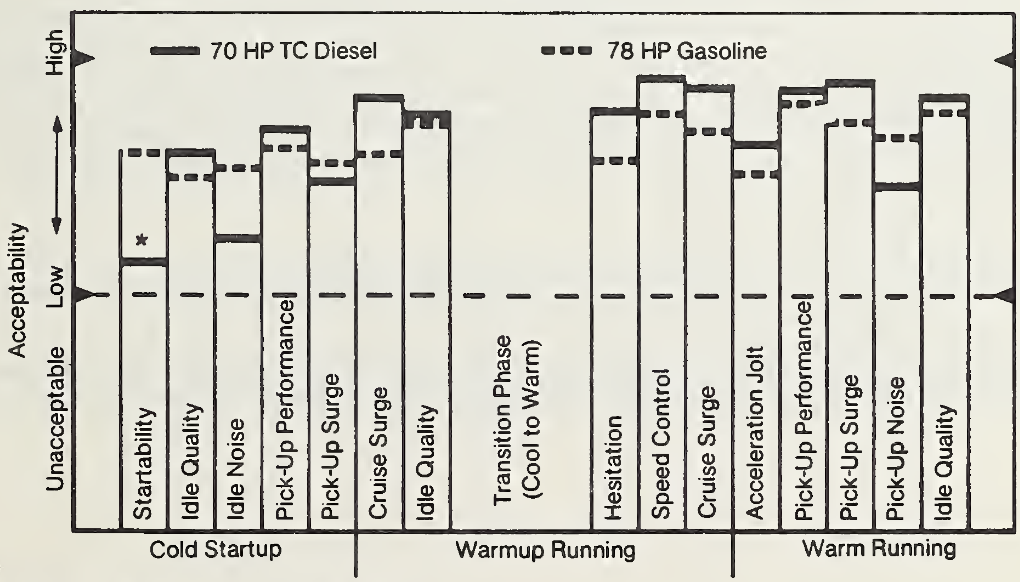


Figure 22: Subjective Driveability Profile.
70 HP turbocharged Diesel versus 78 HP gasoline Rabbit. *TC Diesel, May '77

Figure 23 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.

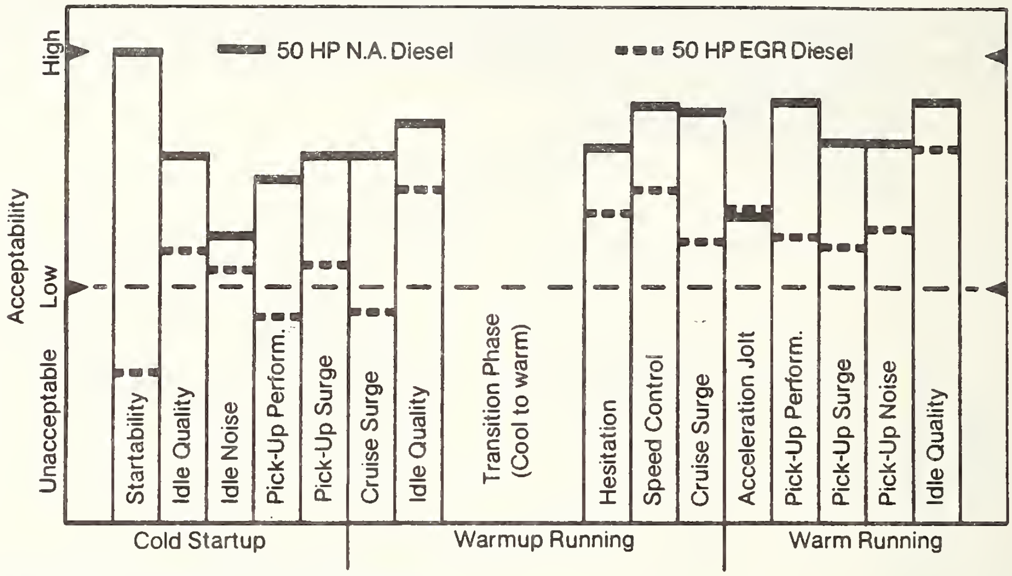


Figure 23: Subjective Driveability Profile.
Comparison of a Rabbit with 50 HP production Diesel engine versus a Rabbit with the same engine equipped with a research EGR device.

4.3.1.3 Startability

At extremely low temperature, the startability of Diesel engines is limited by the self-ignition process. Preheating (all engines were equipped with glow plugs) provided good starting at low temperatures and minimum blue-smoke emissions. The engines tested have shown themselves capable of starting at any temperature above −11°F (−25°C) provided that proper 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 (3281 feet) 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, Maintenance Requirements, and Service Life

The results of experiments at Volkswagen and of extensive durability tests performed prior to this contract were analyzed (300 cars equipped with the 50 HP 4-cylinder naturally-aspirated Diesel engine, '77 Rabbit and Dasher) show that Diesel engines are — as exspected — more durable than spark ignition engines. Available Volkswagen data arrived from 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 could be twice as long as that of the spark ignition engines.

EPA durability tests performed for the above fleet were analyzed 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 relatively stable over 50,000 miles. Based on this, we do not expect commercial U. S. fuels to cause engine troubles. We tested 7 representative fuels, compositions differing in cetane number (47 to 53.5), aromatics content (17-28.4 wt %), CFPP (± 0 to -23° C) and end point (FBP) (319 to > 400°C) in cooperation with the oil industry. Using a multigrade lubricant based on SAE W 15 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.

Analysis of oil viscosity changes as function of mileage indicates that these changes in viscosity are low (due to low soot formation).

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.

It is possible that the production design of the turbocharged engine versions may require some changes. These changes may include pistons, gudgeon pin, cooling system and lubricants. This is mainly required because of higher operating temperatures and higher peak pressure.

4.3.3 Initial Cost and Manufacturing Impacts

The initial costs of the engines tested are higher than the cost of corresponding VW spark ignition 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 operating cost, lower fuel consumption and lower fuel requirements. To date it is impossible to estimate the additional cost of a turbocharged Diesel engine because the engines tested were research engines.

A family of in-line Diesel engines such as the engines studied above has distinct advantages in manufacturing. 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 separate rods 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. Production compatability therefore favours families consisting of in-line engines. This is due to the principal design and the cylinder banks.

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.

4.4 COMPATIBILITY OF DIESEL ENGINES WITH STRUCTURES OF ADVANCED CRASHWORTHINESS

Three typical vehicles were analyzed to study the compatibility between light-weight automotive Diesel power plants and frontal impact crashworthiness at the following three safety levels (Figures 24, 25 and 26).

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

The typical baseline vehicles were:

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

The approach used in the study was to keep the roominess index* of the vehicles constant or variable and to determine the impacts of different engine/vehicle configurations and safety levels on other main vehicle characteristics such as:

- Vehicle weight
- Weight distribution
- Vehicle length
- Location of center of gravity
- Wheelbase
- Luggage capacity

*The roominess index is computed by adding up seven major interior dimensions as defined by the U. S. Motor Vehicle Manufactures Association. The dimensions are: H30, H61, H63, L34, L51, W3 and W4.

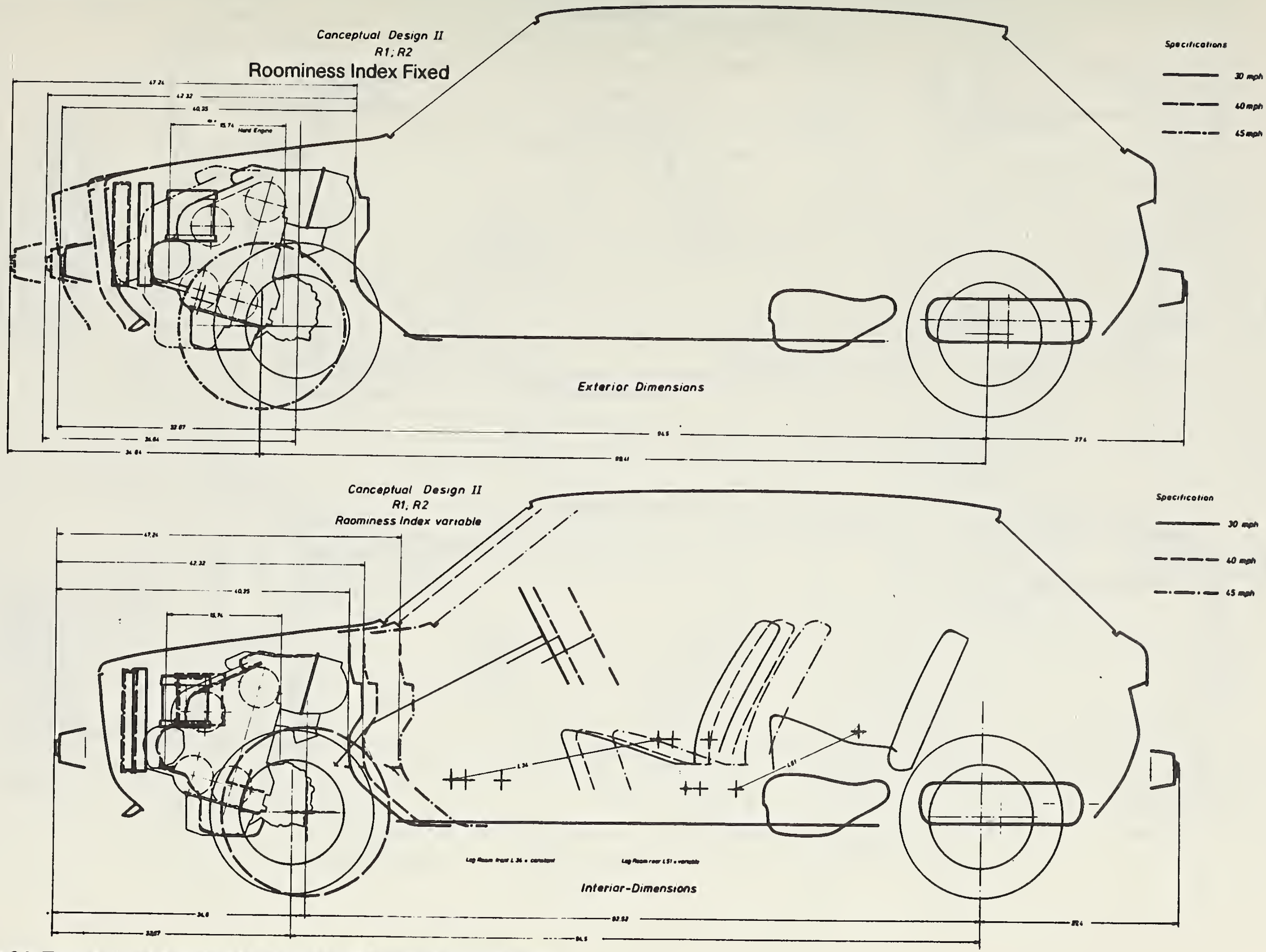


Figure 24: Typical Conceptual Design (Baseline Vehicle VW Rabbit)

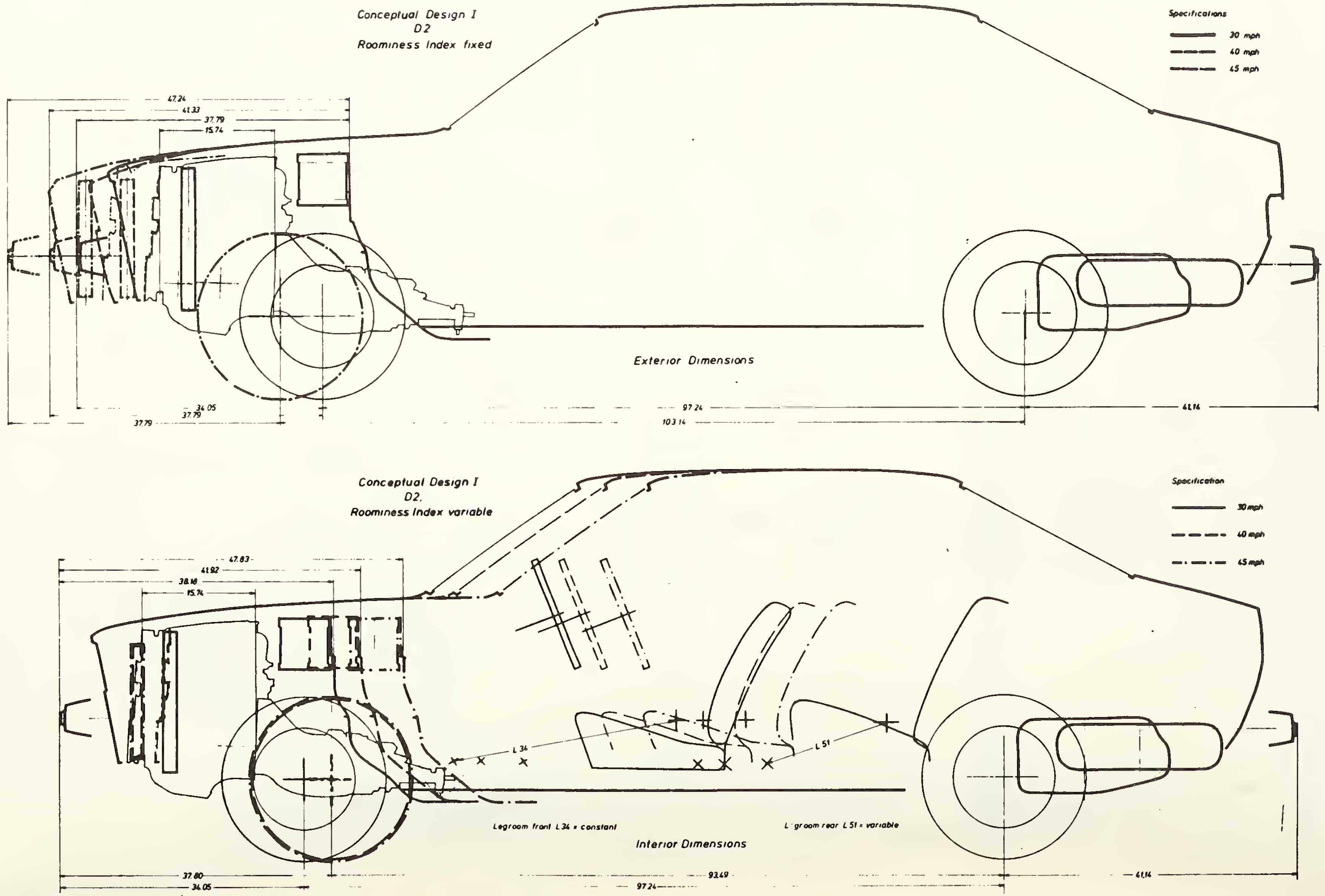


Figure 25: Typical Conceptual Design (Baseline Vehicle VW Dasher)

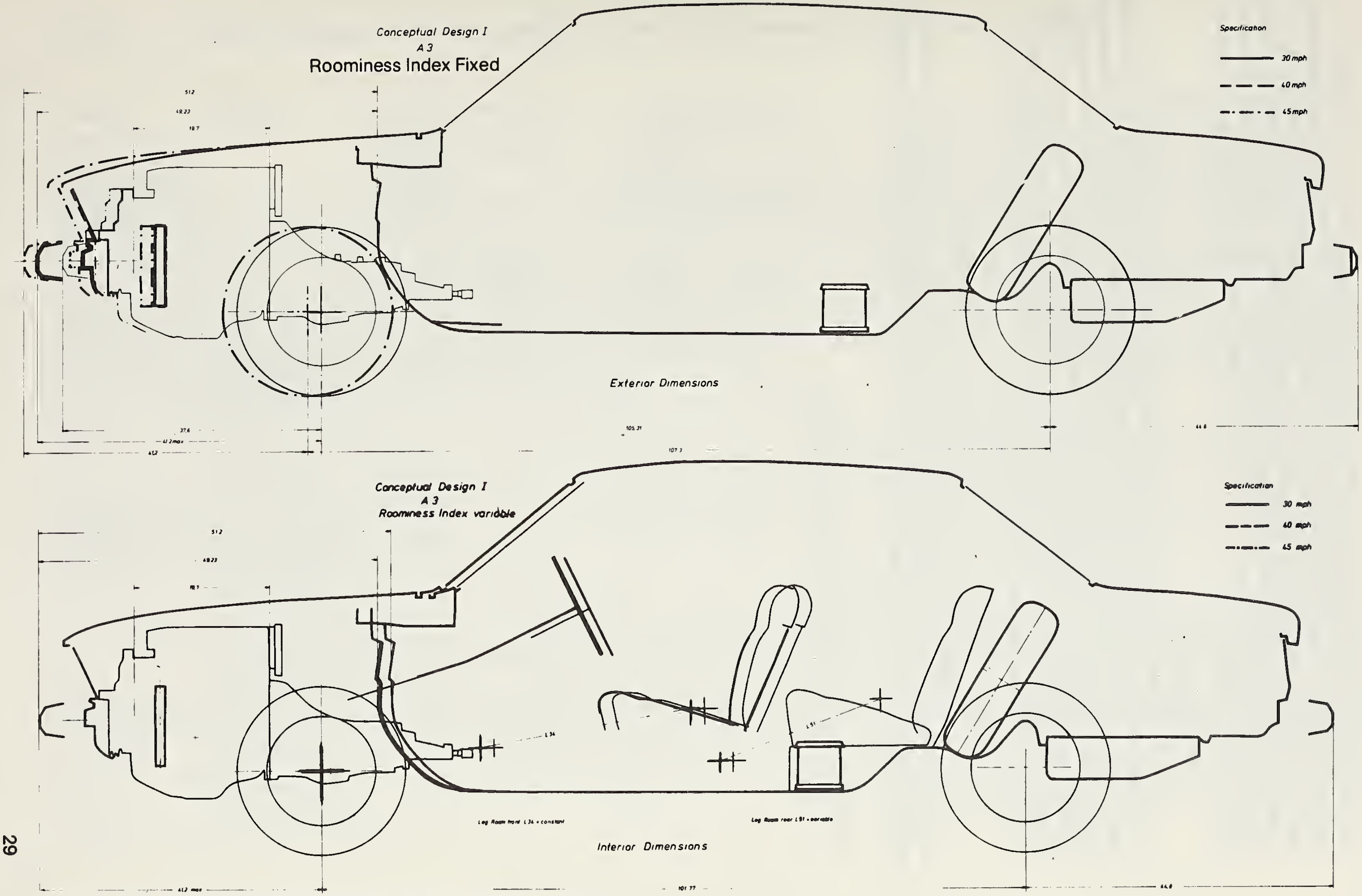


Figure 26: Typical Conceptual Design (Baseline Vehicle Audi 100)

4.4.1 Vehicle Structure

The studies at all three safety levels were based on the assumption that the deformation characteristic of the front structure of the vehicles was rectangular and that the mean deceleration is 25 g. Moreover, it was assumed that the configuration of the front structure of all three typical vehicles is 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 the driver and front passenger. For the rear passenger the characteristic of three point belts was used. For all tests involving higher impact velocities (40 and 45 mph) pretensioners and force limiters were added to the systems. 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 for higher impact velocities (40 and 45 mph) as described above is not yet proven in mass production.

4.4.3 Effects of Installation of the Diesel Engines Studied in Typical Vehicles.

The vehicle weights and lenghts shown in Table 2 (some selected examples), have been calculated on the basis of the assumptions enumerated above and reflects only the weight and lenght changes of the frontal vehicle structure.

*This assumption is valid only for the front passengers.

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

TYPICAL VEHICLES / ROOMINESS INDEX	ENGINES	CURRENT SAFETY PRACTICE, GASOLINE ENGINE, BASELINE 30 MPH FRONTAL IMPACT		CURRENT SAFETY PRACTICE, DIESEL ENGINE 30 MPH FRONTAL IMPACT		CURRENT SAFETY PRACTICE, DIESEL ENGINE AND 40 MPH FRONTAL IMPACT		CURRENT SAFETY PRACTICE, DIESEL ENGINE AND 45 MPH FRONTAL IMPACT	
INCH		Length INCH	Weight KG LB	Length INCH	Weight KG LB	Length INCH	Weight KG LB	Length INCH	Weight KG LB
VW-RABBIT 260	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 269	FRONT ENGINE LENGTHWISE 4-cyl. turbo-charged, 70 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 100 276	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 VW 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:	42.0 mpg
	Highway:	56.0 mpg
	Composite:	47.3 mpg
Emissions:	HC :	0.22 gram/mile
	CO :	0.98 gram/mile
	NOx:	0.93 gram/mile

Acceleration time 0 to 60 mph 15 sec.

Figure 27: VW Integrated Research Vehicle (IRVW)

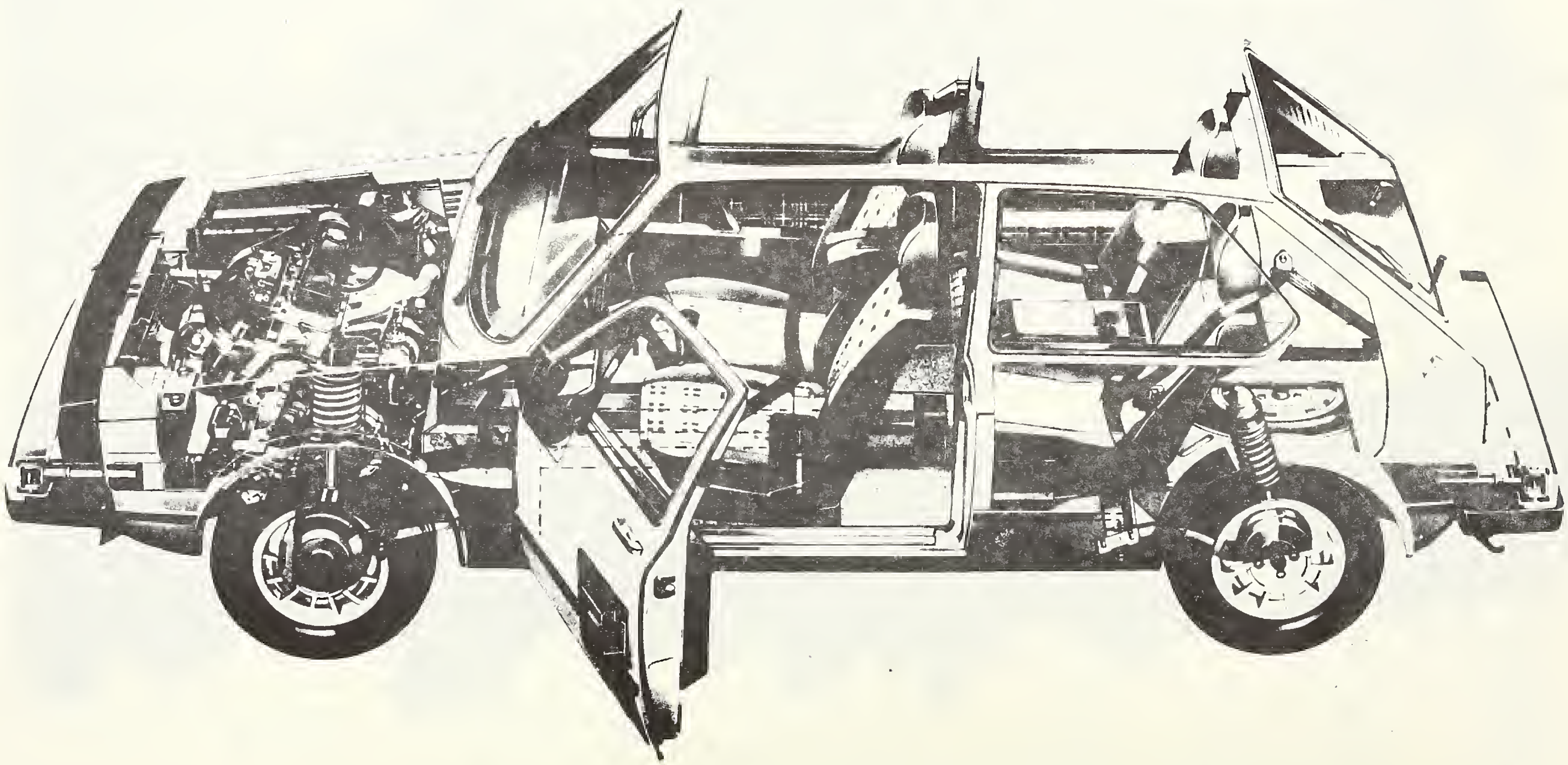


Figure 28: Cutaway View of the VW Integrated Research Vehicle (IRVW)

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 27 and 28) 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 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 29 shows the fuel economy of the IRVW compared to the U.S. gasoline fleet 1977.
Figure 30 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.

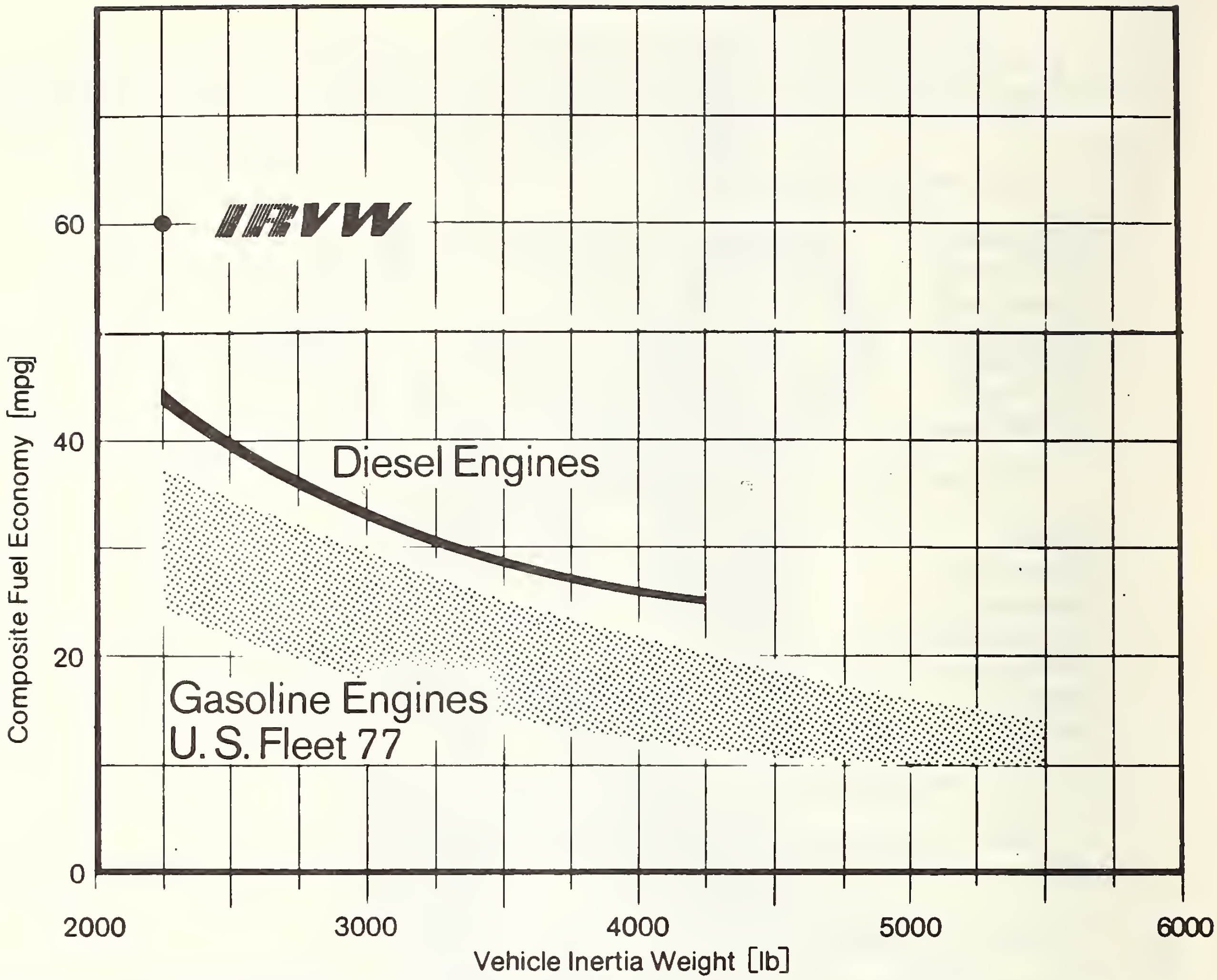


Figure 29: Comparison of Fuel Economy Results.

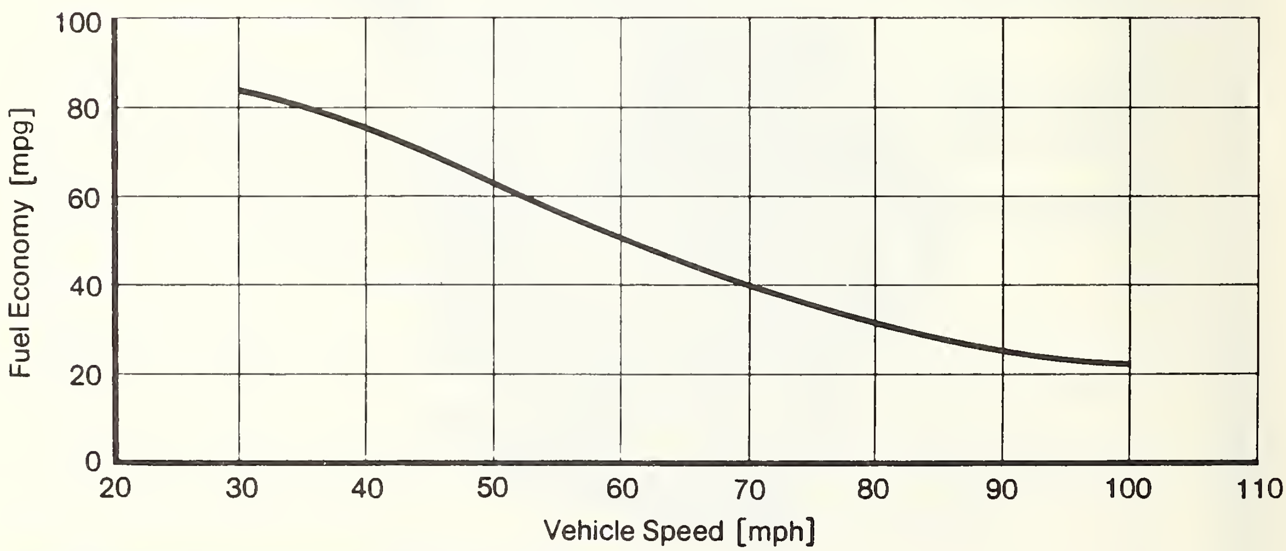


Figure 30: IRVW Fuel Economy at Steady State.

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 (left) Passenger	Driver	Front Passenger	Rear (left) Passenger	Driver Left	Driver Right	Front Passenger Left	Front Passenger 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

**Rear passenger on right side, impact at right side
**Not measured

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