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Light-Duty Diesel Engine Development Status and Engine Needs

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August 1980

Prepared for:

U.S. Department of Energy

Assistant Secretary for Conservation and

Solar Energy

Office of Transportation Programs

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August 1980

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PREFACE

This report, prepared by The Aerospace Corporation for the Automotive Technology Development Division of the U.S. Department of Energy, reviews, assesses, and summarizes the research and development status of diesel engine technology applicable to light-duty vehicles. In addition, it identifies specific basic and applied research and development needs in light-duty diesel technology and related health areas where initial or increased participation by the U.S. Government would be desirable. The material presented in this report updates information provided in the first diesel engine status report prepared by The Aerospace Corporation for the Department of Energy in September, 1978.

The report is divided into nine sections plus an Executive Summary. Section 1, entitled Introduction, provides a brief statement of the study objective. Section 2, Diesel Engine Design and Operating Characteristics, reviews and examines the fuel economy and emissions characteristics of diesel engines utilized in automotive applications. Section 3, Diesel Exhaust Emissions Control Technology, describes techniques, devices, and systems for the control of exhaust pollutants emitted by light-duty diesel vehicles. Section 4, Diesel Exhaust Emissions Measurement Technology, discusses methods used to quantify and otherwise characterize gaseous and particulate emissions in diesel exhaust. Section 5, Diesel Engine Noise Characteristics, treats light-duty diesel vehicle noise emissions, reduction techniques, and legislation. Section 6, Direct Injection Light-Duty Diesel Engine Technology, reviews and assesses recent advances made in direct injection diesel engine technology for application to light-duty vehicles. Section 7, Health Effects of Diesel Exhaust Emissions, briefly examines health effects issues related to gaseous and particulate emissions from light-duty diesel engines. A comprehensive report on diesel health effects will be published by DOE in the near future. Section 8, Current Status of Diesel Engine Research and Development Programs, discusses diesel engine programs conducted by Government Agencies, the automobile industry, and other organizations in the areas of engine and emissions control and measurement technology, and health effects. Finally, Section 9, Diesel Research and Development Needs,

identifies specific program areas in which government participation would be desirable to assure the timely development of diesel engine related technologies and of information regarding the impact of diesel exhaust on human health.

Appreciation is acknowledged for the assistance provided by Mr. Henry A. Themak, U.S. Department of Energy, and Dr. Edward A. Willis, NASA Lewis Research Center, who served as program monitors. Appreciation is also extended to many other individuals (see Reference lists) for their support during the course of this study.

The report is based on technical information and test data published in the open literature, or provided by individuals, prior to January 1980, with the exception of a few 1980 reports referenced in Sections 2, 4, and 8.

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GLOSSARY

AMA	Automobile Manufacturers Association
ANL	Argonne National Laboratory
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BaP	Benzo(a)Pyrene
BETC	Bartlesville Energy Technology Center
bhp	Brake Horsepower
bmep	Brake Mean Effective Pressure
BMW	Bavarian Motor Works
bsfc	Brake Specific Fuel Consumption
BTDC	Before Top Dead Center
C	Carbon
CA	Crank Angle
CAFE	Corporate Average Fuel Economy
cfm	Cubic Feet Per Minute
CFV	Critical Flow Venturi
CID	Cubic Inch Displacement
CN	Cetane Number
CO	Carbon Monoxide
CVS	Constant Volume Sampler
DB	Daimler-Benz
dB	Decibel
dB(A)	Decibel (A-Weighted)
DCM	Dichloromethane
DI	Direct Injection
DNA	Deoxyribonucleic Acid
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
EPE	Estimated Permissible Exposures

FID	Flame Ionization Detector
FTP	Federal Test Procedures
GM	General Motors
g/mi	Grams Per Mile
HC	Hydrocarbon
HERLC	Health Effects Research Laboratory, Cincinnati (EPA)
HFID	Heated Flame Ionization Detector
HP	Horsepower
Hz	Hertz
IDI	Indirect Injection
IERL	Industrial Environmental Research Laboratory (EPA)
IITRI	Illinois Institute of Technology Research Institute
ISO	International Standardization Organization
LeRC	Lewis Research Center
LITRI	Lovelace Inhalation Toxicology Research Institute
LLL	Lawrence Livermore Laboratory
m	Meter
MIT	Massachusetts Institute of Technology
mpg	Miles Per Gallon
NA	Naturally Aspirated
NAAQS	National Ambient Air Quality Standard
NASA	National Aeronautics and Space Administration
NIOSH	National Institute of Occupational Safety and Health
NO	Nitric Oxide
NO _x	Oxides of Nitrogen
N/V	Engine-Speed-to-Road-Speed-Ratio
ORNL	Oak Ridge National Laboratory
PAH	Polynuclear Aromatic Hydrocarbons
PNA	Polynuclear Aromatics
ppm	Parts Per Million
R&D	Research and Development
RES	Rated Engine Speed
RFDV	Reverse Flow Damping Valve
rpm	Revolutions Per Minute
RTI	Research Triangle Institute

RTP	Research Triangle Park (EPA)
SAE	Society of Automotive Engineers
SI	Spark Ignition
SPL	Sound Pressure Level
SWRI	Southwest Research Institute
TARADCOM	Tank-Automotive Research and Development Command (U.S. Army)
TC	Turbocharged
TIA	Total Intensity of Aroma
TSC	Transportation Systems Center (DOT)
TSP	Total Suspended Particulates
UCR	University of California at Riverside
V	Volt
VCO	Valve Covers Orifice
VSO	Valve Seal Orifice
VW	Volkswagen
W	Watt
XP	Xeroderma Pigmentosum

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EXECUTIVE SUMMARY

1. INTRODUCTION

This report reviews and summarizes the status of diesel engine technology applicable to light-duty vehicles. In addition, it identifies basic and applied research and development needs in light-duty diesel technology and related areas of health effects, for which government support would be desirable. The material presented in this report updates the information provided in the first diesel engine status report prepared by The Aerospace Corporation for the Department of Energy (DOE) and issued in September, 1978.

Interest in the diesel as an alternative engine for automobiles and light-duty trucks has grown rapidly during the past several years. In light of the diesel's very low fuel consumption at idle and in the low load-low speed regime, the engine is particularly well suited for vehicles operating under urban driving conditions.

In urban driving, current production diesel automobiles have a fuel economy advantage of 30 to 70 percent relative to their spark ignition (SI) engine powered counterparts. However, most diesel production automobiles have significantly lower acceleration performance, gradability, and top speed capability than SI vehicles of similar size and weight.

Without the use of sophisticated emission control techniques and devices, diesel engines have inherently low hydrocarbon (HC) and carbon monoxide (CO) exhaust emissions, and moderately low emissions of oxides of nitrogen (NO_x). However, there are uncertainties regarding the diesel's capability of simultaneously meeting future NO_x and particulate standards for light-duty vehicles, while maintaining its competitive fuel economy and durability characteristics.

2. DIESEL ENGINE CHARACTERISTICS

Current production diesel engines may be categorized as one of two types: direct injection (DI) or open chamber, and indirect injection (IDI) or divided chamber.

In DI engines, the fuel is injected directly into a single combustion chamber, by means of a high-pressure fuel injection system. Depending upon the magnitude of the induced combustion chamber air swirl, the DI engine category may be subdivided into three classes: (1) quiescent or low swirl chamber, (2) medium swirl or deep bowl chamber, and (3) high swirl, spherical chamber. In general, low swirl DI engines require a sophisticated fuel injection system and have favorable fuel consumption and starting characteristics. Conversely, high swirl engines can utilize a simpler injection system and usually exhibit good multi-fuel capability, but have less favorable startability characteristics at low ambient temperatures.

In IDI engines, the fuel is injected into an antechamber which is connected to the main combustion chamber via a passageway. IDI engines are subdivided into two types according to the shape and size of the antechamber: (1) swirl or turbulence chamber, and (2) precombustion chamber or prechamber. Swirl chamber engines have spherical antechambers, while prechamber engines use pear-shaped antechambers. As combustion in the antechamber proceeds, hot gases are discharged into the main chamber where combustion is completed under conditions of enhanced mixing generated by combustion gases flowing from the antechamber.

IDI engines are favored for light-duty vehicle applications primarily because of their higher speed capability and lower noise and exhaust emissions. Conversely, DI engines have dominated heavy-duty applications because of their superior fuel economy relative to IDI engines. However, the DI engine concept is currently being pursued by some manufacturers for potential use in light-duty vehicle applications.

2.1 LIGHT-DUTY VEHICLE FUEL ECONOMY

Similar to SI vehicles, the fuel economy of light-duty diesel powered automobiles increases with decreasing inertia weight. Over the range of vehicle inertia weights extending from 2250 lb to 5000 lb, the most fuel-efficient diesel automobiles exhibit an Urban Cycle fuel economy advantage

ranging from about 30 to 70 percent, relative to their most fuel-efficient SI vehicle counterparts. It should be noted, however, that current diesel vehicles have lower rated power-to-inertia-weight ratios relative to SI vehicles, implying lower performance for diesel automobiles.

To permit a more meaningful comparison of diesel and SI automobile fuel economy, adjustments must be made to account for differences in engine rated power and displacement, vehicle weight, axle ratio, fuel heating values, and refinery energy consumption associated with the production of diesel fuel and gasoline. For equal performance and inertia weight, diesels typically show a 25 percent fuel economy advantage relative to SI vehicles.

The fuel economy advantage of diesels is attributable to several factors, including operation at leaner air-fuel mixtures, lower pumping losses, and higher engine compression ratio. Since the combined effect of these factors is most prevalent at idle and in the low-load regime, the diesel's fuel economy advantage is highest for urban driving conditions.

2.2 REGULATED VEHICLE EMISSIONS

Diesel vehicles emit both regulated and currently unregulated pollutant species. Regulated species are HC, CO, and NO_x and are subject to standards identical to those for light-duty SI vehicles. However, NO_x waivers allowing NO_x emissions up to 1.5 g/mi instead of the statutory 1.0 g/mi may be granted for the 1981 through 1984 Model Years for diesel vehicles only. In 1982, exhaust gas particulates will be included in the regulated species category, with the initial particulate standard set at 0.6 g/mi. This standard will increase in stringency to 0.2 g/mi in 1985.

Light-duty diesel automobiles have no difficulty meeting current HC and CO emissions regulations, unless NO_x is controlled below approximately 1.5 g/mi. However, the use of exhaust gas recirculation (EGR), which is currently favored by the automobile industry as a means of meeting future more stringent NO_x standards, generally results in an increase in HC, CO, and particulate emissions.

In addition to HC, CO, and NO_x, diesels emit a number of currently unregulated species, including particulates, smoke, sulfates, odor, and aldehydes. There is considerable concern over particulate emissions, because they are generally of respirable size and contain organic compounds known to be mutagenic or even carcinogenic. Particulates emitted from diesels consist of about 65 to 85 percent carbon, plus many different high molecular weight soluble organics, some sulfates, and a number of trace metals. Based on limited data, the organic fraction emitted from IDI diesel engines of current design ranges between 2 and 30 percent of particulate mass and depends on engine design, vehicle inertia weight, driving cycle, and fuel composition.

Current light-duty production vehicles exhibit particulate emissions ranging from about 0.2 up to 1.0 g/mi. Turbocharging has resulted in moderate reductions of particulate emissions in some engines, while others show no improvement with turbocharging. Based on limited test data, fuel and lube oil composition has a significant effect on particulate emissions. Generally, fuels with high aromatic content, low volatility, and low cetane number result in high particulate emissions.

While current design diesel engines have significantly higher levels of particulate emissions than SI engines, the total particulate quantity emitted is rather insignificant on a macroscopic scale. However, the major concern regarding diesel particulates is not their total amount, but the potential for particulate concentrations reaching hazardous levels in urban areas, street canyons, and parking facilities.

Although particulate emissions from light-duty vehicles are of major concern, other currently unregulated diesel emissions also contribute to air pollution. These are smoke, oxides of sulfur, odor, particle adsorbed organics, aldehydes, phenols, and nitrosamines. Exhaust smoke can be controlled to some degree by means of organo-metallic smoke suppressant fuel additives, but at the expense of an increase in total particulate emissions. Oxides of sulfur emissions are directly related to fuel sulfur content, and may be reduced at added cost by use of low sulfur fuel. Diesel odor can be reduced by means of engine and fuel injection system modifications, and to some extent through

modification of fuel composition. The organics adsorbed on particulates are dependent on many factors, including engine design and operation, and fuel composition. Catalytic converters have shown some abatement potential. Aldehydes, phenols, and nitrosamines emissions are affected by engine and fuels parameters, and may be controlled through optimization of these factors.

3. DIESEL EXHAUST EMISSIONS CONTROL TECHNOLOGY

Presently known exhaust emission control techniques applicable to diesel engines can be divided into four categories: (1) engine operational modifications, (2) engine and component modifications, (3) incorporation of control devices, and (4) fuel modifications and additives. Engine operational modifications include variations in engine speed, engine load, gearing, and intake air temperature. Engine and component modifications primarily involve the combustion chamber and fuel injection system, while emission control devices include exhaust gas recirculation, water injection, and exhaust cleanup devices. Fuel modifications include the use of additives and variations in composition.

3.1 ENGINE OPERATIONAL MODIFICATIONS

Test data from both naturally aspirated and turbocharged indirect injection light-duty automotive diesel engines indicate a dependence of HC, CO, and NO_x emissions on engine speed, engine load, and operating temperature. In the low power output regime, HC and CO emissions generally decrease with increasing load, while load variations in the high power regime can result either in reductions or increases in HC and CO, depending upon engine and fuel injection system design and operation. Brake specific NO_x emissions generally decline as engine load increases, while particulate emissions have been observed to increase with decreasing speed for one engine type, but exhibit independence of speed in another engine. Intake air cooling results in a reduction in combustion chamber peak temperatures and pressures, accompanied by lower NO_x formation rates.

3.2 ENGINE AND COMPONENT MODIFICATIONS

Combustion chamber and fuel injection system design, geometry, and operational parameters strongly affect the combustion process in diesel engines, and hence exhaust emissions and fuel consumption. As a result, most diesel engine manufacturers have expended considerable efforts to determine optimal designs with regard to fuel economy and emissions.

The combustion process in IDI diesel engines is strongly affected by a number of flow field parameters within the antechamber, including air swirl turbulence level, and fuel-air mixture ratio, as well as the expulsion process of the combustion products into the oxygen-rich main chamber. These parameters are influenced by the design of the combustion chamber and intake system. In addition, a number of fuel injection system design and operating parameters have been identified which significantly affect diesel engine performance and emissions characteristics. These include (1) start and duration of injection, (2) injection rate, (3) injection pressure, (4) injector orifice size and number, (5) spray angle, and (6) nozzle orientation. To minimize HC and smoke emissions, the injection process must proceed in a stable manner and without the occurrence of secondary injections after completion of the main injection process.

Start and duration of the injection process are the principal fuel injection system parameters affecting exhaust emissions. Advanced electronically controlled systems are under development with the potential to provide better control of exhaust emissions. Early injection timing, particularly when combined with high injection rates, produces high pressure rise rates and high peak cycle temperatures. These conditions generally result in lower specific fuel consumption, but at the expense of an increase in NO_x emissions. While the performance of indirect injection diesels is relatively insensitive to variations in fuel injection rate, an increase in injection rate has resulted in higher NO_x emission levels in some engines. The effect of injection rate variations on fuel consumption and emissions of DI diesels is more pronounced, probably because of the greater importance of air swirl and specific nozzle design parameters on the air-fuel mixing process.

Increasing injection pressure has been shown to decrease particulate emissions in some engines, while increasing NO_x emissions slightly. Injection orifice size, orifice number, and spray angle affect spray formation and penetration, as well as the overall air-fuel mixing process. This, in turn, has a significant impact on the emissions and fuel economy of diesel engines. Orientation of the fuel spray relative to the direction of the air flow within the swirl chamber has a significant effect on the air-fuel mixing process and exhaust emissions. Angling the fuel spray against the direction of swirl has

resulted in lower HC and particulate emissions in some engines, frequently at the expense of an increase in NO_x and noise levels. Conversely, angling the spray in the direction of the swirl produced the opposite effect, probably because of a reduction in the combustion rate as a result of increased wall wetting.

Fumigation, which involves the injection of small quantities of fuel into the intake manifold of diesel engines, has been shown to have the potential for reducing NO_x , smoke, and noise emissions. Test data from a single cylinder DI research engine indicate some reduction in these species at low speed, accompanied by a small increase in fuel consumption, and an increase in HC. However, at rated speed and load, the improvements in exhaust emissions diminished, and fuel consumption increased markedly. Similar trends were observed for IDI prechamber engines.

3.3 EMISSION CONTROL DEVICES

A number of emission control devices and techniques have been and still are being investigated by the automobile industry and other organizations. These include EGR, water addition, exhaust aftertreatment devices, and turbocharging.

EGR has been shown to be an effective technique for controlling NO_x in both IDI and DI diesel engines. The mechanism of NO_x reduction is the same as in the gasoline engine: dilution of the intake charge with exhaust products. As a result, peak combustion temperatures and oxygen concentration in the combustion chamber decline accordingly. However, the use of EGR in diesel engines introduces complications related to increases in HC, CO, and particulate emissions which renders simultaneous control of these species and NO_x extremely difficult. In addition, the use of EGR introduces a number of engine related problems, including lube oil contamination, deposit buildup in the intake system, and excessive wear in vital engine parts.

Water injection into the intake manifold or into the cylinder, either directly or in the form of a fuel-water mixture, is an effective NO_x control technique. In addition, engine tests with fuel-water emulsions have shown significant improvements in particulate emissions, at the expense of a moderate increase in HC. Although water injection appears to be a powerful NO_x reduction technique, a number of critical problem areas mitigate its use for

automobile engine applications. These include potential corrosion of all system parts in contact with water or water vapor, added system complexity, packaging and space requirements of a water storage tank, fillup procedures, freeze protection, and lube oil dilution.

Although particulate removal from the exhaust is not the most desirable approach, as it requires add-on devices and does not alleviate lube oil contamination problems, this technique has received increasing emphasis because of the difficulties in solving the particulate problem within the combustion chamber. Centrifuges, water scrubbers, electrostatic precipitators, oil bath filters, and molten salt baths have been considered by a number of investigators, but appear to be impractical for automotive applications. The most promising particulate control technique appears to be the use of exhaust trap oxidizer systems. In these devices, the particulate matter in the engine exhaust is collected in the trap, with periodic regeneration by means of oxidation of the collected matter. However, a number of problem areas remain to be resolved before catalytic traps can be seriously considered for use in production vehicle applications. These include (1) demonstration of 50,000 mile durability, (2) management of uncontrolled particulate combustion, (3) reduction of sulfate emissions, (4) reduction of catalyst light-off temperature, and (5) development of a viable control system.

The power output of naturally aspirated diesel engines is generally limited by smoke. In the full load regime, this problem can be alleviated by means of turbocharging, which permits an increase in the fuel-air ratio as a result of an increase in the air flow rate supplied to the engine. In this case, HC emissions reductions up to 30 percent have been achieved, at the expense of moderate increases in NO_x emissions and fuel consumption. The use of turbocharging in conjunction with the use of a numerically smaller axle ratio, can result in moderate improvements in vehicle fuel economy. In addition to conventional turbochargers, a number of manufacturers are investigating the Compres Pressure Wave Supercharger. The principal advantage of this device relative to conventional turbochargers is its ability to produce higher boost pressures at low engine speeds, and to provide faster transient response characteristics.

Turbocompounding represents another waste heat utilization technique, which provides a potential for improved fuel economy. In this approach,

the turbine is geared directly to the engine crankshaft to supplement the shaft power output of the engine. In heavy-duty engines, fuel economy improvements of approximately 10 percent have been demonstrated. However, in light-duty applications, the benefits are projected to be less.

3.4 FUEL MODIFICATIONS AND ADDITIVES

In addition to combustion chamber geometry, injection system characteristics, and engine operating parameters, certain fuel parameters have a significant effect on the combustion process and the production of exhaust emissions. These include (1) specific gravity or American Petroleum Institute (API) gravity number, (2) viscosity, (3) boiling range or a number of boiling points, (4) cetane number, (5) sulfur and other impurities content, and (6) hydrocarbon family content, such as percentage paraffins, olefins, naphthenes, and aromatics. However, the response to changes in fuels characteristics cannot always be predicted, and is often affected by engine design and operating conditions. In general, fuels with lower aromatics content and higher volatility result in lower particulate emission levels.

Promulgation of increasingly stringent emission regulations place increasing demands on diesel fuel quality, with additives potentially playing an important role in achieving required performance standards. Typical additive classes are combustion modifiers, cetane improvers, anti-oxidants, metal deactivators, corrosion inhibitors, detergents and dispersants, pour-point depressants, biocides, color stabilizers, and dyes.

Combustion modifiers are designed to suppress the formation of black smoke during combustion through enhancement of the carbon to carbon dioxide conversion process. Complexes of barium and calcium salts as well as metal alkyls of transition elements are effective smoke depressants. However, there is concern regarding the toxicity of some of the end products generated during combustion of these additives, and the potential increase in total particulate emissions.

Fuel cetane number is a most important parameter affecting diesel engine operation. A number of compounds have been shown to be excellent cetane improvers, including mixtures of primary amyl nitrates or primary hexyl nitrates. However, cetane improvers are currently not widely used, probably because of their relatively high cost. A number of other diesel fuel additives have been

used in the past in specialty applications, including low temperature flow improvers, biocides, antistatic additives, and deodorants.

Recent investigations have considered the use of ethanol and methanol as a means of supplementing available supplies of diesel fuel. Alcohol addition can increase engine efficiency, and reduce soot and NO_x emissions. However, a major impediment is the high heat of vaporization of alcohols, which can result in excessive mixture cooling and long ignition delays. To overcome this characteristic of the alcohols, higher engine compression ratios, combined with charge preheating, may be required to achieve satisfactory combustion. However, since the stoichiometric mixture ratio for alcohols is considerably lower than for diesel fuel, the capacity of the fuel injection system must be increased to deliver the larger quantities of alcohol fuels required. Because of the poor ignition characteristics of alcohols, the use of ignition improvers, such as hexyl nitrate, would be required to achieve satisfactory combustion characteristics. However, engine tests using this compound indicate marked increases in HC, CO, and NO_x emissions relative to engine operation on diesel fuel only..

4. DIESEL EXHAUST EMISSIONS MEASUREMENT TECHNOLOGY

Existing Federal Test Procedures (FTP) for exhaust emissions certification of light-duty diesel and spark ignition (SI) vehicles are similar, since only gaseous emissions species are currently regulated. However, the Environmental Protection Agency (EPA) has promulgated major changes in those sections of the FTP applicable to testing of diesel vehicles. These modifications are intended to accommodate measurement of particulate emissions mandated for 1982 and subsequent Model Years.

4.1 PARTICULATE EMISSIONS MEASUREMENT

A dilution tunnel approach to particulate measurement is required by the EPA because of the complex manner in which diesel particulates enter the atmosphere. While gaseous pollutants can be accurately measured in the undiluted exhaust, physical and chemical processes involving particulates are still in progress in the exhaust before as well as after dilution in the atmosphere. For this reason, it is important that a system used for the determination of diesel particulate emissions incorporate a physical simulation of the atmospheric dilution.

In a dilution tunnel, a fraction of the raw, undiluted exhaust from the diesel engine is split off at the muffler and fed to the tunnel to

approximate atmospheric dilution processes. Unfortunately, the dilution ratio and the time scale over which dilution takes place in a dilution tunnel cannot exactly simulate atmospheric conditions. Mixing is more homogeneous in the tunnel, and the time scale of the different processes ranges from milliseconds, for the formation of particulates in the cylinder, to days, for disposal of particulates in the atmosphere. While these differences may impact basic issues such as health effects, the diluted exhaust test samples are more representative of the actual diesel exhaust contribution to particulates in the atmosphere than a sample taken directly from the raw, undiluted exhaust gas.

4.2 GASEOUS EMISSIONS MEASUREMENT

Currently, gasoline vehicle exhaust is diluted in a constant volume sampler (CVS) system, filtered, and collected in sample bags for subsequent determination of HC, CO, and NO_x. For diesel vehicles the procedure is identical, with the exception that (1) a heated flame ionization detector (HFID) is used to prevent condensation of the heavier HC species, and (2) emissions are measured continuously and integrated electronically to determine total HC mass. In the dilution tunnel and CVS method, gas samples are collected by a probe and are passed through a filter to remove all particulate matter from the gas stream prior to detection by the HFID. The entire system including the probe, filter and HFID, is heated to maintain a wall temperature of 375°F ± 20°F. However, it should be noted that the filter in the gas phase collection system is distinct from the particulate collection filter, which is constrained to a temperature no higher than 125°F. This approach is considered by some investigators to have a potential for overestimating the total HC emitted from diesel engines.

4.3 EMISSIONS MEASUREMENT CONSIDERATIONS

A potential difficulty associated with the particulate/gaseous measurement system required by the EPA has been noted by General Motors (GM), and is centered on maintaining different particulate and gas phase filter temperatures. According to GM, the disparity in filter temperatures causes a double-counting of HC. This is said to result because the HC species adsorbed on the particulates, which are retained on the particulate collection filter, have HC counterparts that are desorbed and converted to gas phase species in the separate gas phase particulate filter.

Recent research has quantified the measurement sensitivity of gaseous and particulate emissions to variations in a number of dilution tunnel and other test system parameters. These include (1) the comparison of baffle versus tunnel mixing of exhaust and diluent air, (2) the interactions between filter material and gaseous organics, (3) the effects of probe line length and CVS flow rate on measured emissions, (4) the effects of filter temperature on measured emissions, (5) the choice of isokinetic versus non-isokinetic sampling, and (6) the effects of dilution fraction and fuel type on measured emissions.

Tests of baffle versus tunnel mixing of exhaust and diluent air have shown a loss of about 6 percent in measured particulate mass using baffle mixing. Glass fiber filters can lead to the measurement of larger amounts of particulate mass relative to the use of teflon-coated glass fiber filters. The sensitivity of particulate mass measurements as a function of probe line length and CVS flow rate does not show variations of significance, indicating that probe line length and CVS flow rate are probably not critical factors in the measurement of particulates.

Insensitivity of measured emission levels to isokinetic versus non-isokinetic flow at the particulate sampling probe tip has been demonstrated. In experiments to determine the effect of variations in dilution fraction on total particulate and organic emissions, it was found that no significant differences in either gaseous or particulate emissions were observed for FTP cyclic tests, using dilution factors ranging from approximately 9 to 18.

4.4 ANALYSIS OF PARTICULATE CONTENT

While the EPA particulate regulations, which become effective in Model Year 1982, are limited to the control of particulate mass, future regulations might be developed to control both particulate mass and organic content. Ultimately, promulgation of such regulations will depend on the outcome of large-scale health effects studies currently in progress by the EPA and other organizations. These studies have given rise to a good deal of research and development into methods for characterizing the soluble organic fractions and sulfates using solvent extraction, gas chromatography, and colorimetric determination techniques.

5. DIESEL ENGINE NOISE CHARACTERISTICS

Historically, the diesel engine has been used to power large trucks and buses rather than automobiles. One legacy of this heritage is the perception of the diesel engine as being more noisy than the SI engine. While this is true to some extent, diesel engines do not inherently emit more noise than equivalent SI engines in every instance. In general, diesel noise is of a different constitution as a result of different circumstances of generation.

5.1 NOISE MEASUREMENT AND PERCEPTION

Because of the subjective nature of human perception, an objective measure of sound levels has been devised which is based on the ratio of sound pressure energy with respect to a specific reference. Ten times the common logarithm of this ratio is defined as the sound pressure level (SPL) in decibels (dB), and the reference level is frequently chosen as the faintest sound the average person can hear. The international standard for this level is $20 \mu\text{Pa}$. When considering separate noise sources, the sound energy levels are added to yield the overall SPL.

In addition to intensity level, sound is characterized by its frequency. Nominally, the human ear is able to perceive sounds between about 20 and 20,000 Hertz (Hz), with maximum sensitivity in the range of 800 to 5000 Hz. To correct the sound pressure level for the frequency dependence of the ear, the "A" rating (dB(A)) is often applied.

5.2 DIESEL NOISE EMISSION CHARACTERISTICS

In a typical diesel engine noise spectrum, 90 percent of the perceived noise is radiated in the 500 to 5000 Hz band, with maximum perceived noise confined between 800 and 2000 Hz. These two ranges correspond, respectively, to the frequencies of maximum hearing sensitivity and to frequencies of maximum importance to human speech. Although the perceived sound level below 500 Hz is not significant in itself, it still has a great deal of energy. This energy contributes to the perceived noise level indirectly by exciting structural resonances in the 500-4000 Hz region. During engine warmup, and at idle, the components of the noise spectrum between 800 and 4000 Hz are perceived primarily as "diesel knock."

In terms of dB(A), the noise spectrum of light-duty IDI diesel engines at rated speed is comparable to that of equivalent SI engines. However, there are noticeable differences in the composition of the noise spectrum. In the case of the diesel, 70 percent of the noise lies in the 500-4000 Hz range, with an additional 30 percent contributed by a 125 Hz peak. The SI engine shows just the inverse, with 76 percent of its noise in the 160-315 Hz range, and only 22 percent in the 500-4000 Hz region. Even though the overall noise levels are similar, the diesel will probably be subjectively judged more annoying, because of the speech masking effect of its noise spectrum.

5.3 FEDERAL, STATE, AND LOCAL NOISE REDUCTION LEGISLATION

At present, there is no federal legislation or regulation dealing specifically with the noise emissions of automobiles and light-duty trucks. However, the EPA is currently investigating noise emissions, and has already issued emission standards for medium- and heavy-duty trucks.

The existent light-duty vehicle noise legislation is at the local and state levels. At the local level, legislation generally takes the form of vehicle speed limits. Although set primarily for reasons of public safety, these limits serve the secondary purpose of noise control. At the state level, legislation is typically specified by state vehicle codes. At a minimum, these codes require that a vehicle be equipped with a type-approved muffler. Several states have specified maximum noise emission levels, while others have also implemented new product emission standards and have applied the standards to new automobiles.

5.4 DIESEL ENGINE NOISE SOURCES

Three major sources contribute to the overall noise emission of diesel engines: (1) combustion noise, (2) mechanical noise, and (3) structural response noise. The relative importance of each source is dependent on the size and configuration of the engine. Combustion noise is the predominant source in heavy-duty DI engines, while in the light-duty engines combustion noise and mechanical noise are of similar magnitude. In general, turbocharging reduces overall diesel combustion noise at the expense of increased mechanical noise.

Combustion noise is generated in the chamber during burning of the fuel charge. Microscopically, it is caused by random fluctuations in an

unsteady chamber pressure field, due to turbulence and the rapid release of heat. Mechanical noise is caused by the impacts of engine working parts due to abrupt discontinuous forces acting on these parts. The main sources of mechanical noise are due to piston-cylinder wall impacts, timing gear rattle, and fuel injection equipment forces. Structural response noise is produced by combustion and mechanical sources which are further modified, amplified, and selectively augmented by the physical responses of the various engine structures to the noise and vibration spectra. It is primarily via the structural responses that noise is transmitted from the engine surfaces to the surrounding air.

5.5 NOISE REDUCTION TECHNIQUES

Engine noise may be reduced in several ways, including structural modification, direct force reduction, noise suppression, noise modification, isolation, and shielding. Each technique applies to one or more of the various noise sources. In addition, a few of these techniques can result in a reduction of overall engine noise. However, engine noise cannot usually be significantly reduced by treating a single noise source.

Combustion noise is one of the major contributors to engine noise, and the most difficult one to treat. In general, a reduction in combustion noise is accompanied by a decrease in NO_x and an increase in specific fuel consumption. While turbocharging does not reduce combustion noise, it modifies the frequency spectrum. The net effect is a reduction in noise in the higher frequency range and an increase in the lower frequency range. Increasing the rate of injection and simultaneously reducing the ignition delay has resulted in modest combustion noise reductions. However, the increased injection rate also results in a small increase in mechanical noise, thus offsetting part of the gain. Increasing fuel cetane number in conjunction with a reduction in ignition delay has provided a nearly linear reduction in combustion noise in some engines, while cold start noise can be reduced through the use of high EGR rates.

Abatement of mechanical noise is constrained by many factors, including lubrication requirements, engine wear, thermal expansion, clearances, and component inertia. A number of different techniques investigated in the past have been aimed at reducing the ability of transient forces to generate and transmit noise in mechanical parts, rather than eliminating or reducing

these forces themselves. Piston slap noise can be reduced by lowering the magnitude of piston-cylinder wall impact forces. Another approach involves the reduction of the piston-cylinder wall clearance to reduce piston impact force. Modification of the piston lubrication system is still another approach to noise reduction and is based on providing improved lubrication film properties to cushion piston-wall impacts. The noise reduction treatments of timing gear rattle are designed to mitigate the noise-generating capacity of the transient torque changes in the shaft. The most effective technique for reducing timing gear noise is to eliminate the meshed gears, replacing them with a chain or belt drive.

Structural response noise treatments may be grouped into three major categories: stiffening, isolation, and shielding. Stiffening a structure generally involves adding integral ribbed crossmembers and corrugations, or selectively thickening certain areas. Generally, the intent of stiffening is to shift the structural resonances to higher frequencies where their radiation has less impact on the overall noise. Isolation requires physical separation of the radiating component from the engine structure by means of absorbent intervening structures. Shielding involves the use of lightweight covers on specific engine components or total engine encapsulation.

6. DIRECT INJECTION LIGHT-DUTY DIESEL ENGINE TECHNOLOGY

As a result of the rapidly increasing cost of automotive fuels during the past several years, and in light of the promulgation of increasingly stringent Corporate Average Fuel Economy (CAFE) standards for Model Years 1978 through 1985, a growing number of automobile manufacturers and other organizations have become interested in the DI diesel engine as a power plant for automobile and light-duty truck applications. Based on many years of development work on heavy-duty diesel engines, it has been shown that DI diesels have a fuel consumption advantage of up to 15 percent relative to equivalent IDI diesel engines. Although the DI combustion system is not new to the light-duty engine sector, it has not yet been applied to automobiles because of a number of inherent problem areas. These include (1) limited speed range, (2) high gaseous exhaust emissions, (3) excessive odor, (4) high noise levels, and (5) high engine weight.

AVL of Graz, Austria, has pioneered the development of small, high-speed DI diesel engines for potential application in automobiles since 1974, partly in cooperation with other organizations. This work has culminated in the design and testing of a number of new small and lightweight prototype engine configurations that have the potential for application in automobiles and light-duty trucks.

The principal features incorporated by AVL in its DI engine design are aimed at accelerating the rate of combustion, particularly in the high-speed regime, while minimizing smoke emission levels in the exhaust. Specific design modifications include the use of (1) helical intake ports, (2) bowl-in-piston type combustion chambers, combined with a turbulence rim, (3) multi-hole fuel injection nozzles, (4) fuel injection timing retard, (5) increased engine compression ratio, and (6) zero-sac injection nozzles. The use of helical intake ports is intended to improve the fuel-air mixing process, while the addition of a turbulence rim and the use of multi-hole nozzles is intended to increase the rate of combustion and to improve air utilization. Injection retard is applied as a means of NO_x control, at the expense of a small increase in fuel consumption. HC reduction is achieved by increasing engine compression ratio, combined with the use of zero-sac valve seal orifice (VSO) type injection nozzles. In addition to reducing HC, these modifications have resulted in marked reductions in peak chamber pressure and in the emissions of odor, irritants, white smoke, and noise, combined with significant improvements in engine cold start characteristics.

6.1 GASEOUS EMISSIONS AND FUEL ECONOMY

Limited test data over the Federal Urban Driving Cycle indicate that the gaseous emissions from light-duty vehicles equipped with AVL designed DI diesel engines are similar in magnitude to those measured for equivalent prechamber type IDI vehicles. However, the fuel economy of the DI vehicles shows a 15 percent advantage. Without EGR the DI vehicles will be hard pressed to meet a NO_x standard of 1.5 g/mi. The use of modulated EGR has resulted in the achievement of NO_x emissions below 1 g/mi, accompanied by a moderate increase in CO. With EGR, the fuel economy of the DI vehicles is approximately 20 percent higher than that of the IDI vehicles, indicating a lower fuel economy deterioration with EGR for AVL's DI engine.

PARTICULATE EMISSIONS

Particulate emissions data for AVL's naturally aspirated and turbo-charged DI diesel engine equipped automobiles indicate that the 0.2 g/mi particulate level might be achievable in small vehicles at low mileage without the use of EGR. However, the margin of safety might not be sufficient to account for hardware-to-hardware and test-to-test variations, and for mileage accumulation. The use of EGR in these vehicles to achieve NO_x levels below 1 g/mi was accompanied by a two-fold increase in particulates.

FUEL INJECTION SYSTEM REQUIREMENTS

The achievement of rapid, low-pressure combustion in DI diesel engines, which is required for low emissions of gaseous species, particulates, odor, and noise, is predicated upon the availability of improved fuel injection systems. Low HC emissions require the use of zero-sac VSO nozzles. Other desirable fuel injection system features include (1) constant injection timing over the whole load range, (2) timing advance at start and during warmup, (3) high injection pressure levels, and (4) precise control and stability of the fuel injection process.

AVL has achieved these attributes in its unit injector design, although some disadvantages were incurred relating to complexities in linkage and timing schedule, the need for fuel supply and return lines, and difficulties with torque curve matching. However, it appears that the advantages of unit injectors far outweigh their drawbacks. The use of unit injection in conjunction with the other improvements identified in this report provides the opportunity for overcoming the deficiencies of current DI engines, including their low specific output power, limited speed range, high exhaust emission rates, and high engine weight.

HEALTH EFFECTS OF DIESEL EXHAUST EMISSIONS

Considering the composition of the exhaust of typical current diesel engines, the widespread use of diesel engines could pose a potential threat to human health. While diesel exhaust contains known mutagens, carcinogens, and respiratory irritants, the extent to which this potential threat will actually be realized is currently not quantified. However, health effects of diesel

exhaust are the subject of current widespread experimental work, and the final integrated assessment of the health threat will include projected risks. Despite the presence of species which are known to have adverse effects on human health, conclusive evidence regarding adverse effects in humans chronically exposed to diesel exhaust is lacking.

The presence of adsorbed benzo(a)pyrene (BaP) and other chemicals on diesel particulates is of consequence to human health, because the size of the particulates is small enough to permit them to reach the deep recesses of the lungs. Furthermore, the clearance time in the lung is much longer than for other depositional areas, ranging from days to years. This enhances the probability that adsorbed carcinogens will be absorbed into the body. The small size of particulates also increases atmospheric settling time and the likelihood of inhalation.

Further complicating the analysis of diesel exhaust effects are the interactions which will occur when the exhaust disperses into the atmosphere. Atmospheric interaction of exhaust components with other atmospheric pollutants, influenced by the presence of sunlight, causes the destruction of some substances and the synthesis of others not originally present in the exhaust. At this time, the atmospheric processes are not understood well enough to predict the ultimate disposition of the various pollutant species, except in a general sense.

Although the diesel engine contributions to ambient pollutant levels are generally 1 percent or less of the total burden of each pollutant species, such overall figures must be viewed cautiously because mobile emissions represent concentrated sources distributed where the human population is densest. For example, in 1971, 42 percent of the particulate burden in urbanized Los Angeles County, and virtually all BaP, was attributed to motor vehicles.

Health effects research is being performed by a number of organizations in three major areas: (1) in-vitro testing, (2) in-vivo testing, and (3) human effects studies. The ultimate objective of those investigations is to determine the effects of diesel engine exhaust pollutants on human health.

7.1 IN-VITRO TESTING

The general process of in-vitro testing uses a cellular-level organism, which is maintained in a nourishing medium and subjected to regulated

dosages of the test substance. Following an incubation period, the organism is examined for indications of change in growth and viability. The organism may be of bacterial, mammalian, or human origin, depending on test method. The advantages of in-vitro testing are its short duration and low cost, permitting large numbers of test substances to be tested rapidly and economically. The primary disadvantage of these tests is the difficulty of extrapolating test results to higher animals or to humans. For this reason, in-vitro tests are used primarily for preliminary screening rather than for final determination of hazard levels.

As an illustration of the issues involved in interpreting in-vitro test results, the Ames test serves as an excellent example. Among the in-vitro assay tests, the Ames Salmonella/Mammalian Microsome Mutagenicity test is of major importance as a screening test, because of its simplicity, low cost, and speed of execution. However, the Ames test has several disadvantages including (1) the demonstration of mutagenic activity in a bacterial cell is no guaranty that such activity can be demonstrated in other species, (2) human cells possess sophisticated deoxyribonucleic acid (DNA) repair mechanisms which restore slightly damaged DNA, and these mechanisms differ between species, (3) the test measures a particular mutation at a particular DNA site, and (4) demonstration of DNA mutation, even in human cells, does not ensure that it will lead to a carcinoma.

Ames tests of whole particulates have yielded moderate levels of potential mutagenicity. Tests of particulate extracts have shown a high degree of variability, with sensitivity to both the method of particulate collection and to the solvent used to elute the adsorbed particulate components.

7.2 IN-VIVO TESTING

In-vivo studies use live animals for effects testing. In these tests, whole diesel exhaust may be inhaled by the test animals, or particulates may be instilled directly into bronchial passages. Also, soluble extracts of particulates may be painted on their skins, or injected beneath it. While in-vivo studies do provide better data for establishing human dose-response relationships than in-vitro tests, they are still not completely analogous to human exposure.

Some animal inhalation studies have shown only moderately detrimental effects. Other studies have demonstrated increases in respiratory resistance, decreases in lung clearance rates, anthracotic lesions in the lungs, acute pneumonia, and emphysema. Depending on exposure, the effects are partially reversible within three to four days following the end of exposure. However, major long-term inhalation studies have not yet been completed, most exposures lasting only a few weeks.

Skin painting studies have shown a high degree of induced tumors in laboratory mice. Epoxide isomers of BaP have demonstrated varying degrees of carcinogenicity, reinforcing the significance of the interaction of atmospheric pollutants with adsorbed BaP. Benzene extracts of exhaust particulates have also shown capacity to induce tumors. However, such extracts have been challenged as being nonrepresentative of ambient human exposure mechanisms.

7.3 HUMAN EFFECTS STUDIES

To date, human effects studies have been limited to acute exposure tests at moderate pollutant levels and to epidemiological surveys of chronic, usually occupational, exposures. Further insight is also afforded by historical episodes of acute urban air pollution. Absence of a demonstrated cause-effect relationship in epidemiological studies should not be considered adequate evidence to exonerate a substance completely. Rather, that exposure level should only be considered as a potential upper limit. Further substances which exacerbate common respiratory ailments or cancers will often not be noticed unless there is a large excess rate of risk.

Acute human exposure tests have found little effect from moderate exposures of up to four hours. Among asymptomatic asthmatics, slightly higher sensitivity has been noted, but because of the small sample size, the result might have been due to the subject's personal thresholds rather than to synergistic effects of the aerosol with the subject's asthmatic conditions. Chronic exposures to diesel exhaust have not produced clear health trends in workers. Most past studies of diesel-exposed workers have been found to be of limited usefulness due to confounding factors not considered.

Those studies which have shown visible health effects have generally relied not upon exposure to diesel exhaust but upon exposure to non-diesel

generated pollutants similar to those present in diesel exhaust. However, some caution in interpreting such results is necessary, because the generating processes may not be equivalent to those of diesel engines and, in the case of ambient air samples, the ultimate source of the pollutant may not be known. Several studies of coke workers, coal-gas workers, and roofers exposed to higher than average levels of polynuclear aromatic hydrocarbons (PAH), particularly BaP, have found correlation between increased levels of PAH and excess cancer mortalities. Similarly, several studies of urban and rural dwellers have found the same trends in the general population. Ambient particulate levels do not correlate well with urban versus rural levels of respiratory disease, but acute episodes of high urban particulates have produced severe respiratory illnesses and deaths in susceptible subpopulations.

8. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS

A number of government agencies, automobile manufacturers, and other organizations are currently involved in various aspects of diesel engine related research and development programs. An overview and summary of these programs is presented in Tables 1 through 3.

9. DIESEL RESEARCH AND DEVELOPMENT NEEDS

Many organizations, including the automotive industry, government agencies, and a number of other institutions, are currently involved in diesel engine technology and health effects research and development activities. Although there are indications that industry is actively pursuing diesel technology and health effects research, many of its programs are short-term oriented and are primarily directed towards meeting the stringent particulate standards promulgated by the EPA for Model Years 1982 and 1985. Since results from programs conducted by industry are not always available in a timely manner, more aggressive government participation in the diesel health effects and technology research and development areas is required to provide the basic information needed for the assessment of the near- and long-term emissions and fuel conservation potential of light-duty IDI and DI diesel engines developed for use in automobile applications.

Currently, the Environmental Protection Agency (EPA), the Department of Transportation (DOT), the Department of Energy (DOE), and the National

TABLE 1. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS --
GOVERNMENT AGENCIES.

RESEARCH CATEGORY	GOVERNMENT AGENCY	CONTRACTOR	STATUS	COMMENTS
<u>ENGINE TECHNOLOGY</u>				
Indirect Injection Diesel	DOT	Chrysler Fiat Ricardo }	Vehicle Testing Near Completion In Progress	The Objectives of the Chrysler and Fiat Programs are the Determination of the Fuel Economy and Emissions Potential of Light Duty Diesels Through Optimization of Engine Design and Emission Control Devices and Techniques. Ricardo Investigates the Potential of Both State-of-the-Art and Advanced Engine Design and Control Technology.
Direct Injection Diesel	DOT	-----	Future Program	To Provide a Fuel Economy, Performance, and Emissions Data Base For Light Duty Diesel Engines, and to Assess the Effects of State-of-the-Art Emission Control Technology on Engine Operation, Fuel Economy, and Emissions.
Adiabatic Diesel	U. S. Army	Cummins	In Progress	Adiabatic Engine Operation Eliminates the Need for a Cooling System, Resulting in Higher Engine Efficiency. A 250HR Feasibility Demonstration Will Be Completed Early in 1980. The Development of Ceramic Piston Caps and Ceramic Coatings For the Piston, Cylinder Liner, Cylinder Head, and Valve Heads Will Be Continued During FY 1980. Development Efforts On a Low Friction Adiabatic Engine With Turbocharging Have Been Initiated. This Engine Will Be Unlubricated and the Goal is to Reduce Mechanical Friction by 50 Percent, Fuel Consumption By 10 Percent.
Low Compression Diesel	U. S. Army	Cummins	Ongoing	The Objective of This Program is to Demonstrate the Feasibility of Converting Commercial Engines to Military Applications and, in Conjunction With Turbocharging, Achieve High Efficiency in a Compact Design.
Turbocharging	DOT	Chrysler Fiat Ricardo Teledyne and Thermo- Mechanical Systems (TMS) }	In Progress In Progress	The DOT-Sponsored Work Involves Incorporation of State-of-the-Art Turbochargers in Chrysler and Fiat Diesel Engines. Engine and Vehicle Tests are Nearing Completion. Single Cylinder Tests Will Be Initiated by Ricardo in the Near Future. Fiat Vehicle Data Indicate Significant Reductions in Particulate Emissions With Turbocharging. A High Efficiency Variable Area Turbocharger Developed By Teledyne and TMS is Being Tested and a Phase II Design is Scheduled for Testing in FY 1980. TMS is Developing an Advanced Turbocharger Having High Efficiency, Wide Range, and High Pressure Ratio.
Turbocompounding	DOE	Cummins	Vehicle Tests in Progress	Turbocompounding Increases Engine Power Output, Reduces Fuel Consumption, and in Conjunction With Injection Retard Has the Potential of Providing NO _x Control. One Cummins Engine Incorporating the Turbocompound Feature Has Been Tested in a Truck Over 2000 Miles. Another Engine Will Be Tested in a Truck Operated Over 50,000 Long Distance Miles.
Combustion Chamber Optimization	DOT	Chrysler Fiat Ricardo Inhouse (BETC)	In Progress Completed In Progress Future Program	Chrysler is Exploring the Effects of Valve Timing and Compression Ratio Variations on Emissions and Fuel Economy. Ricardo Examines Prechamber to Main Chamber Volume Ratio Variations As a Means of Optimizing Fuel Economy and Emissions Under Light Load Operating Conditions, and Will Investigate Means of Reducing Wall Quenching. BETC Will Examine the Effects of Engine Modifications on Fuel Economy and Emissions.
Injection System Optimization	DOT	Chrysler Fiat Ricardo	In Progress Near Completion Soon to be Initiated	Chrysler is Optimizing Injection Timing as a Function of Load, With Particular Emphasis on the Light Load Regime. Fiat Has Completed Its Injection Timing Optimization Work. Ricardo Will Collect Fuel Consumption and Emissions Data on a Single Cylinder Engine, as Affected by Injection Timing, Rate, and Spray Angle Variations.
Advanced Fuel Injection System	U. S. Army	Physics International	In Progress	The Initial Design of a High Pressure Fuel Injection System Has Been Completed and Bench Tests Have Been Started. The System is Designed to Provide Very High Injection Rates For Optimum Fuel Economy and Emissions Operation.

TABLE 1. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS --
GOVERNMENT AGENCIES (Continued).

RESEARCH CATEGORY	GOVERNMENT AGENCY	CONTRACTOR	STATUS	COMMENTS
<u>EMISSION CONTROL</u>				
Exhaust Gas Recirculation	DOT EPA DOE	Chrysler Fiat Ricardo SWRI Inhouse (BETC)	In Progress In Progress Planned for FY 1980	Chrysler, Fiat, and Ricardo Have Performed Vehicle Tests with EGR to Determine the Effect On Gaseous and Particulate Emissions. While NO _x Declines With EGR, Particulate Levels Increase Significantly. Ricardo Will Investigate EGR Characteristics in a Single Cylinder Engine Test Program. SWRI Will Perform Emissions Baseline Tests of EGR Equipped Heavy Duty Diesels. Light Duty Diesel Testing Has Been Completed by SWRI. As Part of a Comprehensive Control Technology Assessment Program, BETC Will Determine the Effects of EGR on Exhaust Emissions of Production Vehicles.
Catalytic Converter	DOT DOE EPA Bureau of Mines	Chrysler Fiat Ricardo Inhouse (BETC) Inhouse at Michigan T. U. and at SWRI Engelhard	In Progress Planned for FY 1980 In Progress In Progress	The DOT-Sponsored Work Includes Engine/Vehicle Tests With Exhaust Catalysts. HC and CO Reductions Have Been Demonstrated, Permitting a NO _x /HC Tradeoff to be Made in Conjunction With Other Engine Modifications. Ricardo Will Perform Technology Development Work With Catalysts Placed Inside the Combustion Chamber. BETC, EPA, and Michigan Technological University Will Perform Assessments of the Pollutant Control Effectiveness of Catalysts. SWRI Will Establish an Emissions Data Base for Diesel Automobiles, and Will Examine the Effectiveness of Catalysts as a Technique for Control of Organics. Engelhard is Conducting Engine Tests of Various Catalysts.
Particulate Traps and Scrubbers	DOE Bureau of Mines EPA	Inhouse (BETC) Inhouse and with Engelhard Inhouse	Future Program In Progress In Progress	BETC Will Evaluate the Effectiveness of Traps as a Means of Reducing Particulate Emissions From Diesel Engines. The Bureau of Mines is Determining the Effectiveness of Particulate Filters and Scrubbers. 65 Percent Initial Particulate Removal Effectiveness Has Been Achieved in These Tests, But Device Deterioration is an Unresolved Problem Area. The EPA is Investigating the Particulate Removal Characteristics of Different Traps.
Fuel Composition	DOE Bureau of Mines EPA DOT	Inhouse and at Cummins Inhouse SWRI Ricardo	In Progress In Progress In Progress Completed	BETC is Establishing the Emissions Characteristics of Four Production Diesel Vehicles as Affected by Fuels Modifications, and Cummins Will Be Evaluating the Multifuel Capability of Its Adiabatic Engine, With Particular Emphasis on Gaseous and Particulate Emissions. A Comprehensive Assessment of Fuels Effects on Diesel Engine Performance and Emissions is Planned for FY 1980. The Bureau of Mines Has Found that Low Aromaticity Results in Lower BAP Emissions. A Vehicle Test Program is Underway at SWRI to Isolate Those Fuels Parameters That Have a Beneficial Effect on Particulate Emissions. Ricardo Has Determined the Effect of Cetane Number on Emissions and Found Little Change in the Particulate Level.
Noise Emission Control	Bureau of Mines EPA	Inhouse Inhouse and at SWRI, Purdue, and Ricardo	In Progress In Progress	The Bureau of Mines is Actively Involved in Noise Reduction of Underground Machinery. Potential Noise Abatement Techniques are Engine Enclosures and the Use of Acoustic Materials. EPA is Developing Noise Test Procedures for LDVs. Studies of Light, Medium, and Heavy Truck Engine and Tire Noise Reduction are Planned. Purdue Will Explore Noise Reduction Through Engine Encapsulation. Ricardo Will Demonstrate Noise Reduction Techniques in Vehicles Powered by Internal Combustion Engines.
<u>EMISSIONS AND MEASUREMENT TECHNOLOGY</u>				
Regulated Emissions	EPA DOT	Inhouse and at SWRI Chrysler Fiat Ricardo SWRI Inhouse (BETC)	In Progress In Progress In Progress In Progress	EPA Continues Emissions Certification Testing and Continues to Perform Emissions and Fuel Economy Testing of Prototype Vehicles. SWRI is in the Process of Establishing Baseline Emissions Maps for a Number of Heavy Duty Diesels and Will Establish an Emissions Data Base for Advanced Diesel Engine/Vehicle Configurations. Chrysler and Fiat are Establishing Baseline HC, CO, and NO _x Emissions as Affected by Various Control Techniques. BETC is Characterizing the Emissions of Four Diesel Passenger Cars to Isolate Modal Effects.

TABLE 1. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS --
GOVERNMENT AGENCIES (Continued).

RESEARCH CATEGORY	GOVERNMENT AGENCY	CONTRACTOR	STATUS	COMMENTS
EMISSIONS AND MEASUREMENT TECHNOLOGY (Cont'd)				
Unregulated Emissions	EPA DOE Bureau of Mines DOT	Inhouse and at SWRI Inhouse (BETC) Inhouse Chrysler Fiat Ricardo	In Progress In Progress Future Program In Progress	The EPA Will Perform Exhaust and Crankcase Emissions Measurements of Currently Unregulated Pollutants, Including Ammonia, Formaldehyde and Sulfates. SWRI Will Determine the Emissions of Particulates and Other Unregulated Species for a Number of Heavy Duty Diesels. In Addition SWRI Will Collect Samples for EPA's Bio-Assay Test Program. BETC is in the Process of Characterizing Total Particulate and Organic Mass Distributions for Four Production Diesels Over the Urban Driving Cycle and at Steady State. The Bureau of Mines Has Plans to Measure Exhaust PNA's and Particulates of a DI Diesel. Chrysler, Fiat, and Ricardo are Involved in the Characterization of Particulate Emissions From IDI Diesels, and in the Measurement of Total Particulates and Organics from IDI Engines Incorporating Emission Control Equipment.
Measurement Technology Development	EPA DOE Bureau of Mines	Inhouse and at Michigan T. U. Inhouse (BETC) Inhouse and at A. D. Little	Near Completion In Progress In Progress	Rulemaking for Particulate Measurement Of Light Duty Engines is Being Finalized by EPA and Investigations of Methodologies for Partitioning Organics are in Progress. BETC is Involved in the Development of Particulate Measurement Techniques. The Bureau of Mines Has Developed a Sulfate Test Procedure, and A. D. Little Has Completed an Assessment Study of Diesel Exhaust Measurement Methods.
HEALTH EFFECTS				
In-Vitro Testing	EPA DOE	Inhouse and at Battelle Columbus LITRI, MIT and Inhouse (BETC)	In Progress In Progress	At EPA, Bacterial and Mammalian Cell Bioassays Will Be Used to Compare the Mutagenic Activity of HDD and LDD Truck Exhaust as Well as Emissions From Other Sources. LITRI Will Research the Effect of Extraction Solvent on PAH Desorption Rates, and the Biological Characterization of Exhaust Components. BETC, in Cooperation With LITRI, Will Perform Ames Tests.
In-Vivo Testing	EPA DOE	Oak Ridge IITRI Inhouse LITRI	Continuing In Progress	Oak Ridge is Performing Mutagenesis Studies Involving Whole Exhaust Exposures of Mice and Drosophila. Skin Painting Studies Will Focus on Extracts of Diesel and Other Exhausts. IITRI Will Use Chronic Intratracheal Instillation of These Test Substances. EPA Will Use Chronic Inhalation and Intraperitoneal Injection to Assess Transport and Oncogenesis Effects. LITRI Will Pursue In-Vivo Studies of Chronic Whole Exhaust Exposures and Extraction Solvent Effects on PAH Desorption. Respirator Deposition Will Be Studied, Using Surrogate Aerosols of Known Composition.
Epidemiological Studies	EPA DOE NIOSH	Inhouse Inhouse Inhouse	In Abeyance Future Program In Progress	EPA Continues Its Search of Suitable Study Populations. DOE Will Embark on a Study of Occupational Exposures to Diesel and Gasoline Engine Exhausts. NIOSH is Continuing Its Epidemiological Studies of Mine Workers Exposed to Diesel Exhaust.
Integrated Assessment Studies	EPA DOE	Inhouse LITRI	Future Program Future Program	EPA Will Establish Relative Potencies of Various Diesel and Non-diesel Compounds as an Aid to Estimating Dose-Response Relationships. LITRI Will Define an Integrated Assessment of the Human Risk Issue.

TABLE 2. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS --
AUTOMOBILE MANUFACTURERS.

CATEGORY	COMPANY	STATUS	COMMENTS
ENGINE TECHNOLOGY DEVELOPMENT			
Indirect Injection Diesel	British Leyland Daimler-Benz Fiat General Motors Isuzu Nissan Peugeot Toyota Volkswagen BMW Chrysler Ford Toyo Kogyo	In Production Under Development	General Motors and a Number of European and Japanese Automobile Manufacturers are Marketing Diesel Automobiles or Light Duty Trucks. BMW, With Assistance From AVL, is Developing a Turbocharged Diesel Engine for Production in 1983, and Toyo Kogyo Will Start Production of Two New Engines in the Near Future. Chrysler is Dieseling Its 225 CID Gasoline Engine and Ford is Involved in Diesel Study and Development Efforts. Except for Daimler-Benz all Manufacturers Use Swirl Chambers. Current Daimler-Benz Engines are of the Prechamber Type, But Swirl Chamber Configurations are Being Evaluated. Daimler-Benz Feels That Prechamber Engines Have Lower HC, CO, and NO _x Emissions Potentials, at the Expense of a Small Loss in Fuel Economy. All Manufacturers Are Involved in Engine Improvement and Emission Control Technology Programs.
Direct Injection Diesel	BMW British Leyland Chrysler Cummins Daimler-Benz Fiat Peugeot	Under Study or Development	These Manufacturers are Involved in the Design and Development of Prototype DI Engines for Potential Application in Passenger Cars or Light Duty Trucks. Projected Fuel Economy Improvements Relative to IDI Diesels Vary from About 10 to 15 Percent for Naturally Aspirated Engines, and From 15 to 25 Percent for Turbocharged Engines. Noise, NO _x and HC Emissions are Considered by Some Manufacturers to Be Principal Problem Areas.
Adiabatic Engine	Fiat	Studies in Progress	Preliminary Design Investigations Have Been Initiated. Fiat Expects to Achieve Lower Particulate and HC Emissions and Better Startability Relative to Conventional Diesels.
Turbocharging	Daimler-Benz Peugeot Volkswagen Fiat BMW British Leyland Cummins Toyota Chrysler Ford	In Production In Production Near Production Near Production In Development Under Study	These Manufacturers are Considering the Use of Turbocharging as a Means of Improving Engine/ Vehicle Performance, and/or Reducing Fuel Consumption and Gaseous and Particulate Emissions. Some Manufacturers are in the Process of Conducting Vehicle Testing. Fuel Economy Improvements of 5-15 Percent Relative to Naturally Aspirated Engines are Projected When Turbocharging is Combined With Gearing Changes.
Engine Component Modifications	BMW British Leyland Chrysler Cummins Daimler-Benz Fiat Ford General Motors Isuzu Nissan Peugeot Toyo Kogyo Toyota Volkswagen	In Progress	All Manufacturers Have Active Programs in the Areas of Combustion Chamber and Fuel Injection System Modifications as a Means of Optimizing Engine Torque, Fuel Economy, Exhaust Emissions and Noise in Conjunction With the Use of Other Emission Control Devices and Techniques. Parameters Under Examination Include Chamber Shape and Volume Ratio, Compression Ratio, Prechamber/ Main Chamber Passage, Glow Plug Location, Materials Selection, Valve Timing, Fuel Injection Timing, Injection Pressure and Rate, Injection Nozzle Design, Sac Volume, Fuel Spray Formation, Spray Pattern, and Air/Fuel Mixing. High Pressure Injection Systems Permit the Use of High Injection Rates, Resulting in Improvements in Fuel Economy and Emissions.
Electronically Controlled Fuel Injection	Chrysler	In Progress	Several New Systems are Being Developed to Provide Better Control of Injection and Combustion Parameters in DI Diesels. These Designs Feature High Speed Valving Devices and Other Means for Precise Fuel Flow Control.
EMISSION CONTROL			
Exhaust Gas Recirculation	Robert Bosch BMW British Leyland Chrysler Cummins Daimler-Benz Fiat Ford General Motors Isuzu Nissan Peugeot Toyo Kogyo Toyota Volkswagen	In Progress	EGR is Considered to Be a Promising NO _x Control Technique. 40-60 Percent NO _x Reduction Has Been Achieved, Generally at the Expense of Higher Particulate, Smoke, HC, CO, and Odor Emissions. In Experimental 4500LB IW Vehicles, General Motors Has Achieved NO _x Levels Below 1 Gram/Mile. Potential Problem Areas are Deposit Buildup, Engine Wear and Lube Oil Contamination. Improved Modulated EGR Systems are Being Developed by a Number of Manufacturers. Daimler-Benz and Peugeot Have Tested the Bosch Hydraulic-Pneumatic EGR System. Peugeot is Continuing With the Bosch System, While Daimler-Benz is Developing an Electronically Controlled System. Toyota is Evaluating Both Mechanically and Electronically Controlled Systems. Daimler-Benz's 1980 California Diesel Vehicles Will Incorporate EGR to Meet the 1.5 Gram/Mile NO _x Standard.

**TABLE 2. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS --
AUTOMOBILE MANUFACTURERS (Continued).**

CATEGORY	COMPANY	STATUS	COMMENTS
EMISSION CONTROL (Cont'd)			
Catalytic Converter	British Leyland Daimler-Benz Fiat Ford Chrysler General Motors Peugeot Volkswagen	Under Consideration	Divided Chamber Light Duty Diesels Have Inherently Low HC and CO Emissions. However, the Use of EGR for NO _x Control Results in Higher HC and May Require the Use of a Catalyst to Meet the 0.41 Gram/Mile HC Standard. Problem Areas are Catalyst Degradation and an Increase in Sulfate Particulate Emissions. With Catalysts, Test Data Indicate Significant Reductions of the Organic Particulate Fraction.
Water Injection and Emulsions	Cummins Daimler-Benz Fiat Peugeot Toyota	Inactive Under Evaluation Inactive Under Consideration	Effective NO _x Control Technique. Daimler-Benz is Evaluating Water Injection and Induction Systems of Different Designs. In Conjunction with EGR and Turbocharging, They Have Achieved 0.4 Gram/Mile NO _x Plus Improved Fuel Economy in an Experimental Vehicle. Problem Areas are Corrosion, System Complexity, Cost, and Freezing of the Water. Toyota Has Experimented With Water/Fuel Emulsions and Has Demonstrated the Beneficial Effects Caused by "Micro Explosions". Emulsion Stability and Cost are Problem Areas.
Particulate Traps and Trap Oxidizers	Chrysler Daimler-Benz Fiat General Motors Peugeot Volkswagen	In Progress Under Investigation R & D Initiated Testing In Progress Under Investigation	Daimler-Benz Has Achieved Some Success With Experimental Trap Oxidizers. GM Has Demonstrated That Traps With In-Situ Regeneration By Incineration Are the Most Practical Means of Particulate Removal. Tests Have Indicated Problems With Back-Pressure, Loss of Trapping Efficiency, Durability and Safety. Peugeot Has Contracted Work to Ricardo While Volkswagen Has an Inhouse Program and Has Ricardo Under Contract. Problem Areas are Durability and Uncontrolled Lightoff of Carbonaceous Material.
Fuels and Lubricants Composition and Additives	Daimler-Benz Fiat General Motors Peugeot Volkswagen	Under Investigation	Daimler-Benz Data Indicate That Modification in Fuel Composition Can Have Beneficial Effects on HC and Particulate Emissions Levels. Fiat Has Shown Reductions in HC, Particulates and Organics Through Fuel Modifications and Use of Additives. Low Aromatic Fuels Give Low PNA's and Soot, While High Volatility Improves Engine Startability and Particulate Emissions. GM Has Used Carbon-14 Tracers to Determine the Effects of Fuel and Lubricant Compositions on Emissions, and Has Evaluated the Emissions Effects of Additives. Peugeot Has Found That the Low Cetane Rating of U.S. Diesel Fuels Relative to European Fuels Has an Adverse Effect on Emissions.
Noise Emission and Control	British Leyland Cummins Daimler-Benz Fiat General Motors Peugeot Volkswagen	In Progress	All Manufacturers are Engaged to Some Degree in Noise Characterization and Control Programs as Part of Their Normal R & D Activities. Daimler-Benz Has Constructed an Experimental Vehicle Featuring an Encapsulated Engine. General Motors has Experimented With Transmission Noise Reduction, and Has Proposed an Alternative Part-Throttle Test Procedure to EPA. Peugeot is Experimenting With Noise Reduction Via Shielding, Damping, and Engine Support Modifications, and is Experimenting With Turbocharging as a Means of Noise Reduction Through Engine Operation at Lower RPM. VW Has Achieved Some Reduction of Cold Knock Via EGR.
EMISSIONS AND MEASUREMENT TECHNOLOGY			
Pollutant Species Characterization	BMW British Leyland Chrysler Daimler-Benz Fiat Ford General Motors Peugeot Volkswagen	Ongoing Efforts	In Addition to Measuring Regulated Pollutants, Most Manufacturers are Involved in Determining Particulate Size Distributions and Particulate Organic Composition Through Inhouse Efforts or Contracted Work. BMW Has SWRI Under Contract to Characterize Particulates. Fiat Has Found That Turbocharging can Reduce the Organic Fraction. Manufacturers Will Be Using the Procedures Established by EPA For Certifying Diesels. Concern Over the Double-Counting of Hydrocarbons Has Been Expressed. The Effects of the Characterization of Organic Compounds Are Being Studied.
Measurement Technology Development	Daimler-Benz Peugeot Toyota	Studies in Progress	Daimler-Benz is Analyzing Different Sample Collection Methods, and is Developing a Chromatography-Based Method Identifying Odorous Constituents of Diesel Exhaust. Dilution Ratio Has Been Determined to Be a Very Important Parameter. Peugeot Has Experimented With Different Odor Measurement Techniques and Has Established a Need For More Reliable Instrumentation.
HEALTH EFFECTS			
In-Vitro Testing	BMW CCMC Chrysler Daimler-Benz General Motors Peugeot Volkswagen Volvo	In Progress	BMW and Volkswagen Have Contracted Work in This Area to German Biological Labs. Daimler-Benz Will Compare the Effects of Gasoline and Diesel Engine Exhausts on Bacterial and Mammalian Cells. GM Will Study the Effects of Diesel Exhaust Products Using Bacterial, Mammalian, and Human Cell Bioassays. CCMC Plans to Investigate the Effects of Extraction Solvent on Mutagenic Response. Peugeot Will Analyze Particulate Extracts With the Ames Test Procedure Through Contracts to Outside Labs. Volvo, in Cooperation With the Swedish Government, Will Investigate the Influence of Engine Operating Condition On In-Vitro Bioassays.
In-Vivo Testing	British Leyland CCMC Daimler-Benz Peugeot	In Progress	British Leyland is Performing Animal Inhalation Tests, and CCMC and Daimler-Benz are Conducting Chronic Inhalation Studies. GM Has Begun Exposure Tests in Its Chronic Inhalation Test Facility. Test Animals Will be Examined Periodically for Pathological, Oncological, and Respiratory Changes. Peugeot Plans to Study Exhaust Gases Via Chronic Inhalation or Skin Painting Experiments.

TABLE 3. DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS --
OTHER ORGANIZATIONS.

RESEARCH CATEGORY	ORGANIZATION	STATUS	COMMENTS
ENGINE TECHNOLOGY DEVELOPMENT			
Direct Injection Engine	AVL Ricardo	In Progress In Progress	AVL is Pursuing the Development of DI Engines for Automobile Applications. DI has 15-20 Percent Fuel Economy Advantage and Comparable Emissions Relative to IDI.
Turbocharging	AVL Ricardo	Under Consideration Under Consideration	AVL and Ricardo are Investigating the Effects of Turbocharging on Fuel Consumption, Performance, and Exhaust Emissions. Moderate Reductions in Particulate Emissions Have Been Achieved.
Engine Modifications	AVL CAV Ltd. Ricardo	In Progress	Investigations are Underway to Characterize the Effects of Combustion Chamber and Intake Modifications on Efficiency, Performance, Exhaust Emissions, and Noise.
Fuel Injection System Modification	AVL Robert Bosch CAV Ltd. Ricardo	In Progress	Ongoing Projects are Concerned with Optimization of Injection Pressure, Rate, Spray Angle, and Nozzle Geometry, to Achieve Acceptable Compromise Between Emissions and Engine Efficiency.
EMISSION CONTROL			
Exhaust Gas Recirculation	AVL Robert Bosch CAV Ltd. Ricardo	In Progress In Progress Under Consideration Under Consideration	AVL is Experimenting With Modulated EGR as a NO _x Control Technique for DI Engines. Bosch is Optimizing an Integrated Hydro-Pneumatic EGR Fuel Injection System. CAV and Ricardo are Examining the Effects of EGR on Fuel Economy, HC, Particulates, and Smoke.
Catalytic Converters	AVL Ricardo	In Progress In Progress	Catalyst Tests are Being Performed to Determine the HC, CO, Particulates, and Odor Reduction Potential of Catalysts. Low Sulfur Fuels May be Required to Limit Sulfate Particulate Formation.
Particulate Trap and Trap Oxidizer Systems	AVL Exxon Ricardo	Under Investigation Future Program Under Investigation	AVL and Ricardo are Testing Trap and Trap Oxidizer Systems. High Initial Particulate Trapping Efficiency Has Been Demonstrated. Durability is a Major Problem Area. Control of Light-Off Temperature is Difficult.
Water Injection	Ricardo	Inactive	Previous Efforts were Concerned With the Effects of Water Injection on Emissions, NO _x , Smoke, and Fuel Consumption Were Reduced, While HC Remained Unchanged for Water to Fuel Flow Ratios up to 0.85.
Fuel Modifications	AVL Exxon Mobil Ricardo	In Progress	Test Data Indicate a Reduction in Smoke Level with Low Boiling Point Fuel. European Diesel Fuel has Lower Aromatic Content and Higher Cetane Number, and Generally Results in Lower HC, NO _x , and Particulates. Exxon and Mobil are Investigating the Effects of Fuels Properties and Additives on the Performance and Emission Characteristics of Light Duty Diesels.
Noise	AVL CAV Ltd. Purdue U. Ricardo U. of Southampton	In Progress	These Organizations are Engaged in Engine Noise Characterization Work. AVL Has Done Extensive Work on Structural Noise Reduction and Engine Encapsulation. University of Southampton and CAV are Examining the Effects of Combustion Systems and Engine Component Design Variations on Noise Generation. CAV has Also Explored the Effects of Combustion Noise Control Measures on Fuel Consumption and Exhaust Emissions. Ricardo has Measured the Full-Throttle Noise Test Ratings of Passenger Vehicles, and is Investigating Noise Abatement Techniques.
Instrumentation and Measurement	AVL CAV Ltd. Michigan Technological University Mobil Ricardo	In Progress	These Organizations are Involved in the Development and Application of Particulate Measurement Devices and Techniques. CAV is Considering High Speed Photography, Raman Spectroscopy, and Laser Doppler Technology. Michigan Technological University is Developing Methods for Chemically Characterizing Particulate Organic Matter.
HEALTH EFFECTS			
In-Vitro Testing	Battelle Columbus MIT	In Progress In Progress	Battelle has been Investigating the Influence of Fuel and Engine Operating Conditions on In-Vitro Samples. Diesel Extracts have Shown Positive Test Responses. Based on Limited Samples, MIT has Demonstrated the Presence of a Powerful Direct Mutagen in Diesel Exhaust Components Extracted with a Pentane-Toluene Solvent.
In-Vivo Testing	Battelle Columbus	In Progress	Inhalation Studies are Continuing with Emphasis on Establishing In-Vitro/In-Vivo Correlations for Particulate Matter From Diesel Engines.

Aeronautics and Space Administration (NASA) are conducting a number of diesel engine related research programs. However, additional government-supported efforts are desirable to supplement ongoing programs. Candidate program areas include in-vitro and in-vivo tests, as well as a variety of projects examining the formation, composition, and abatement of particulate and organic matter in diesel engines.

Since conclusive results from ongoing health effects programs are not expected to be available for some time, well conceived and well conducted basic and applied technology research and development programs are needed, with particular emphasis on the control of particulates and organic compounds. Should the health effects programs prove conclusively that diesel particulates and organics are not harmful to human health, work in this area would be terminated, and the emphasis would then be placed on NO_x control and fuel economy improvement. Conversely, should the health effects research clearly show that diesel exhaust is indeed harmful to human health, research and development efforts in the area of particulate control would be further accelerated, considering such techniques as modification of the combustion process, variation in fuel composition, and incorporation of aftertreatment devices.

Diesel engine research and development areas, in which additional government support is considered to be desirable, may be divided into four major categories: (1) Basic Diesel Combustion Research, (2) Applied Diesel Research and Development, (3) Health Effects Research, and (4) Measurement Technology Development. Specific program needs in these areas are identified in the following subsections.

9.1 BASIC DIESEL COMBUSTION RESEARCH

Because of the complex nature of diesel combustion, there is still a lack of fundamental understanding of many of its aspects despite the many years of research in the field. However, recent advances in the fields of diagnostic instrumentation and computer technology give promise for the achievement of new insight into the combustion processes of diesel engines. The program areas identified below are designed to provide a better understanding of basic combustion and pollutant formation phenomena occurring in IDI and DI diesel engines, when operated on conventional and alternative fuels.

HC Emissions

Investigate the formation of HC species in heterogeneous combustion processes for both conventional and alternative fuels. Parameters to be considered include flame quenching, ultra-lean fuel-air mixture zones, exhaust gas recirculation, and fuel spray distribution.

Investigate the transfer processes of unburned hydrocarbons from the quench-layer into the bulk gases, and search for combustion chamber design modifications which would inhibit the discharge of the quench layer into the engine exhaust.

NO_x Emissions

Examine the formation mechanisms of NO_x and other potentially toxic nitrogen compounds, as affected by engine design parameters, fuel composition, and engine operation.

Particulate Emissions

Investigate the processes governing the formation of particulates, polynuclear aromatics, and sulfates. Factors to be considered include fuel-air ratio, pyrolysis, air turbulence level, fuel injection system parameters, and fuel composition.

Exhaust Odor

Investigate the formation mechanisms of odor-producing compounds, as affected by engine design, engine operation, and fuel composition, and identify promising odor control techniques.

Exhaust Gas Recirculation

Examine the effects of EGR on flame speed, misfire limits, reaction kinetics, fuel droplet vaporization, combustion, and pollutant species formation.

Emulsified Fuels

Investigate the effects of water and other fluids in emulsions on the diesel combustion processes.

Droplet and Spray Combustion

Study the mechanisms governing the formation, vaporization, ignition, and combustion of unsteady fuel sprays, as affected by injection characteristics, bulk flow turbulence levels, fuel-air ratio, and fuel composition.

Modeling

Develop basic emission models for regulated and unregulated emission species, considering such factors as combustion chamber geometry, fuel spray characteristics, air swirl, fuel composition, and heat transfer.

9.2

APPLIED DIESEL RESEARCH AND DEVELOPMENT

The objective of the programs identified below is the development of technology required to achieve significant reduction in exhaust emissions from IDI and DI diesel engines, and to alleviate specific problems that otherwise might inhibit engine acceptance or degrade fuel efficiency.

Gaseous Emissions

Characterize the gaseous emissions of modern light-duty diesel engines, with particular emphasis on toxic, mutagenic, and carcinogenic compounds.

Determine the composition of the HC species from these engines, as affected by component design, operating condition, and fuel composition.

Particulate Emissions

Characterize the particulate emissions from light-duty IDI and DI diesel engines, and assess the effects of variations in engine design and operating parameters, and fuel composition on the formation mechanism.

Fuel Injection System

Assess the emissions and fuel economy improvement potential achievable through optimization of the injection process.

Explore the potential benefits of hypergolic combustion.

Emission Control Technology

Characterize the gaseous and particulate emissions and fuel economy benefits associated with the use of turbocharging IDI and DI diesel engines.

Examine the effects of EGR system variables on HC, NO_x, and particulate emissions.

Characterize the HC, CO, odor reduction benefits of catalytic converter systems, and develop low-light-off temperature catalysts for use in diesel engines.

Develop trap oxidizer technology and evaluate durability and effectiveness characteristics as a function of variations in combustion chamber and fuel injection system design and operation, EGR rates, and fuel composition.

Develop viable EGR and alternative NO_x control techniques; determine the effects of these systems on other pollutants.

Characterize the effects of variations in fuel composition on gaseous and particulate emissions formation, fuel consumption, and refinery requirements.

High-Speed DI Diesel

Characterize the particulate and gaseous emissions of light-duty high-speed DI diesel engines, as affected by variations in engine design and fuel composition.

Assess the emissions and fuel consumption improvement potential of light-duty DI diesel engines and determine critical engine design and operating parameters.

Starting and Transients

Investigate the effects of cold start and transient operation on currently regulated and unregulated emissions, and search

for new techniques to improve the cold start characteristics of diesel engines.

Advanced
Engines

Evaluate the fuel conservation and emissions potential of the adiabatic diesel engine in light-duty applications, with particular emphasis on NO_x and particulate emissions.

Investigate the potential benefits derived from the use of low compression ratio diesels, with particular emphasis on particulate formation.

9.3

HEALTH EFFECTS RESEARCH

The objectives of the following projects are to identify dangerous substances in diesel exhaust, and to determine conclusively whether the pollutant species and concentrations emitted from light-duty IDI and DI diesel engines pose a hazard to human health.

Particulate
Characterization

Characterize the particulates emitted from a select group of diesel engines of modern design, with particular emphasis on chemical composition, organic fractions, and fuels composition.

In-Vitro Versus
In-Vivo Tests

Examine the validity of the Ames test through comparison with in-vivo results.

Develop in-vitro test procedures which are more representative of in-vivo behavior.

Animal Tests

Determine the long-term effects of diesel exhaust on higher organisms and animals, with particular emphasis on carbonaceous material, organic compounds, dosage rate, and safe exposure limits.

Identify the toxic and carcinogenic compounds in the exhaust of diesel engines, as affected by engine design and operation, fuel composition, and emission control technology.

Photochemistry
in the Atmosphere

Determine the photochemical reactivity of diesel exhaust and study the formation of ozone and aerosols.

9.4

MEASUREMENT TECHNOLOGY DEVELOPMENT

The objective of the following project is to develop instrumentation for the measurement and characterization of particulate and organic matter emitted from diesel engines, and to explore new diagnostic instrumentation for in-situ measurement of combustion parameters.

Validation and
Standardization

Develop and verify dilution tunnel design criteria, considering tunnel geometry, dilution ratio, sampling rate, filter types, and sampling temperature as principal parameters.

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SECTION 1

INTRODUCTION

Because of its desirable efficiency, reliability, and durability characteristics, the diesel engine has been the favored power plant for use in heavy-duty automotive, industrial, marine, and rail applications for many decades. During the past several years, interest in the diesel as an alternative engine for automobiles and light-duty trucks has grown rapidly. In light of the diesel's very low fuel consumption at idle and in the low-load-low-speed regime, the engine is particularly well suited for vehicles operating under urban driving conditions.

In urban driving, current production diesel vehicles, which are equipped with swirl chamber or prechamber engines, have a fuel economy advantage of 30 to 70 percent relative to their spark ignition engine powered counterparts. However, most diesel production automobiles have significantly lower acceleration performance, gradability, and top speed capability than spark ignition vehicles of similar size and weight.

Without the use of sophisticated emission control techniques and devices, diesel engines, particularly those equipped with divided combustion chambers, have inherently low hydrocarbon (HC) and carbon monoxide (CO) exhaust emissions, and moderately low emissions of oxides of nitrogen (NO_x). However, there are uncertainties regarding the diesel's capability of simultaneously meeting future NO_x and particulate standards for light duty vehicles, while maintaining its competitive fuel economy and durability characteristics. In addition, there is concern about the organic compounds adsorbed on the particulates, some of which have been determined to be mutagenic or even carcinogenic. Resolution of these uncertainties is required, either by conclusively demonstrating that diesel exhaust is not harmful to human health, or through successful development of effective and durable particulate abatement techniques, before the diesel can be considered a viable long-term alternative powerplant for automobiles.

The development of high-speed, light-duty, divided chamber diesel engines was pioneered by Daimler-Benz of Germany and Peugeot of France. More recently, many domestic, European, and Japanese automobile manufacturers have introduced or have plans to introduce diesel powered automobiles in the United States and/or abroad. These manufacturers include Audi, BMW, British Leyland, Chrysler, Fiat, General Motors, Isuzu, Mitsubishi, Nissan, Toyota, Volkswagen, Volvo, and others.

The objective of this report is to review and summarize the recent status of light-duty diesel engine technology, and to update the information presented in the first diesel engine technology status report prepared by The Aerospace Corporation and published by the Department of Energy in September 1978.

SECTION 2

DIESEL ENGINE DESIGN AND OPERATING CHARACTERISTICS

This section examines the fuel economy and exhaust emissions characteristics of light-duty diesel engine powered vehicles. Principal design parameters for indirect and direct injection diesels are highlighted in Subsection 2.1. Fuel economy data of late model diesel powered certification automobiles, tested over the Federal Urban and Highway Driving Cycles, are presented in Subsection 2.2. Currently regulated and unregulated emissions species are treated in Subsection 2.3, including hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), particulates, organic fractions, smoke, sulfates, odor, aldehydes, phenols, and nitrosamines. The NO_x and particulate emissions limits projected to be realistically achievable in the near to midterm are addressed in Subsection 2.4.

2.1 DIESEL ENGINE CONFIGURATIONS

All current production diesel engines can be placed in one of two categories: direct injection (DI) or open chamber, and indirect injection (IDI) or divided chamber. Depending upon specific combustion chamber, fuel injection system, and air induction system features used in the design of these engines, these two categories can be subdivided into a number of distinct engine classes. Direct injection diesel configurations have been and still are being favored by most manufacturers and users of heavy-duty vehicular, industrial, rail, and marine engines, primarily because of their superior fuel consumption characteristics relative to spark ignition (SI) and IDI diesel engines. Conversely, the IDI diesel engine is preferred for automobile and other light-duty applications because of its higher speed and specific power output capability, and its lower noise and exhaust emissions potential. However, interest in the DI engine type as an alternative power plant for light-duty vehicle applications is growing rapidly.

2.1.1 Direct Injection Diesel Engines

Direct injection diesel engines utilize a single combustion chamber per cylinder, formed by the piston in its top dead center position and the

cylinder head. In general, the fuel is injected by means of a high-pressure injection system several degrees before piston top dead center. Air-fuel mixing enhancement is achieved by means of air swirl conditions set up in the combustion chamber through specific design provisions incorporated in the intake manifold, valves, and pistons. Depending upon the magnitude of the swirl, DI diesel engines can be subdivided into the following three classes: (1) quiescent or low swirl chambers, which are favored by many domestic manufacturers, (2) medium swirl, deep bowl chambers, used primarily in Europe, and (3) high swirl, spherical combustion chambers used in special applications. To maximize thermal efficiency, relatively low compression ratios in the range of 14 to 16 are used, representing a reasonable compromise between friction losses, which increase with increasing compression ratio, and startability, which becomes more difficult as compression ratio is reduced.

The low swirl, open chamber configuration features a shallow dish combustion chamber. In the absence of an induced air swirl, air-fuel mixing is achieved by means of a sophisticated fuel injection system, using one or more injection nozzles, each having several fuel injection orifices (Refs. 2-1 through 2-4). Generally, engine speeds are limited to relatively low values as a direct result of the low air swirl, which places the burden of air-fuel mixing almost entirely on the fuel injection system, and restricts engine operation to leaner fuel-air ratios than normally used in high swirl diesels. Because of the low air swirl in the chamber and the lean air-fuel mixture operation, heat losses to the cylinder wall and head are minimized, resulting in favorable fuel consumption and starting characteristics. Another feature of this engine type is its relatively low fuel sensitivity.

Medium swirl engines are utilized primarily in medium size applications. Since the fuel quantities injected are relatively small in these cases, efficient air-fuel mixing by means of multiple fuel sprays is no longer possible, and the use of some air swirl is required to achieve adequate mixing levels. In most designs, the air swirl is generated by means of either directed intake ports or masked intake valves (Ref. 2-5). In general, medium swirl diesel engines exhibit good fuel economy, combined with acceptable starting characteristics and relatively low heat losses into the cooling system.

The high swirl diesel utilizes high air swirl, which is generally generated by means of corkscrew-type intake ports and the squish action of the specially designed piston. Frequently, this engine utilizes a single injector nozzle which supplies a coarsely atomized spray into the spherical combustion chamber. Most of the fuel is carried to the wall by centrifugal forces where it is deposited in the form of a thin film. Approximately 5 percent of the fuel is finely atomized during the injection process and is then ignited. As combustion proceeds, the flame front progresses to the chamber wall region and ignites the vaporized fraction of the fuel initially deposited on the wall. The burning rate of this fuel is controlled by the fuel vaporization process, resulting in relatively low maximum combustion pressures and pressure rise rates. The principal advantage of this engine is its multifuel capability. Since combustion is vaporization controlled, almost any type of fuel can be burned, and the engine runs very quietly, even on gasoline. The major drawback of the engine is related to the high heat transfer into the chamber wall during compression, which results in poor startability characteristics, particularly at low ambient temperatures.

Performance data from a high-speed, DI experimental diesel engine currently in development in Europe, for potential use in light-duty applications, are presented in Section 6 of this report.

2.1.2 Indirect Injection Diesel Engines

Indirect injection diesel engines have two chambers, a main chamber and an antechamber which is connected to the main chamber through one or more communicating flow passages. This engine category consists of two specific classes: (1) swirl chamber or turbulence chamber, a configuration favored by a number of European and Japanese light-duty diesel engine manufacturers, and (2) precombustion chamber or prechamber, which is employed in a number of European and domestic light-duty and heavy-duty designs. In these engines, the fuel is injected into the antechamber, with ignition occurring in the vicinity of the chamber throat, followed by diffusion-flame type combustion. As the pressure in the antechamber rises, the hot combustion gases are discharged into the main chamber where the combustion process is then completed. Upon leaving the antechamber, a strong secondary air swirl is generated which enhances flow mixing in the main chamber and assures high combustion efficiency.

Typically, the swirl chamber is spherical or semi-spherical in shape, and has a capacity of the order of 50 percent of the total clearance volume (Ref. 2-6). During the compression stroke, air is forced from the main chamber into the swirl chamber through a connecting passage, and a high degree of air swirl is then generated by the intruding air. Conversely, the prechamber is generally pear-shaped, and its size is only 20 to 30 percent of the total clearance volume. The passage connecting the prechamber and the main chamber is more restricted than in the case of the swirl chamber. This increases air turbulence in the main chamber and tends to confine the initial shock, occurring during combustion, to the prechamber (Ref. 2-7).

Relative to DI engines, IDI configurations have a number of inherent advantages, including higher speed capability and lower fuel sensitivity, maximum pressures, pressure rise rates, temperatures, and exhaust emissions. The principal disadvantage of IDI diesels is their higher fuel consumption, which primarily results from the higher surface-to-volume ratio of the combustion chamber and the high swirl velocities in the case of the swirl chamber engine. During a cold start, some of the compression heat is transferred to the antechamber as a result of the air swirl, and high compression ratios and starting aids such as glow plugs are required to improve the engine's startability characteristics.

The performance and fuel consumption characteristics of light duty IDI diesel engines, as exemplified by the Mercedes-Benz 2 liter automobile engine, are presented in Figures 2-1 and 2-2, respectively (Ref. 2-7). Figure 2-1 shows wide open throttle power output and torque as a function of engine speed. As indicated, the maximum torque of the diesel engine is substantially lower than that of the gasoline engine. However, in the low-speed regime, the torque difference is small, which accounts for the relatively good low-speed acceleration characteristics of diesel vehicles relative to equivalent gasoline engine powered cars.

Specific fuel consumption islands of the Mercedes-Benz 2 liter diesel and gasoline engines without emission control are presented in Figure 2-2, as a function of engine speed and mean effective pressure. As indicated, the minimum specific fuel consumption of the diesel is only slightly lower than tha

FIGURE 2-1. DIESEL AND GASOLINE ENGINE PERFORMANCE PARAMETERS: MERCEDES-BENZ AUTOMOTIVE ENGINES (Ref. 2-7).

FIGURE 2-2. MERCEDES-BENZ PRECOMBUSTION CHAMBER DIESEL AND UNCONTROLLED SPARK IGNITION ENGINE PERFORMANCE MAPS (Ref. 2-7).

of the gasoline engine. However, in the low-load regime, the diesel exhibits far superior fuel consumption characteristics as the combined result of lean air-fuel mixture operation, lower pumping losses, and higher engine compression ratio.

Interest in the light-duty IDI diesel engine as a power plant for automobiles has been growing significantly during the past few years. This is evidenced by the rapidly increasing sales figures shown in Tables 2-1 and 2-2 (Refs. 2-8 and 2-9).

TABLE 2-1. DIESEL AUTOMOBILE SALES IN THE UNITED STATES
(Refs. 2-8 and 2-9).

MANUFACTURER ⁽¹⁾	SALES PERIOD			
	1980 1st QTR	1979 1st QTR	1979 CAL YR	1978 CAL YR
OLDSMOBILE	33,400	29,800	111,200	57,000
VOLKSWAGEN	28,200	21,600	85,700	44,300
MERCEDES-BENZ	10,000	9,100	35,600	24,600
AUDI	2,300	--	2,500	--
CADILLAC	10,600	3,900	26,700	3,800
PEUGEOT	2,900	2,100	8,600	5,500
CHEVROLET ⁽²⁾	2,100	--	400	--
PONTIAC ⁽²⁾	1,800	--	300	--
TOTAL	91,300	66,500	271,000	135,200
% OF U. S. MARKET	3.6	2.4	2.5	1.2
⁽¹⁾ Other manufacturers considering marketing diesel cars in the U.S. in the future include Chrysler, BMW, Fiat, Isuzu, Renault, and Volvo. ⁽²⁾ Estimated.				

2.2

LIGHT-DUTY VEHICLE FUEL ECONOMY CHARACTERISTICS

Urban Cycle fuel economy data for 1978 and 1979 model year diesel powered certification automobiles equipped with automatic or manual transmissions are presented in Figure 2-3 (Refs. 2-10 and 2-11). Except for the Mercedes-Benz vehicles, which employ prechambers, the diesel vehicles shown incorporate swirl chamber engines. Also shown in Figure 2-3 are the Urban Cycle fuel economy data of the 1979 Model Year SI engine equipped certification automobile fleet, calibrated to meet 49 States' emissions regulations. Diesel vehicle identification is

TABLE 2-2. DIESEL AUTOMOBILE SALES IN VARIOUS COUNTRIES
(Refs. 2-8 and 2-9).

NATION	ANNUAL SALES		
	1979	1978	1977
UNITED STATES	271,000	115,000	37,000
WEST GERMANY	220,000	153,000	121,000
FRANCE	150,000	127,000	122,000
ITALY	130,000	61,000	34,000
JAPAN	70,000	NA	NA
NETHERLANDS	50,000	NA	NA
SWEDEN	36,000	8,000	9,000
SPAIN	20,000	NA	NA
UNITED KINGDOM	6,000	7,000	6,000

FIGURE 2-3. URBAN CYCLE FUEL ECONOMY OF 1978 AND 1979 MODEL YEAR DIESEL, AND 1979 MODEL YEAR SPARK IGNITION ENGINE POWERED CERTIFICATION VEHICLES (Refs. 2-10 and 2-11).

provided in Table 2-3. Although vehicle VW4 was certified by the Environmental Protection Agency (EPA), the vehicle was never sold by Volkswagen (VW) in the

TABLE 2-3. 1978 AND 1979 MODEL YEAR DIESEL CERTIFICATION
VEHICLE IDENTIFICATION AND SPECIFICATIONS
(Refs. 2-10 and 2-11).

Model Year	Manufacturer	Model	Transmission	Rated Power, hp	N/V ⁽¹⁾ Ratio	A/C ⁽²⁾ Simulation	Vehicle ⁽³⁾ Identification
1979	GM	Cutlass	Auto	96	32.7	Yes	GM1,2
		Cutlass Wagon	Auto	120	31.1	Yes	GM3
		Ninety Eight	Auto	120	30.6	Yes	GM4
		Delta 88	Auto	120	31.3	Yes	GM5,6
		Deville	Auto	120	28.3	Yes	GM7
		Cutlass	Manual	96	34.9	Yes	GM8
	MB	240D	Auto	62	53.7	Yes	MB1
		300D	Auto	77	50.7	Yes	MB2
		300SD	Auto	110	44.8	Yes	MB3
		240D	Manual	62	51.4	Yes	MB4
	Peugeot	504	Auto	71	52.5	Yes	P1
		504 Wagon	Auto	71	56.0	No	P2
		504 Wagon	Auto	71	56.0	Yes	P3
		504	Manual	71	51.4	No	P4
		504 Wagon	Manual	71	55.9	Yes	P5
	VW	Rabbit	Manual	48	57.6	No	VW1
		Rabbit	Manual	48	45.1	No	VW2
		Dasher Wagon	Manual	48	56.9	No	VW3
1978	GM	Delta 88	Auto	120	30.6	Yes	GM9
		Custom Wagon	Auto	120	33.9	Yes	GM10
	MB	240D	Auto	62	53.6	Yes	MB5
		300D	Auto	77	50.7	Yes	MB6
		300SD	Auto	110	44.8	Yes	MB7
		240D	Manual	62	51.4	Yes	MB8
	Peugeot	504	Auto	71	52.3	Yes	P6
		504	Auto	71	52.5	No	P7
		504 Wagon	Auto	71	56.0	No	P8
		504 Wagon	Auto	71	56.0	Yes	P9
		504	Manual	71	51.4	No	P10
		504	Manual	71	51.4	Yes	P11
		504 Wagon	Manual	71	56.0	No	P12
		504 Wagon	Manual	71	56.0	Yes	P13
	VW	Rabbit	Manual	48	44.0	No	VW4
		Rabbit	Manual	48	57.6	No	VW5

(1) Ratio of Engine Speed to Road Speed, in Top Gear.

(2) "Yes" Indicates Vehicle was Tested with Air Conditioning Load Simulated.

(3) Vehicle Identification Used in Figures.

United States. Because of a low engine-speed-to-road-speed ratio (N/V) of 44, the acceleration performance of this vehicle was unsatisfactory.

As expected, fuel economy increases with decreasing inertia weight, and is significantly higher for the diesel vehicles. For example, the most fuel efficient diesel vehicles in the 2250, 3500, 4000, 4500, and 5000 lb inertia weight classes have a fuel economy advantage of 43, 55, 39, 31 and 67 percent relative to the most fuel efficient SI vehicles. It should be noted, however, that current diesel vehicles have rated power-to-inertia-weight ratios varying between 0.018 and 0.030 hp/lb, while the most fuel efficient SI vehicles have higher values, ranging from 0.028 to 0.035 hp/lb, as shown in Figure 2-4 for the most fuel efficient configurations.

To permit a more meaningful comparison of the fuel economy characteristics of diesel and SI engine powered vehicles, adjustments must be made to account for differences in engine rated power, displacement, and vehicle axle ratio. In addition, the differences in fuel heating values and refinery energy consumption associated with the production of diesel fuel and gasoline must be considered before a meaningful comparison can be made of the real fuel economy advantage of diesel vehicles relative to equivalent SI vehicles (Ref. 2-12). Based on General Motors (GM) data, diesel engine equipped vehicles show a 25 percent advantage in fuel economy relative to SI vehicles of equal performance and inertia weight (Ref. 2-13).

Combined Urban and Highway Cycle fuel economy data for diesel and SI certification vehicles are presented in Figure 2-5. As indicated, the most fuel efficient diesel vehicles in the 2250, 3500, 4000, 4500, and 5000 lb inertia weight classes provide fuel economy improvements of 41, 48, 38, 33 and 64 percent, respectively, relative to the most fuel efficient SI vehicles. These improvements are somewhat lower than those shown in Figure 2-3 for the Urban Cycle, reflecting the declining fuel consumption advantage of the diesel at high engine loads, as previously noted in Figure 2-2.

FIGURE 2-4. ENGINE RATED POWER TO VEHICLE INERTIA WEIGHT RATIO OF THE MOST FUEL EFFICIENT GASOLINE AND DIESEL ENGINED 1979 MODEL YEAR VEHICLES, 49 STATES CALIBRATION (Refs. 2-10 and 2-11).

2.3

LIGHT-DUTY DIESEL VEHICLE EMISSIONS

Like all internal and external combustion engines, diesels emit finite quantities of regulated and currently unregulated pollutants, including HC, CO, NO_x, sulfur oxides, smoke, particulates, polynuclear aromatics, and odor. These species are examined in the following subsections.

FIGURE 2-5. COMBINED FUEL ECONOMY OF 1978 AND 1979 MODEL YEAR DIESEL, AND 1979 MODEL YEAR SPARK IGNITION ENGINE POWERED CERTIFICATION VEHICLES (Refs. 2-10 and 2-11).

2.3.1 Regulated Gaseous Species

As shown in Table 2-4, HC, CO, and NO_x are the only currently regulated pollutant species that are controlled by the EPA. These standards are identical for diesel and SI engine powered light-duty vehicles, except that NO_x waivers may be granted for 1981 and 1982 Model Year diesel vehicles. Also listed in Table 2-4 are the permissible 1982 and 1985 Model Year particulate levels of 0.6 g/mi and 0.2 g/mi for diesel vehicles, which had been originally proposed by the EPA for Model Years 1981 and 1983, respectively. Particulate emissions are treated in Subsection 2.3.2 of this report.

The 4000 mile HC emissions of 1978 and 1979 Model Year diesel and 1979 model year SI certification vehicles with manual and automatic transmissions are presented in Figure 2-6 as a function of inertia weight (Refs. 2-10 and 2-11). Vehicle identification is provided in Table 2-2. With few exceptions, the HC emissions from diesel certification vehicles are within the data envelope of the

TABLE 2-4. EXHAUST EMISSION STANDARDS FOR
LIGHT-DUTY DIESEL AND SPARK IGNITION VEHICLES.

MODEL YEAR	EMISSIONS, g/mi			
	HC	CO	NO _x	PARTICULATES
1980	0.41	7.0	2.0	--
1981	0.41	3.4 ⁽¹⁾	1.0 ⁽²⁾	--
1982	0.41	3.4 ⁽¹⁾	1.0 ⁽²⁾	0.6 ⁽³⁾
1985 AND LATER	0.41	3.4	1.0	0.2 ⁽⁴⁾

(1) Waiver for 2 years possible.
 (2) Waiver through Model Year 1984 possible for diesels only; 1.5 g/mi.
 (3) Originally proposed for Model Year 1981.
 (4) Originally proposed for Model Year 1983.

FIGURE 2-6. 4000 MILE HC EMISSIONS OF 1978 AND 1979 DIESEL,
AND 1979 SPARK IGNITION ENGINE POWERED CERTIFICATION
AUTOMOBILES (Refs. 2-10 and 2-11).

SI vehicles. Parameters affecting the formation and emission of HC include combustion chamber geometry, fuel injection timing and rate, injection nozzle sac volume, secondary injections, air-fuel mixing, and quench effects near the chamber wall and in ultra-lean air-fuel mixture zones.

The HC emission levels of the swirl chamber engines used by General Motors (GM), Peugeot, and VW are generally comparable to SI vehicles, and range between about 0.4 and 1 g/mi. Conversely, the Mercedes-Benz vehicles, all of which employ prechambers, show HC levels of about 0.1 to 0.3 g/mi. It is apparent from these data that some reduction in the HC emissions is required for most engines to meet the 0.41 g/mi standard, particularly if exhaust gas recirculation (EGR) is used to provide NO_x control. It should be noted that most of the SI vehicles require the use of catalysts, combined with a closely controlled air-fuel ratio, EGR, and spark advance schedules as a function of engine speed and load. Conversely, none of the diesel vehicles uses sophisticated control techniques, although some injection system modifications were introduced by a number of engine manufacturers during the past few years. These design changes involve primarily a reduction in injector sac volume and the minimization of secondary injections, which have been found to be responsible for a large fraction of the total diesel HC emissions. In addition, EGR is used in a number of Model Year 1980 California diesel automobiles.

There is some evidence that HC emissions from diesel engines include other constituents beside unburned fuel. Based on the gas chromatography data shown in Figure 2-7, the distillation range of the collected HC is higher than that of the original fuel (Ref. 2-14). This is especially true for the relatively volatile No. 1 diesel fuel, for which about 75 percent of the HC emissions measured has a boiling point above the 300°C endpoint of the fuel. This suggests that a significant fraction of the total HC emissions consists of combustion-modified fuel constituents.

CO emission certification data for diesel and SI automobiles are presented in Figure 2-8 (Refs. 2-10 and 2-11). The formation of CO is the result of incomplete combustion occurring in oxygen-deficient regions of the combustion chamber. Although the overall air-fuel mixture is always lean in diesel engines, the excess oxygen may actually not reach all CO molecules until the temperature of the combustion products is too low for further CO reactions to occur.

FIGURE 2-7. BOILING RANGES FOR FUELS AND GASEOUS HC BY GAS CHROMATOGRAPH, MERCEDES 240D AUTOMOBILE (Ref. 2-14).

As shown in the figure, current diesel automobiles have very low CO emission levels, particularly the prechamber equipped Mercedes-Benz vehicles, varying between about 1 and 2.5 g/mi.

Of the currently regulated pollutants, NO_x represents the principal species emitted from diesel engines. The formation of NO_x during the combustion process is kinetically controlled and increases with increasing peak cycle temperature, oxygen level, and residence time near peak temperature. As illustrated in Figure 2-9, the NO_x emissions of the larger size certification diesel vehicles range between about 1.5 and 2 g/mi, and are near or even slightly beyond the upper boundary of the SI vehicle data band. Conversely, the VW Rabbit at an inertia weight of 2250 lb has NO_x emissions of about 1 g/mi, which is near the lower limit of the SI data band. While most SI vehicles require the use of EGR

FIGURE 2-8. 4000 MILE CO EMISSIONS OF 1978 AND 1979 MODEL YEAR DIESEL, AND 1979 MODEL YEAR SPARK IGNITION ENGINE POWERED CERTIFICATION AUTOMOBILES (Refs. 2-10 and 2-11).

and/or a 3-way catalyst to achieve these NO_x levels, none of the 1978 and 1979 Model Year diesel production vehicles is equipped with EGR. However, the 1980 Model Year diesel cars marketed by Mercedes-Benz and Peugeot in California are equipped with EGR.

The previously shown HC and NO_x emissions data for diesel and SI engine powered certification vehicles are replotted in Figure 2-10 for individual vehicles in terms of HC versus NO_x . As illustrated, the diesel vehicles are comparable to the oxidation catalyst equipped SI vehicles, except for the Mercedes-Benz cars, which show extremely low HC levels. Compared to non-catalyst SI vehicles, the diesels show similar NO_x levels, but considerably lower HC.

2.3.2 Currently Unregulated Emissions

In addition to HC, CO, and NO_x , diesel engines emit a number of currently unregulated species, including particulates, smoke, sulfates, odor, and aldehydes. There is considerable concern over the particulates, not only

FIGURE 2-9. 4000 MILE NO_x EMISSIONS OF 1978 AND 1979 MODEL YEAR DIESEL, AND 1979 MODEL YEAR SPARK IGNITION ENGINE POWERED CERTIFICATION AUTOMOBILES (Refs. 2-10 and 2-11).

because of their small size, but also because they contain organic compounds, several of which have been shown to be mutagenic or even carcinogenic. Particulate emissions regulations have been promulgated by the EPA for 1982 and 1985 Model Year diesel vehicles, as previously shown in Table 2-4.

Particulate emissions consist of about 65 to 85 percent carbon, plus many different high molecular weight soluble organics, some sulfates, and a number of trace metals. Based on limited data, the organic fraction emitted from indirect injection diesel engines of current design varies between 2 and 30 percent of total particulate mass, depending upon engine design, vehicle operation, and fuels composition. Sulfate emissions are related to the fuel sulfur content. During combustion most of the sulfur is oxidized to sulfur dioxide, but about 1 to 3 percent of the sulfur is converted to sulfur trioxide, which in turn forms sulfuric acid by reacting with water. Sulfate emissions amount to about 2 to 10 percent of the total particulate mass emitted from diesel engi

FIGURE 2-10. HYDROCARBON VERSUS NO_x EMISSIONS OF DIESELS AND SPARK IGNITION CERTIFICATION VEHICLES.

Following a cold start, diesel engines can emit visible blue or white smoke as a result of incomplete combustion of lube oil or condensation of water vapor. Black smoke, which sometimes occurs at high loads, is composed of carbon particles and adsorbed organic compounds.

Diesel odor is a very undesirable exhaust product, which is attributed to many compounds. Odor intensity is affected to some degree by engine operation and fuels composition. In the past, odor data have been difficult to correlate, but there seems to be a relationship between odor and HC emissions.

Aldehyde emission levels from diesel engines are comparable to those from SI engines, amounting to about 15 to 60 mg/mi for vehicles in the 2000 to 3000 lb weight class. Driving cycle, engine design, and fuels composition can have an effect on the aldehyde formation process.

2.3.2.1 Particulates

Particulate emissions data from a number of diesel production and developmental vehicles, operated over the Federal Urban Cycle, are presented in Figure 2-11. As expected, particulate levels tend to increase with increasing vehicle inertia weight. Some of the lighter vehicles show particulate emissions less than 0.6 g/mi, which has been selected by the EPA as the standard for model year 1982. The heavier production vehicles are generally above that level. As indicated in the figure, wide variations exist at the same inertia weight, suggesting that engine and fuel injection system design and operating parameters may have a strong impact on particulate formation. It is encouraging, however, that a number of experimental naturally aspirated and turbocharged diesels have achieved particulate levels in the 0.2 to 0.4 g/mi range at low mileage.

FIGURE 2-11. URBAN CYCLE PARTICULATE EMISSIONS OF PRODUCTION AND EXPERIMENTAL DIESEL AUTOMOBILES.

The available data on the effects of turbocharging on particulate emissions are inconsistent. Moderate reductions are shown in some engines, while others show no improvement with turbocharging. These trends may be related to the higher loads required by some naturally aspirated engines to negotiate the driving cycle, as engine operation near the smoke limit would be expected to

generate higher particulate emissions. In this specific case, turbocharging might be expected to reduce particulate emission levels.

Although current diesel engines have significantly higher particulate emission levels than their catalyst-equipped SI counterparts, the total quantity is rather insignificant on a macroscopic scale, as illustrated in Table 2-5 (Ref. 2-15). According to Table 2-5, the tonnage of diesel particulates is but a small fraction of the total emissions placed into the atmosphere by all sources. Even with a massive shift to diesel powered cars, little change in total emissions would occur. For example, a fleet of 100 million diesel automobiles, with an annual mileage of 12,000 miles and emitting 0.6 g/mi particulates per vehicle, would generate about 800,000 tons of particulates per year. However, the real concern regarding diesel particulates is not their total amount, but the carcinogenic organic compound adsorbed on these particulates, and the potential of the particulate concentration reaching hazardous levels in urban areas, street canyons, and parking facilities.

Diesel engine particulate emissions consist of carbon particles and organic compounds adsorbed onto the surface of a carbonaceous core, and are the result of incomplete combustion of the fuel and lubricating oil (Ref. 2-16). The relative contributions of the fuel and lubricant vary with engine design, speed, and load. In general, the effect of the lubricant is much greater in 2-stroke engines than in 4-stroke designs (Ref. 2-17). GM has conducted tests on a 350 cubic inch displacement diesel engine in which the lube oil was doped with carbon-14 tagged octacosane (Ref. 2-18). These experiments indicate that the lubricant contributes between 1.5 and 25 percent of the overall particulate emissions, with the highest fraction occurring in the high-speed, low-load regime. Virtually all of the tagged carbon atoms were found in the soluble organic fraction, and not in the carbonaceous core. Tagging of various diesel fuel constituents indicates that olefins were the class of compounds least likely to form particulates, while paraffins had a stronger tendency to do so. The activity of the aromatics in particulate formation was found to be about double that of the paraffins, and triple that of the olefins (Ref. 2-18).

Typical particle size distributions for diesel and oxidation catalyst equipped automobiles are shown in Figure 2-12 (Ref. 2-19). As illustrated,

TABLE 2-5. SIGNIFICANT SOURCES OF PARTICULATE POLLUTION
(Ref. 2-15).

Pollution Source	Emissions, tons/yr	Subtotals, tons/yr
Natural dusts		63,000,000
Forest fires		56,400,000
Transportation		1,200,000
Gasoline vehicles	420,000	
Diesel vehicles	260,000	
Aircraft	30,000	
Railroads	220,000	
Water transport	150,000	
Nonhighway use	120,000	
Incineration		931,000
Municipal incineration	98,000	
On-site incineration	185,000	
Wigwam burners	35,000	
Open dump incineration	613,000	
Other sources		1,284,000
Rubber from tires	300,000	
Cigarette smoke	230,000	
Cosmic dust	24,000	
Aerosols from spray cans	390,000	
Ocean salt spray	340,000	
TOTAL POLLUTION		122,815,000

diesel particulate emissions peak at a particle diameter of about 0.15 micron (μ), compared to 0.02 micron for the SI engine. Photo-micrographs show that diesel particulates have a very light and fluffy structure, with a density of about 0.07 g/cc (Refs. 2-20, 2-21, and 2-22). Because of their low density, particulate emissions have a tendency to load up and plug any filtering device that might be used in the exhaust stream.

Elemental particulate analyses performed for a Mercedes-Benz 240D and a VW Diesel Rabbit vehicle show that the particulate mass collected from the VW is lower in carbon content and higher in hydrogen than that of the Mercedes-Benz.

FIGURE 2-12. COMPARISON OF AEROSOL FROM A DIESEL CAR (CAR D) AND FROM CATALYST CARS (Ref. 2-19).

(Ref. 2-14). As shown in Table 2-6, there is no appreciable difference between the particulates collected in the Mercedes during the cold start FTP test and during idle. However, in the case of the Rabbit, the particulates emitted at idle contain much less carbonaceous matter than in the case of the cold start FTP, while hydrogen, nitrogen, and sulfur mass remains nearly unchanged.

The effects of fuel properties on the composition of the particulate emissions are shown in Table 2-7 for two heavy-duty diesel engines tested on the engine dynamometer, and two light-duty diesel vehicles tested over the Urban Cycle (Refs. 2-14 and 2-23). Five different fuels were used in these tests, including No. 2 emissions test fuel, a blend formulated to represent "National Average" No. 2 fuel, a No. 1 fuel, a "Minimum Quality" No. 2 fuel with a low cetane number and a high aromatic content, and a "Premium Quality" No. 2 fuel with a high cetane number and a low aromatic content. Examination of the test data indicates a correlation between particulate levels and fuel aromatic contents. Although there is no clear relationship between the soluble organic fraction and

TABLE 2-6. ELEMENTAL PARTICULATES COMPOSITION FROM TWO LIGHT-DUTY DIESEL VEHICLES (Ref. 2-14).

Parameter	Particulates Composition, weight percent			
Vehicle	MB 240D		VW Rabbit	
Driving Cycle	Cold FTP	Idle	Cold FTP	Idle
Carbon	76.3	70.5	68.3	34.6
Hydrogen	3.0	3.3	4.0	4.9
Nitrogen	0.5	0.8	0.4	1.0
Sulfur	1.0	0.7	0.7	0.6
TOTAL	80.8	75.3	73.4	41.1

the fuel's properties, it is interesting to note that for all four engines tested, the carcinogen benzo(a)pyrene has a maximum for the Minimum Quality fuel.

2.3.2.2 Smoke

While the appearance of visible smoke in the exhaust of diesel engines is always an indication of high particulate levels, the absence of visible smoke is not necessarily synonymous with low particulate emissions. For example, the use of organo-metallic smoke suppressants can result in a reduction in smoke opacity, at the expense of an increase in total particulate emissions (Ref. 2-21). Also, while the formation of smaller size particulates results in a reduction in smoke opacity, the total particulate mass might actually increase.

Smoke opacity values measured for the Mercedes-Benz 240D and the Volkswagen Rabbit at various points during the FTP driving cycle are listed in Table 2-8 for the five fuels identified in Table 2-7. The fuel-to-fuel differences in the measured smoke intensities vary widely, but generally the minimum quality fuel produced more smoke than the premium quality fuel. The smoke opacity of the Rabbit is higher during the starting cycle than for the Mercedes, but the Mercedes emits higher smoke levels during the acceleration peaks and also at idle.

TABLE 2-7. EFFECT OF FUEL PROPERTIES ON DIESEL PARTICULATE EMISSIONS
(Refs. 2-14 and 2-23).

<u>Fuel Properties</u>					
Type	2D ET	NA NO. 2	NO. 1	MQ NO. 2	PQ NO. 2
Identification	EM238F	EM239F	EM240F	EM241F	EM242F
API Gravity, degrees	36.0	36.1	44.1	32.8	38.7
Cetane Number	48.6	48.7	47.4	41.8	53.0
Initial Boiling Point, °C	192	186	162	182	183
End Point, °C	349	337	268	327	327
Aromatic Content, percent	29.8	21.6	13.0	34.6	12.4
Sulfur Content, percent	0.35	0.23	0.04	0.26	0.26
<u>Particulates</u>					
Cummins 3208, gm/hp-hr	0.66	0.65	0.39	0.73	0.63
DDAD 6V-71, gm/hp-hr	1.38	1.43	1.25	1.32	1.40
MB 240D, gm/mile	0.530	0.506	0.378	0.612	0.470
VW Rabbit, gm/mile	0.362	0.351	0.285	0.604	0.312
<u>Soluble Organic Fraction</u>					
Cummins 3208, percent	11.9	11.8	13.1	16.8	10.9
DDAD 6V-71, percent	47.1	48.8	58.0	49.0	53.4
MB 240D, percent	9.4	8.3	14.3	5.4	6.2
VW Rabbit, percent	12.2	11.6	13.2	11.8	13.5
<u>Benzo(a)pyrene</u>					
Cummins 3208, µg/kg fuel	1.8	3.6	3.6	8.6	5.3
DDAD 6V-71, µg/kg fuel	-	1.0	4.5	4.6	1.8
MB 240D, µg/mile	0.62	0.74	0.52	1.00	0.37
VW Rabbit, µg/mile	1.82	2.14	1.90	5.86	1.69
EPA 13-mode cycle for heavy-duty engines 1975 FTP for light-duty engines 2D ET: #2D emissions test fuel NA NO. 2: National average No. 2D fuel NO. 1 : No. 1 diesel fuel (similar to Jet A) MQ NO. 2: Minimum quality No. 2D fuel PQ NO. 2: Premium quality No. 2D fuel					

TABLE 2-8. SMOKE DATA FOR TWO DIESEL VEHICLES AND FIVE FUELS (Ref. 2-14).

Vehicle	Test Condition and Fuel	Average Smoke, PHS Percent				
		238	239	240	241	242
Mercedes 240D	Cold start peak	22	36	39	59	21
	Cold idle avg. (after start)	4.2	2.6	2.3	2.2	3.4
	1st accel peak	18	15	15	14	18
	Idle at 125 sec, avg.	2.0	1.4	1.4	2.4	2.1
	Accel at 164 sec, peak	6.6	13	7.2	9.8	12
	Hot start peak	26	38	23	29	22
	Hot idle avg. (after start)	2.2	1.4	1.4	2.3	2.3
	Hot 1st accel peak	7.0	7.8	5.8	11	7.5
	Hot idle at 125 sec, avg.	1.8	1.7	1.3	2.2	1.8
	Hot accel at 164 sec, peak	5.4	6.2	4.6	5.2	6.2
VW Rabbit Diesel	Cold start peak	71	79	58	89	85
	Cold idle avg. (after start)	0.5	3.0	1.8	72	3.5
	1st accel peak	16	5.8	6.8	41	23
	Idle at 125 sec, avg.	0.3	0.5	0.4	0.4	0.4
	Accel at 164 sec, peak	18	22	10	27	22
	Hot start peak	41	37	28	48	34
	Hot idle avg. (after start)	0.4	0.4	0.2	0.2	0.3
	Hot 1st accel peak	3.5	3.0	2.9	4.2	2.2
	Hot idle at 125 sec, avg.	0.4	0.4	0.2	0.2	0.5
	Hot accel at 164 sec, peak	31	23	13	28	17

Tests performed by VW indicate that the use of EGR increases smoke, especially when operating at high elevations (Ref. 2-24). Excessive smoke can also be observed when an underpowered vehicle is operated at the smoke limit during acceleration. VW analyses show that the use of a more powerful turbocharged engine will reduce smoke in this case, since the turbocharged engine provides additional margin between normal operating conditions and the smoke limit (Ref. 2-25).

2.3.2.3 Sulfates

Because of the high sulfur content of diesel fuel relative to gasoline -- 0.23 percent by weight for No. 2 diesel fuel, and 0.03 percent for unleaded gasoline -- sulfate emissions from diesel engines are potentially higher than fr

SI engines (Ref. 2-26). The primary oxide of sulfur appearing in the exhaust gas is sulfur dioxide, SO_2 , while only about 2 percent of the fuel sulfur is oxidized to sulfur trioxide, SO_3 (Ref. 2-27). At high temperatures, SO_2 is the more stable compound, while SO_3 is more stable at low temperatures. As the piston descends, the temperature of the combustion products decreases, and the equilibrium shifts toward the formation of SO_3 . In the presence of water vapor, the SO_3 hydrolyzes to produce sulfuric acid, H_2SO_4 , or sulfates. The levels of sulfate emissions from diesel vehicles are of some concern, because of their corrosive and irritant properties.

Other sulfate formation mechanisms involve the simultaneous adsorption of SO_2 , water, and oxygen by the carbon particles, and the conversion of SO_2 to SO_3 in oxidation catalysts (Refs. 2-28 and 2-29).

Sulfate emission data from a number of diesel vehicles tested over the Urban Cycle, using fuels with different sulfur contents, are plotted in Figure 2-13 (Refs. 2-14, 2-24, 2-30, and 2-31). Without the use of an oxidation catalyst, sulfate emissions from diesel engines tend to be proportional to the product of fuel consumption and fuel sulfur content. Since fuel consumption increases as vehicle size increases, the larger inertia weight classes show higher sulfate emissions. In the case of European fuel, the use of a catalyst resulted in a five-fold increase in sulfate emissions relative to operation of the engine without a catalyst. Consequently, the reduction in HC which can be achieved by adding a catalyst to a diesel exhaust system must be balanced against the harmful effects resulting from the associated increase in sulfate emissions.

Equations correlating the sulfur and sulfate contents of typical diesel particulate emissions to the fuel sulfur content are presented in Table 2-9 (Refs. 2-14, 2-24, 2-30, and 2-31). It is interesting to note that the equations predict finite sulfur and sulfate values even at zero fuel sulfur content, indicating that the lubricant may contribute some sulfur to the total emissions.

2.3.2.4 Odor

Diesel exhaust odor is one of the unregulated emissions which the public finds most objectionable. It is also the emission which is most difficult to quantify, since it is composed of many different components present in microscopic quantities. Gas chromatography has been used to identify 100 compounds

FIGURE 2-13. SULFATE EMISSIONS OF DIESEL VEHICLES OPERATED OVER THE URBAN CYCLE (Refs. 2-14, 2-24, 2-30, and 2-31).

influencing diesel odor (Ref. 2-24). Concentrations are extraordinarily small, with the total quantity of odorants representing about 1/1000th of the total HC emissions, and individual odorants ranging down to 1/10 millionth of total HC (Ref. 2-32).

VW has experimentally determined the odor levels of four of its diesel powered research vehicles, as shown in Figure 2-14 (Ref. 2-24). Without EGR, there is little difference in the odor levels of naturally aspirated and turbocharged engines. However, the use of EGR in the two vehicles resulted in significant differences in the observed odor intensity. Since the ordinate in Figure 2-14, which represents total intensity of aroma (TIA), is a logarithmic quantity, the difference between engines with and without EGR represents a factor of 10 in intensity. The U.S. No. 2 diesel fuel produces consistently higher odor levels than the European fuel, which has a cetane number of about 50, compared to about 42 for the diesel No. 2 (Ref. 2-33). In addition to the higher odor intensity, the low cetane U.S. fuel results in longer ignition delay periods and higher HC emissions.

TABLE 2-9. EQUATIONS RELATING PARTICULATE SULFUR AND SULFATE CONTENTS TO FUEL SULFUR CONTENT (Ref. 2-14).

Parameter	Equation ⁽¹⁾	r ² (2)
<u>Sulfur in Particulates</u>		
MB 240D	$y = 4.63 + 150x$	0.835
VW Rabbit	$y = 4.28 + 123x$	0.974
<u>Sulfate in Particulates</u>		
MB 240D	$z = 19.8 + 363x$	0.937
VW Rabbit	$z = 35.3 + 325x$	0.884
(1) x: Sulfur content of fuel, weight percent y: Sulfur emissions, mg sulfur/kg fuel z: Sulfate emissions, mg sulfate/kg fuel. (2) Coefficient of Determination.		

Daimler-Benz (DB) is experimenting with a 2-stage gas chromatographic process to permit identification and quantification of individual odorants in the exhaust (Ref. 2-32). However, because of the high degree of complexity involved, this procedure may not be suited for real-time odor analysis under actual driving cycle conditions.

2.3.2.5 Organic Compounds

It has been already established that particulate emissions consist of a carbonaceous core on which high molecular weight organic compounds are adsorbed (Ref. 2-18). Beginning with Model Year 1982, only the total mass of particulate emissions will be regulated. However, the quantity and composition of the adsorbed organic compounds are the primary points of interest, since much of any adverse health effects related to particulate emissions might be due to the organic fraction and not the carbonaceous nucleus. In many recent studies of diesel emissions, the organic fraction has been separated and characterized in order to gain a better understanding of the effects of engine operating parameters on the formation of organic compounds.

FIGURE 2-14. DIESEL ODOR EMISSIONS OVER THE URBAN DRIVING CYCLE, AS AFFECTED BY FUEL COMPOSITION AND EXHAUST GAS RECIRCULATION (Ref. 2-24).

The accepted method of particulate collection uses a dilution tunnel to cool and dilute the engine exhaust stream. A portion of this diluted stream is then pumped through a glass fiber or teflon-coated filter, where the particulate matter is collected. The organic compounds are subsequently extracted from the particulate filter by using organic solvents. It has been shown that conditions in the dilution tunnel influence the organic content of the particulate matter collected on the filter. The boiling points of soluble organic compounds found on particulates ranges from 300°C to over 600°C, as shown in Figure 2-15 (Ref. 2-14). For comparison, undiluted exhaust gas temperature during the FTP ranges from 150°C to 500°C, with 200°C being the median temperature (Ref. 2-34). Because the higher exhaust temperatures during the cycle overlap the lower end of the organic compound boiling range, the adsorbed organics will be affected by dilution ratio and transit time in the tunnel.

FIGURE 2-15. BOILING RANGES FOR FUELS, OILS, AND SOLUBLES
(Ref. 2-14).

In addition, the tunnel surfaces can influence particulate-bound organics by condensing some of these compounds before they are adsorbed onto the particles (Ref. 2-35). This is evidenced in work performed by GM, where two different particulate fractions were characterized. One of these fractions was collected on a filter during a routine particulate emissions test, while the other sample consisted of particulate matter collected from the walls of the tunnel, and which had been deposited on the tunnel walls during different tests over a span of many weeks (Ref. 2-36). Figure 2-16 shows the carbon number distribution for these two particulate samples, termed the "defined" and "mixed" samples, respectively. As indicated, the defined exhaust extract has a larger percentage of low molecular weight material than the mixed extract.

The mix of organic compounds present in diesel exhaust is quite complex. Table 2-10 shows the substances which were extracted from the particulate matter collected from a medium-duty Caterpillar 3208 engine (Ref. 2-37).

FIGURE 2-16. GAS CHROMATOGRAPH TRACES OF DEFINED AND MIXED EXHAUST EXTRACTS (Ref. 2-36).

TABLE 2-10. COMPOUNDS EXTRACTED FROM DIESEL PARTICULATE MATTER (Ref. 2-37).

<u>Aromatic Compounds</u>	<u>Paraffinic Compounds</u>	<u>Acidic Compounds</u>	<u>Oxygenated Compounds</u>
Benzene	Pentane	Phenol	Hydroquinone
Toluene	Hexane	Cresol	9,10-Anthraquinone
Diphenyl	Octane	Dinitro-o-cresol	Furfural
Anthracene	n-Tetradecane	Benzoic acid	Furfuryl alcohol
Styrene	n-Pentadecane	o,m,p-Phenylphenols	Cyclohexanol
Xylene	n-Hexadecane		2-Hexanone
Pyrene	n-Octadecane	<u>Basic Compounds</u>	Methylacetate
Chrysene	n-Nonadecane	Pyridine	Crotonaldehyde
Benzo(a)pyrene	n-Eicosane	Aniline	2-Pentanone
Benzo(j)fluoranthene	Cyclohexane	Benzacridene	
Benzo(b)fluoranthene	Methylcyclohexane	o-Toluidine	<u>Transitional Compounds</u>
Trimethylnaphthalene			Dioxane
Ethylfluorene			Methoxyphenanthrene
Dimethylphenanthrene			

Many of these compounds have been shown to be mutagens in the Ames test, indicating possible carcinogenic properties in man.

Benzo(a)pyrene (BaP) is one particulate constituent that is of particular interest, because of its carcinogenic properties. As shown in Figure 2-17, BaP is found in the exhaust of both diesel and SI engines (Ref. 2-38). The SI engines without catalyst show wide variations in BaP emissions, ranging from about 0.3 to 5.5 $\mu\text{g}/\text{mi}$, but the average BaP emission level of these vehicles is quite comparable to the two diesel vehicles, which have BaP emissions of about 3 $\mu\text{g}/\text{mi}$. The catalyst equipped SI vehicles have BaP emissions of less than 0.1 $\mu\text{g}/\text{mi}$, indicating the potential usefulness of oxidation catalysts as a BaP control device. However, the use of a catalyst in diesel vehicle "I" was not effective in terms of BaP abatement, perhaps because of the low exhaust temperature characteristic of diesels. Obviously, considerable additional efforts are required in this area, before conclusive statements can be made regarding the applicability of catalysts as a BaP control technique in diesel engines.

FIGURE 2-17. BENZO(a)PYRENE EMISSION RATES DETERMINED UNDER TEST CONDITIONS PROPOSED FOR LIGHT-DUTY DIESEL VEHICLES (Ref. 2-38).

BaP has been found to be unstable under the conditions prevailing in vehicle testing. The measured emission rates of BaP are affected by the filter medium used, as well as the presence of light, air, and smog in the particulate collection system (Ref. 2-16). Test data show that BaP was stable when stored in the dark with air for up to 48 hr, but when stored in the light in the presence of smog, 50 percent was destroyed within 1 hr. This raises the question as to how well the dilution tunnel test simulates the behavior of an actual vehicle freely dispersing pollutants into the atmosphere. Similar observations were made for other polynuclear aromatic hydrocarbons (PAH).

BaP and other PAH compounds are formed through incomplete combustion of fuels and lubricants. Consequently, their formation rates are expected to be dependent on the physical condition of the engine and the injection system. Test data indicate zero BaP emissions for a completely warmed-up diesel engine with a clean injection system, and up to 1/00 $\mu\text{g}/\text{min}$ of BaP for a deteriorated engine with a dirty injection system (Ref. 2-39). Engine oil consumption is another important variable affecting BaP emissions in SI engines. For example, an increase in the oil consumption of a V-8 SI engine from about 1 qt per 1600 mi to 1 qt per 200 mi was accompanied by an increase in BaP emissions from about 20 $\mu\text{g}/\text{mi}$ to 250 $\mu\text{g}/\text{mi}$. Similar trends might be expected for diesel engines.

Other factors influencing BaP emissions include fuel properties and the type of driving cycle used. This is illustrated in Figure 2-18, which shows the BaP emission rates for three diesel powered automobiles, and compares these rates with those of SI vehicles. Minimum Quality diesel fuel, having low cetane number, low volatility, and high aromatic content, generally produces higher BaP emissions than does High Quality diesel fuel. A comparison of Jet A fuel with Emissions Test diesel fuel in the Peugeot 504D shows higher BaP emissions for Jet A in both highway and SET tests, even though Jet A tends to produce lower particulate emissions.

With regard to driving cycle effects on BaP emissions, the VW Rabbit shows higher BaP levels over the Urban Cycle than over the New York City Cycle, while the Mercedes 240D shows the opposite trend.

2.3.2.6 Aldehydes

Although aldehydes are currently not regulated, the level of aldehyde emissions from diesel automobiles is of concern, since aldehydes are eye,

FIGURE 2-18. BENZO(a)PYRENE EMISSION OF DIESEL AND SPARK IGNITION VEHICLES.

nose, and throat irritants, and are principal participants in the formation of photochemical smog (Ref. 2-40). Aldehyde emissions formation is strongly influenced by fuel properties, vehicle design, and driving cycle. This is illustrated in Table 2-11 and Figure 2-19 (Refs. 2-14 and 2-30). Fuel properties are listed in Table 2-7. As shown, the No. 1 diesel fuel resulted in lower quantities of aldehydes than did the Minimum Quality fuel. The No. 1 fuel used in these tests was low in aromatics and had a low specific gravity, while the Minimum Quality fuel can be characterized by low cetane number, high aromatic content, and high specific gravity. In the case of the VW Rabbit, the Minimum Quality fuel resulted in lower aldehyde emissions than did the National Average fuel, while for the Mercedes 240D the fuel effects were reversed. In general, the Rabbit was more fuel sensitive than the 240D, and produced higher BaP emissions, in spite of its significantly lower inertia weight. In all cases, the aldehyde emission levels were higher for the low-speed New York City Cycle than for the Urban Cycle, which has a higher average speed.

Other diesel vehicles tested over the Urban Cycle with No. 2 diesel fuel show aldehyde levels consistent with the Rabbit and 240D data, except for

TABLE 2-11. TOTAL ALDEHYDE MASS EMISSIONS, AS AFFECTED BY VARIATIONS IN DRIVING CYCLE AND FUEL PROPERTIES (Ref. 2-14).

VEHICLE	OPERATING SCHEDULE ⁽²⁾	TOTAL ALDEHYDE MASS EMISSIONS BY TEST FUEL, mg/km ⁽¹⁾				
		EM-238-F	EM-239-F	EM-240-F	EM-241-F	EM-242-F
MERCEDES 240D	FTPC (avg)	18.	13.	16.	21.	14.
	FTPH (avg)	16.	18.	16.	26.	19.
	CFDS	8.3	14.	11.	18.	7.4
	FET	8.4	17.	24.	8.1	8.7
	NYCC ⁽¹⁾	81.	53.	31.	39.	52.
	IDLE ⁽¹⁾	330.	160.	170.	250.	430.
	50 km/hr	7.2	2.0	5.2	4.7	6.9
	85 km/hr	4.9	1.6	3.2	3.5	3.4
VW RABBIT DIESEL	FTPC (avg)	35.	16.	18.	65.	18.
	FTPH (avg)	24.	10.	18.	43.	10.
	CFDS	83.	32.	15.	10.	1.8
	FET	13.	11.	9.1	9.8	8.1
	NYCC ⁽¹⁾	94.	76.	36.	53.	75.
	IDLE ⁽¹⁾	860.	1200.	410.	940.	970.
	50 km/hr	20.	7.7	9.5	38.	8.7
	85 km/hr	8.4	4.8	6.3	8.8	5.4

(1) Idle emissions in mg/hr instead of mg/km.
(2) "Total" aldehyde mass emissions defined in text.

FIGURE 2-19. ALDEHYDES EMISSIONS OF DIESEL VEHICLES (Refs. 2-14 and 2-30).

the Perkins 6-247 diesel equipped International Harvester pickup truck. The aldehyde emissions from the Perkins engine are 2.5 to 8 times higher than those of

the Mercedes and Peugeot vehicles, which is consistent with the HC emissions trends of these vehicles. Over the Urban Cycle, the aldehyde emissions of the diesel automobiles considered in Figure 2-19 are in the 20 to 85 mg/mi range, which is significantly above the 12 mg/mi value determined for an oxidation catalyst equipped 1975 Model Year Plymouth automobile (Ref. 2-41).

2.3.2.7 Phenols

Although phenolic compounds, including cresol (C_7H_8O), dimethyl phenol ($C_8H_{10}O$), methoxy phenol ($C_7H_8O_2$), allyl phenol ($C_9H_{10}O$), indenol (C_9H_8O), and indanol ($C_9H_{10}O$) are only moderately toxic, these compounds are irritants and contributors to the "smokey-burnt" odor of diesel exhaust (Ref. 2-42). The concentrations of phenolic compounds in the exhaust of diesel and SI engines are quite low, in the parts per billion range. Typically, phenol emissions from diesel engines have been detected both in the gaseous phase and adsorbed onto the particulates. There is evidence that phenols, in addition to being formed in the combustion process, are generated in photochemical reactions with other pollutant species.

Gaseous and particulate bound phenol emissions data, determined experimentally for two diesel vehicles under steady-state operating conditions and with five different fuels, are listed in Tables 2-12 and 2-13 (Ref. 2-14). Pertinent fuels parameters are provided in Table 2-7. As shown in these tables, the Mercedes 240D produces significantly lower phenol emissions than the VW Rabbit for all operating conditions and fuel types tested. This indicates that engine and fuel injection system design and operating parameters might be important factors affecting phenol formation. In general, phenol levels increase with increasing vehicle speed (engine speed and load), except for the gaseous phenols from the Rabbit when the vehicle is operated on Minimum Quality fuel or No. 2D Emissions Test fuel.

2.3.2.8 Nitrosamines

Nitrosamines are carcinogenic compounds associated with smoky combustion. They can be found in cigarette smoke, in charcoal-broiled foods, and even in Scotch whiskey. DB indicates that no nitrosamines have been detected in the exhaust of any of its vehicles (Ref. 2-42). However, it is conceivable

TABLE 2-12. GASEOUS PHENOL EMISSIONS FROM TWO DIESEL AUTOMOBILES
(Ref. 2-14).

Vehicle	Operating Condition	Units	Fuel Code ⁽¹⁾				
			ET2	NA2	JA1	MQ2	PQ2
MB 240D	Idle	mg/hr	0.0	0.0	0.38	0.52	0.0
	31 mph	mg/mi	0.0	0.016	0.015	0.034	0.0
	53 mph	mg/mi	0.100	0.081	0.034	0.042	0.072
VW Rabbit	Idle	mg/hr	0.35	0.22	0.67	13.56	0.54
	31 mph	mg/mi	0.150	0.037	0.061	0.859	0.018
	53 mph	mg/mi	0.114	0.043	0.216	0.604	0.138
(1) See Table 2-7.							

TABLE 2-13. PHENOL EMISSIONS DEPOSITED ON PARTICULATES FOR TWO
DIESEL AUTOMOBILES (Ref. 2-14).

Vehicle	Operating Condition	Units	Fuel Code ⁽¹⁾				
			ET2	NA2	JA1	MQ2	PQ2
MB 240D	Idle	mg/hr	0.0	1.0	0.0	0.0	0.0
	31 mph	mg/mi	0.071	0.0	0.0	0.0	0.0
	53 mph	mg/mi	0.021	0.037	0.045	0.0	0.008
VW Rabbit	Idle	mg/hr	0.19	0.20	0.0	0.07	0.0
	31 mph	mg/mi	0.0	0.008	0.024	0.003	0.010
	53 mph	mg/mi	0.037	0.0	0.024	0.121	0.029
(1) See Table 2-7.							

that vehicle exhaust might contribute indirectly to nitrosamine formation through chemical reactions, involving nitrogen dioxide (NO₂), nitrous oxide (NO), and water vapor (Ref. 2-42).

Although the NO_x emissions of diesel engines may have a role in producing nitrosamines in the atmosphere, human exposure through inhalation is less than from other sources. Even at the highest measured urban nitrosamine concentration, 0.96 ppb, exposure through inhalation is about 1.2 µg per day. In comparison, a one pack per day smoker is exposed to 24 µg per day (Ref. 2-42). Nitrosamine concentrations in the air are generally far lower than the 0.96 ppb extreme value quoted above. For example, in New York City, average concentrations are about 0.26 ppb, and concentrations measured in the Los Angeles area are in the 0.01 - 0.33 ppb range.

2.3.3 Effect of Driving Cycle on Emissions

Available test data showing the effects of variations in driving cycle on the gaseous and particulate emissions of a Mercedes 240D automobile are presented in Table 2-14 (Ref. 2-14). As indicated, most gaseous and particulate species tend to increase in quantity as the average speed over the Driving Cycle decreases. For example, all listed species reach their highest levels over the New York City Cycle, which may be characterized as a stop-and-go cycle. Since the diesel's fuel economy advantage relative to SI vehicles is particularly strong under congested urban driving conditions, the energy conservation benefits associated with the diesel must be weighed against the negative impacts caused by its emissions characteristics.

2.4 DIESEL NO_x, HC, AND PARTICULATE EMISSIONS POTENTIAL

NO_x, HC, and particulate emissions test data are presented in Figures 2-20 and 2-21 in terms of HC versus NO_x and particulates versus NO_x, with pertinent test vehicle parameters listed in Table 2-15. Except for vehicles G and H, all vehicles are late model production vehicles, using prototype or pre-prototype EGR systems as the principal NO_x control technique. Vehicles G and H represent computer simulations performed by Ford on the basis of engine dynamometer mapping data.

TABLE 2-14. EFFECT OF DRIVING CYCLE ON EMISSIONS (Ref. 2-14).

DRIVING CYCLE	g/mi				mg/mi			$\mu\text{g/mi}$
	HC	CO	NO _x	PARTIC	ORGA-NICS	SULF-ATES	ALDE-HYDES	B(a)P
URBAN	0.19	0.92	1.26	0.53	58.3	13.2	27.1	0.62
HIGHWAY	0.10	0.56	1.09	0.34	21.8	20.8	13.5	0.12
SULFATE TEST	0.14	0.63	1.35	0.42	32.3	16.1	13.3	0.21
NEW YORK CITY	0.43	1.79	1.88	1.09	124	20.9	130	3.06
31 mph	0.13	0.43	0.76	0.28	28.6	6.4	11.6	0.23
53 mph	0.13	0.58	1.35	0.32	24.6	15.7	7.9	0.13

FUEL: No.2 EMISSIONS TEST FUEL
 VEHICLE: MERCEDES 240D
 DATA FROM SAE 790424

FIGURE 2-20. HC VERSUS NO_x EMISSIONS OF DIESEL VEHICLES EQUIPPED WITH EXPERIMENTAL NO_x CONTROL SYSTEMS.

FIGURE 2-21. PARTICULATES VERSUS NO_x EMISSIONS OF DIESEL VEHICLES EQUIPPED WITH EXPERIMENTAL NO_x CONTROL SYSTEMS.

The data in Figure 2-20 show a definite trend for HC emissions to be lower with small amounts of EGR relative to vehicle operation without EGR. This may be due to the increased temperature of the intake mixture which reduces ignition delay and promotes more complete combustion. However, as NO_x levels approach the 0.7 to 0.8 g/mi range -- which allows some margin for satisfying a 1.0 g/mi statutory limit -- HC levels increase sharply, and may be too high to meet the 0.41 g/mi HC limit with an acceptable margin. For the turbocharged vehicles A and B, the observed rate of increase in HC at low NO_x levels is greater than for the naturally aspirated engine. Although an oxidation catalyst may be used to counteract the increase in HC, it has been shown that the addition of an oxidation catalyst to diesel engines can result in an increase in particulate emissions by producing higher levels of sulfates.

Figure 2-21 shows a large increase in particulate emissions as NO_x is reduced by means of EGR to below 1.0 g/mi. The increase in particulates is

TABLE 2-15. DIESEL VEHICLE AND CONTROL SYSTEM IDENTIFICATION.

Identification	Vehicle Type	Engine Type ⁽¹⁾	Inertia Weight, lb	Comments	Reference
A	Peugeot 504	T C	3500	Prototype EGR system with electro-valve control, 2.3 liter engine and manual transmission.	2-33
B	Peugeot 504	N A	3500	Preprototype EGR system, 2.3 liter engine and manual transmission.	2-33
C	Mercedes 300D	N A	3750	Prototype EGR system (MY 1982), 3.0 liter engine, automatic transmission.	2-42
D	Mercedes 240D	N A	3500	As above, except 2.4 liter engine.	2-42
E	Oldsmobile 98	N A	4500	EGR system developmental vehicle, 5.7 liter engine and automatic transmission.	2-43
F	Chevrolet/Opel	N A	2500	Modulated EGR (throttle control), 2.1 liter engine and manual transmission.	2-43
G	Ford ⁽²⁾	N A	3000	Results based on engine dynamometer mapping.	2-44
H	Ford ⁽²⁾	N A	2250	Same as (G).	2-44
I	Vega/Opel	N A	3000	Modulated EGR (Analog Electric Control, 2.1 liter engine and automatic transmission.	2-43
J	Mercedes 300SD	T C	4000	Experimental EGR and water injection, 3.0 liter engine and automatic transmission.	2-42
K	Mercedes 240D	N A	3500	Same as (J) except 2.4 liter engine.	2-42
L	Mercedes 240D	N A	3500	Same as (K) except manual transmission and oxidation catalyst.	2-42
(1) Either naturally aspirated (N A) or turbocharged (T C).					
(2) Computer simulation.					

especially pronounced for vehicles with high inertia weights. Since heavy vehicles tend to have high particulate and NO_x emissions, meeting stringent emission regulations simultaneously for these two species is more difficult than for lighter vehicles. In addition to increases in HC and particulates, the use of EGR generally results in a marked increase in CO, smoke, and exhaust odor.

The effect of NO_x control on Urban Cycle fuel economy of these vehicles is shown in Figure 2-22. Generally, fuel economy deteriorates as NO_x emission levels are reduced. However, two vehicles, F and L, show an increase in fuel economy. In light of these results it appears that a systems approach is needed which involves simultaneous optimization of all engine and emission control system components and parameters.

FIGURE 2-22. FUEL ECONOMY VERSUS NO_x EMISSIONS OF EXPERIMENTAL DIESEL ENGINES AND/OR CONTROL SYSTEMS.

Recent statements by representatives from the automotive industry regarding NO_x and particulates for production vehicles are summarized as follows:

Daimler-Benz: There is no known technology capable of meeting a 1.0 g/mi NO_x standard in conjunction with existing HC and CO standards and the 0.6 g/mi particulate standard promulgated by the EPA for 1982. Efforts toward achieving 0.4 g/mi NO_x center around the use of EGR, water injection, and oxidation catalysts.

Ford: Technology does not exist to simultaneously meet a 1.0 g/mi NO_x standard and a 0.6 g/mi particulate standard, particularly for larger vehicles. Because engine modifications have not yielded sufficient reductions in particulates, some form of exhaust after-treatment will be required.

- General Motors: Technology is not available to meet a 1.0 g/mi NO_x standard while still meeting HC, particulate, and durability requirements. The most promising approach is the use of EGR. However, the associated increase in particulate emissions and the loss in engine durability are serious and unresolved problems.
- Peugeot: Technology is not presently available to simultaneously meet a NO_x standard of 1.0 g/mi and a particulate standard of 0.6 g/mi^x in 3500 lb production vehicles. Electronic controls for fuel injection and EGR optimization are required to meet a 1.0 g/mi NO_x standard while exhaust filters are needed to reach particulate levels below 0.6 g/mi.
- Ricardo: The use of a microprocessor controlled fuel injection pump might result in NO_x emissions as low as 1.0 g/mi in smaller vehicles, without increasing particulates above the 0.3 g/mi level currently obtainable from engines timed for optimized performance.
- Volkswagen: Fuel injection timing modifications can reduce NO_x emissions to 1.0 g/mi in vehicles weighing less than 2500 lb, while heavier vehicles will also require the use of EGR and particulate trap-oxidizers. The minimum realistically obtainable particulate level for production vehicles in the near future appears to be about 0.4 g/mi. This requires the use of a turbocharger and a trap-oxidizer system on vehicles of all sizes.
- Volvo: At this time, engineering judgement indicates that the lowest feasible particulate level is 0.4 g/mi. EGR and injection timing modifications should permit meeting a 1.0 g/mi NO_x standard.

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SECTION 3

DIESEL EXHAUST EMISSIONS CONTROL TECHNOLOGY

This section addresses presently known exhaust emission control techniques applicable to diesel engines. These techniques can be divided into the following four categories:

1. Engine Operational Modifications
2. Engine and Component Modifications
3. Incorporation of Control Devices
4. Fuel Modifications and Additives.

Engine operational modifications are addressed in Subsection 3.1. These include variations in engine speed, engine load, gearing, and intake air temperature. Engine and component modifications, involving primarily the combustion chamber and fuel injection system, are covered in Subsection 3.2. Emission control devices and techniques potentially applicable to diesels are examined in Subsection 3.3, including exhaust gas recirculation, water injection, and exhaust cleanup devices. Section 3.4 assesses the effects of variations in fuel composition and the use of additives on engine fuel economy and emissions characteristics.

3.1 ENGINE OPERATIONAL MODIFICATIONS

3.1.1 Engine Speed and Load Variations

Test data from both naturally aspirated and turbocharged indirect injection light-duty automotive diesel engines indicate that brake specific hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions, expressed in terms of grams per brake horsepower-hour, are affected by variations in engine speed and load (Refs. 3-1 and 3-2). In the low power output regime, HC and CO emissions generally decrease with increasing load, while load variations in the high power regime can result either in reductions or increases in HC and CO, depending upon engine and fuel injection system design and operation. Brake specific NO_x emissions from a 3 liter light-duty pre-chamber diesel engine are presented in Figure 3-1, indicating a decline in NO_x as engine load increases (Ref. 3-1).

FIGURE 3-1. BRAKE SPECIFIC NO_x EMISSIONS MAP OF A 3 LITER LIGHT-DUTY PRECHAMBER DIESEL^x ENGINE (Ref. 3-1).

Brake specific particulate emissions data from two General Motors (GM) diesel engines are presented in Figure 3-2 (Ref. 3-3). As indicated, at a given set of engine speed and load conditions the Oldsmobile has higher particulate emissions than the Opel. At constant load, particulate emissions of the Oldsmobile increase with decreasing speed, but are nearly independent of speed in the case of the Opel, reflecting the effects of engine design on pollutant formation.

Incorporation of a lower numerical rear axle ratio as a means of reducing engine speed has resulted in small reductions in gaseous exhaust emissions over the Federal Urban Driving Cycle. For example, a rear axle ratio change from 3.2 to 2.8 in a 3000 lb inertia weight vehicle with a 2.5 liter engine

FIGURE 3-2. EFFECT OF ENGINE LOAD AND SPEED ON PARTICULATE EMISSIONS OF OLDSMOBILE AND OPEL LIGHT-DUTY DIESEL ENGINES (Ref. 3-3).

resulted in a reduction in HC, CO, and NO_x emissions by about 6, 12, and 6 percent, respectively. These reductions were accompanied by an improvement in combined cycle fuel economy of about 8 percent, and a reduction in 0 to 60 mph acceleration time by about 2 percent (Ref. 3-2). Test data from another 3000 lb vehicle, equipped with a 2.1 liter engine, indicate even larger reductions in emissions. In this case the use of a rear axle ratio of 3.34 instead of 4.15 resulted in HC, CO, and NO_x reductions of 26, 14, and 17 percent, respectively, accompanied by an improvement in combined cycle fuel economy of 14 percent and an increase in 0 to 60 mph acceleration time by 22 percent.

Somewhat different results were obtained when transmission modifications were utilized to increase engine load and reduce speed. Incorporation of a torque converter lock-up feature into a 3-speed automatic transmission resulted in an increase in HC and CO emissions of 43 and 25 percent, respectively,

while NO_x was reduced by 16 percent. Simultaneous incorporation of an over-drive 4th speed resulted in a reduction in HC emissions of about 35 percent relative to the 3-speed configuration, while NO_x increased from 16 to 21 percent (Ref. 3-3).

3.1.2 Intake Air Temperature Variations

Intake air cooling results in a reduction in combustion chamber peak temperatures and pressures accompanied by lower NO_x formation rates. In addition, intake air temperature reduction increases the density of the air entering the engine, which in turn increases output power and improves combustion. However, in the low-load regime, this approach can result in higher HC and CO emissions.

Although intake air cooling has only a limited NO_x reduction potential, this approach deserves further consideration for turbocharged engines in which fuel injection retard is used as a NO_x control technique (Ref. 3-4). In addition, the engine efficiency losses generally associated with timing retard can be at least partially compensated for by the lower fuel consumption resulting from the use of charge cooling (Ref. 3-5).

Test data from a heavy-duty 6.7 liter turbocharged diesel engine are presented in Figure 3-3, indicating significant NO_x and CO reductions with charge cooling (Ref. 3-4). In addition, maximum engine power increased from 210 bhp to 230 bhp, without exceeding piston temperature limits, and brake specific fuel consumption (bsfc) declined by 2 percent. Although no information is available on the effects of charge cooling on particulate emissions, the use of an air cooler in a 12 liter turbocharged engine resulted in marked reductions in smoke emissions in the high-load operating regime. These reductions were particularly significant at lower engine speeds (Ref. 3-4).

3.2 ENGINE AND COMPONENT MODIFICATIONS

Combustion chamber and fuel injection system design, geometry, and operational parameters strongly affect the combustion process in diesel engines and hence, exhaust emissions and fuel consumption. As a result, most diesel engine manufacturers have expended considerable efforts to determine optimal designs with regard to fuel economy and emissions. For example, prior to finali-

FIGURE 3-3. EFFECT OF AIR CHARGE COOLING ON 13-MODE TEST CYCLE EMISSIONS OF A HEAVY-DUTY 6.7 LITER TURBOCHARGED DIESEL ENGINE (Ref. 3-4).

zing the design of its 350 cubic inch displacement (CID) V-8 light-duty diesel engine, GM investigated more than 300 prechamber, swirlchamber, and injection nozzle configurations, and found that complex relationships exist between the various pollutant species emitted from diesels and the combustion system modifications investigated (Refs. 3-3 and 3-6).

3.2.1 Combustion Chamber Modifications

The combustion process in indirect injection (IDI) diesel engines is strongly affected by a number of flow field parameters within the antechamber, including air swirl, turbulence level, and fuel-air mixture ratio, as well as the expulsion process of the combustion products into the oxygen-rich main chamber. These parameters are influenced by the geometry of the combustion chamber. The effects of combustion chamber geometry variations on the combustion process, as evidenced by measurements of fuel economy and exhaust emissions, were recently investigated by the University of Alabama in conjunction with the Cummins Engine Company (Ref. 3-7). In this single cylinder test engine program a parametric evaluation was performed, involving the length-to-diameter ratio, the prechamber-to-main-chamber-volume ratio, and a number of connecting passage parameters.

Experimental results from this program are presented in Figure 3-4, indicating the existence of optimum fuel-to-air and length-to-diameter ratios

(Ref. 3-7). Unfortunately, the minimum bsfc points do not coincide with minimum NO_x , CO, and smoke emissions, although the optimal length-to-diameter ratio with respect to fuel consumption is also optimal for the pollutants shown in Figure 3-4.

FIGURE 3-4. EMISSIONS AND FUEL CONSUMPTION CHARACTERISTICS FOR THREE PRECHAMBER LENGTH-TO-DIAMETER RATIOS (Ref. 3-7).

Much of GM's initial combustion chamber optimization and characterization work was performed on its 2.1 liter swirl chamber Opel diesel engine. In this program many combustion chamber modifications were examined, including

geometric changes to vary chamber swirl, plated surfaces to catalytically enhance combustion, ceramic liners and coatings to reduce heat transfer, and application of an electrostatic field to achieve precipitation of particulate matter (Ref. 3-3). Geometry modifications designed to produce localized turbulence within the swirl pattern resulted in an increase in particulate emissions for a given smoke level, while conversion from a single passageway configuration to a dual passageway design led to a reduction in particulate emissions. The use of low swirl chamber configurations and of copper or platinum plated chamber surfaces resulted in lower NO_x emissions levels, but at the expense of higher particulates and smoke. The use of ceramics had little or no effect on exhaust emissions. In general, the results achieved were considered disappointing by GM, which is not surprising, since the baseline Opel engine had previously achieved a high state of development.

Over the years, Daimler-Benz (DB) has been very active in the area of prechamber diesel engine development. A number of improvements have been incorporated in the 1980 model year engine, and investigations involving modified prechamber and swirl chamber designs are continuing (Ref. 3-8). The 1980 model year improvements consist of an increase in the number of connecting passages from five to six, and a change in the piston head cutout from a cylindrical to a star-like shape. Implementation of these modifications has resulted in significant reductions in exhaust emissions, amounting to about 20 percent for HC, 15 percent for NO_x , and up to 50 percent for particulates, accompanied by a small but measurable improvement in fuel economy. More importantly, the new design is compatible with exhaust gas recirculation (EGR), and its application has resulted in an additional 20 percent reduction in NO_x , down to about 1.3 g/mi, with little or no effect on HC, CO, particulates, and fuel consumption. With EGR, DB's experimental swirl chamber configurations have NO_x and particulate emission levels that are similar to its 1980 model year production light-duty engines. However, HC and CO are higher than for the prechamber engine.

The effects of intake port-induced swirl on fuel economy and exhaust emissions was investigated by AVL of Austria for a direct injection bowl-in-piston diesel engine (Ref. 3-9). AVL concluded that smoke was primarily controlled by velocity and turbulence level in the center of the bowl, while bsfc was strongly affected by the tangential velocity at the periphery of the bowl.

Increased swirl velocity tends to lower both smoke and bsfc, especially in conjunction with injection timing retard. However, these improvements are generally accompanied by higher NO_x emissions.

Valve timing, which affects the cylinder charging and scavaging processes, can have some effect on diesel exhaust emissions. For example, camshaft modifications performed by GM to accelerate valve closing by 20 degrees resulted in an increase in volumetric efficiency at low engine speeds, which effectively increased the fuel-air ratio. As shown in Figure 3-5, HC and noise emissions were reduced, while NO_x and smoke remained nearly constant (Ref. 3-6). Peugeot's new turbocharged 2.3 liter XD2S diesel engine, which is used in its 604 series vehicles, incorporates early valve closure as a means of achieving a 10 percent increase in volumetric efficiency and output power in the low speed regime. These improvements are accompanied by a reduction in HC, smoke, and noise, while NO_x and vehicle driveability remained constant. In addition, engine compression ratio was reduced without degradation in smoke emissions and engine startability. The increase in mechanical efficiency associated with the reduction in compression ratio resulted in a torque increase of about 3 percent. Of course, earlier intake valve closure resulted in a loss in

FIGURE 3-5. EFFECT OF EARLIER INTAKE VALVE CLOSURE ON THE EMISSION OF GM'S 5.7 LITER DIESEL ENGINE (Ref. 3-6).

volumetric efficiency at high engine speeds, and a corresponding loss in engine power. On the XD2S engine, this loss amounted to 8 percent, which is tolerable since the turbocharger produces sufficient boost pressure to reach the desired power level (Ref. 3-10).

3.2.2 Fuel Injection System

3.2.2.1 Injection Characteristics

A number of fuel injection system design and operating parameters have been identified which significantly affect diesel engine performance and emissions characteristics. These include (1) start and duration of injection, (2) injection rate, (3) injection pressure, (4) injector orifice size and number, (5) spray angle, and (6) nozzle orientation. To minimize HC and smoke emissions, the injection process must proceed in a stable manner and without the occurrence of secondary injections after completion of the main injection process (Ref. 3-11). This is illustrated in Figure 3-6, showing acceptable and non-acceptable needle lift versus crank angle traces for direct injection diesel engines. Traces for

FIGURE 3-6. NEEDLE LIFT VERSUS CRANK ANGLE FOR DIRECT INJECTION DIESEL ENGINE (Ref. 3-11).

indirect injection diesels are presented in Figure 3-7. The use of an initially low injection rate results in soft, low noise combustion which is particularly desirable for light-duty vehicle applications.

Start and duration of the injection process are the principal fuel injection system parameters affecting engine performance and emissions (Ref. 3-11). Unfortunately, the systems currently available generally lack sufficient flexibility to provide optimum conditions throughout the operating regime. Advanced electronically controlled systems are under development which are expected to better meet these requirements (Refs. 3-3 and 3-12).

FIGURE 3-7. NEEDLE LIFT VERSUS CRANK ANGLE FOR INDIRECT INJECTION DIESEL ENGINE (Ref. 3-11).

3.2.2.2 Secondary Injection

Secondary injection involves the release of small quantities of fuel at the end of the injection process. Generally, secondary injections are accompanied by substantial increases in HC and CO resulting from poor fuel atomization and incomplete combustion of the large fuel droplets generated during

this phase of the injection process. Closing the needle valves of the injection nozzles generates pressure waves which travel upstream to the injection pump. Since the pump delivery valve is already closed at that time, the pressure wave is reflected back to the injection nozzle, creating the possibility of opening the spring loaded needle valve. The occurrence of secondary injections can be eliminated by carefully tuning the dynamic characteristics of important injection system parameters, including passage lengths and diameters, nozzle opening pressure, needle valve and spring mass, and needle valve lift (Ref. 3-11). Another approach involves the use of a reverse flow damping valve (RFDV), which consists of a disc valve located downstream of the delivery valve. This valve is designed to allow free fuel flow towards the injection nozzle, while eliminating the return pressure wave by means of a small orifice located in the disc. The RFDV design utilized by DB in its late model vehicles is shown in Figure 3-8 (Ref. 3-13).

FIGURE 3-8. SECTIONED VIEW OF REVERSE FLOW DAMPING VALVE (Ref. 3-13).

Upon completion of the main injection process, the fuel contained in the sac volume is discharged into the combustion chamber too late in the cycle to be fully burned, resulting in high HC and CO emissions. During the past few years the automotive industry has expended considerable efforts aimed at the development of viable low sac volume nozzles. Test data from a number of GM experimental nozzles are presented in Table 3-1 (Ref. 3-3). As indicated, fuel economy and HC, CO, and NO_x emissions decrease with decreasing sac volume, except for the Valve Covers Orifice (VCO) design. Although the VCO permits the use of very small sac volumes, this modification alters the spray character-

istics, requiring additional development prior to incorporation into production engines (Ref. 3-14).

TABLE 3-1. EFFECT OF SAC VOLUME ON EMISSIONS AND FUEL ECONOMY OF A 5.7 LITER DIESEL ENGINE EQUIPPED AUTOMOBILE (Ref. 3-3).

Nozzle Type	Sac Volume, mm ³	Emissions, g/mi			Fuel Economy, mpg		
		HC	CO	NO _x	Urban	Hwy	Comb
Short Sac	0.59	0.53	1.89	1.69	21.1	27.5	23.6
Conical Sac	0.35	0.48	1.66	1.65	23.6	30.8	26.4
Tapered Sac	0.20	0.43	1.52	1.56	23.3	31.7	26.5
VCO	0.10	0.43	1.71	1.79	22.1	29.0	24.7

3.2.2.3 Fuel Injection Timing

Early injection timing, particularly when combined with high injection rates, produces high pressure rise rates and high peak cycle temperatures. These conditions generally result in lower specific fuel consumption, but at the expense of an increase in NO_x emissions. The effects of fuel injection timing on nitric oxide (NO) emissions and brake specific fuel consumption (bsfc) of a 2.5 liter indirect injection diesel engine operated at full load are presented in Figure 3-9 (Ref. 3-15). As shown, minimum bsfc is obtained in the range of 12 to 18 degrees before top dead center (BTDC). As timing is retarded from that point to about 5° BTDC, NO declines by about 40 percent, while bsfc increases by 6 to 20 percent, depending upon the total injection period selected.

The effects of both fuel injection timing and injection rate on HC, NO_x, smoke, and bsfc are presented in Figure 3-10 for a turbocharged 2.4 liter indirect injection diesel engine (Ref. 3-15). As shown, minimum HC and bsfc, and maximum NO_x are obtained under nearly identical values of timing and duration. Smoke emissions are strongly dependent upon timing, but are nearly

FIGURE 3-9. EFFECT OF INJECTION TIMING ON FUEL CONSUMPTION AND NO OF A NATURALLY ASPIRATED 2.5 LITER DIESEL ENGINE (Ref. 3-15).

independent of injection rate over a wide range of operating conditions. In the case of this engine, the use of timing retard resulted in a reduction in smoke emission level, which is contradictory to other published data. Recent data by GM indicate that smoke versus timing trends are load dependent (Ref. 3-3).

Test data from a 3500 lb inertia weight automobile, equipped with a 2.1 liter indirect injection diesel engine and operated over the Federal Urban Driving Cycle, indicate that timing retardation by 6 degrees reduced NO_x from 1.46 g/mi to 0.97 g/mi, an improvement of about 33 percent (Ref. 3-3). However, this improvement was accompanied by large increases in HC and CO emissions, amounting to 350 and 50 percent, respectively. Additionally, fuel economy

FIGURE 3-10. EFFECTS OF INJECTION TIMING AND DURATION ON FUEL CONSUMPTION AND EMISSIONS - TURBOCHARGED 2.4 LITER DIESEL ENGINE (Ref. 3-11).

declined by 6 percent, and 0 to 60 mph acceleration increased by about 15 percent. While CO remained well below the 1981 standard of 3.4 g/mi, the HC emissions at 0.56 g/mi fail to meet the existing standard of 0.41 g/mi.

3.2.2.4 Fuel Injection Rate and Pressure

The rate of fuel injection can have a significant effect on the emissions and fuel consumption characteristics of diesel engines. While the performance of indirect injection (IDI) diesels is relatively insensitive to variations in fuel injection rate, an increase in injection rate has resulted in higher NO_x emission levels in some engines (Ref. 3-5). The effect of injection rate variations on fuel consumption and emissions of direct injection (DI) diesels is more pronounced, probably because of the greater importance of air swirl and specific nozzle design parameters, all of which affect the degree of fuel atomization and impingement on the combustion chamber wall. Test data from a non-impinging single cylinder DI diesel research engine are presented in Figure 3-11 (Ref. 3-15). As indicated, bsfc and smoke levels decrease

FIGURE 3-11. EFFECTS OF FUEL INJECTION PERIOD ON BSFC, SMOKE, AND NO OF A DIRECT INJECTION RESEARCH DIESEL ENGINE (Ref. 3-15).

markedly as the fuel injection period is reduced, while NO_x increases. Also shown is the effect of nozzle size, indicating that optimum nozzle sizes exist for each performance parameter, depending upon the fuel injection period selected.

The effects of injection pressure variations on NO_x and particulate formation are shown in Figure 3-12 for a 4-cylinder 2.1 liter IDI swirl chamber engine (Ref. 3-3). In general, particulate emissions decrease with increasing injection pressure, while NO_x increases slightly. For example, for a

FIGURE 3-12. EFFECT OF INJECTION PRESSURE ON 2.1 LITER SWIRL CHAMBER DIESEL ENGINE (Ref. 3-3).

6 degree BTDC timing, an increase in injection pressure from 5000 psi to 10,000 psi results in a 55 percent reduction in particulate emissions, accompanied by a 70 percent increase in NO_x. However, the increase in NO_x could be

offset by retarding injection timing by 4 degrees. In this case particulates increase by about 10 percent, relative to the 6 degree BTDC setting.

The response of this engine to injection pressure variations differs with engine speed and load. For example, an increase in injection pressure at low speeds produces large increases in NO_x but only small changes in particulates. In the high-load regime, relatively high injection pressures are required to achieve significant particulate reductions.

GM data from a production swirl chamber diesel engine are presented in Figure 3-13, showing the effects of injection duration and nozzle size on particulate emissions (Ref. 3-3). As indicated, the lowest particulate levels were obtained with the 0.011 inch diameter nozzle operated with an injection duration of about 20 degrees. The smallest orifice size resulted in the lowest NO_x level and was the least sensitive configuration with regard to variation in injection rate.

3.2.2.5 Orifice Size and Spray Angle

Injection orifice size, orifice number, and spray angle affect spray formation and penetration, as well as the overall air-fuel mixing process, which in turn has a significant impact on the emissions and fuel economy of diesel engines. Test data from one engine indicate a 20 to 40 percent reduction in NO_x as a result of an increase in orifice diameter from 0.0055 inch to 0.0065 inch (Ref. 3-5). However, this improvement was accompanied by a 3 percent increase in bsfc, a 70 to 100 increase in CO, and moderately higher smoke levels.

Test data from an IDI prechamber research engine indicate that a pintle nozzle with a 4 degree cone angle minimized fuel consumption, while a cone angle of 8 degrees minimized NO_x (Ref. 3-7).

Orientation of the fuel spray relative to the direction of the air flow within the swirl chamber has a significant effect on the air-fuel mixing process and exhaust emissions. For example, angling the fuel spray against the direction of swirl has resulted in lower HC and particulate emissions in some engines, frequently at the expense of an increase in NO_x and noise levels (Ref. 3-3). Conversely, angling the spray in the direction of the swirl produced the opposite effect, probably because of a reduction in the combustion rate as a result of increased wall wetting.

FIGURE 3-13. EFFECTS OF INJECTION DURATION AND NOZZLE SIZE ON PARTICULATE EMISSIONS (Ref. 3-3).

3.2.2.6 Fumigation

Fumigation involves the injection of small quantities of fuel into the intake manifold of diesel engines. This technique has been shown to have the potential of reducing NO_x, smoke, and noise. Test data from a single cylinder DI research engine indicate some reduction in these species at a speed of 1700 rpm, accompanied by small loss in fuel consumption, and an increase in HC. However, at rated speed and load, the improvements in exhaust emissions diminished, and fuel consumption increased markedly (Ref. 3-14). Similar trends were observed on an IDI prechamber engine (Ref. 3-14).

The principal disadvantage associated with fumigation is the large increase in HC, particularly at light loads. In this case, the fuel in-

jected into the cylinder engages only a part of the very lean air-fuel charge, resulting in incomplete combustion of the fumigated charge (Ref. 3-14).

3.3 EMISSION CONTROL DEVICES

3.3.1 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) has been shown to be an effective means of controlling NO_x in both IDI and DI diesel engines. The mechanism of NO_x reduction is the same as in the gasoline engine, dilution of the intake charge with exhaust products. As a result, peak combustion temperatures and oxygen and nitrogen concentrations in the combustion chamber decline accordingly. However, the use of EGR in diesel engines introduces complications that do not arise in spark ignition (SI) engines. As shown in Figures 3-14 and 3-15, HC and particulate emissions increase sharply as EGR rates are increased beyond certain levels (Refs. 3-8, 3-10, 3-12, 3-16, and 3-17). It is evident that HC

FIGURE 3-14. EFFECT OF EXHAUST GAS RECIRCULATION ON NO_x AND HC EMISSIONS - URBAN CYCLE (Refs. 3-8 and 3-12).

FIGURE 3-15. EFFECT OF EXHAUST GAS RECIRCULATION ON NO_x AND PARTICULATES EMISSIONS - URBAN CYCLE (Refs. 3-10, 3-16, and 3-17).

risks above the 1981 standard of 0.41 g/mi if EGR is used to control NO_x to levels much below 1 g/mi. Similar trends are shown in Figure 3-15 for particulates. The increase in particulate emissions are especially significant, not only because of the recently promulgated particulate regulations, but also because of the unfavorable effects of high particulate emission rates on engine durability.

Recent efforts on the part of light-duty diesel engine manufacturers in the area of EGR system development are summarized in the following paragraphs. The EGR systems described are developmental in nature, with the exception of a DB system, which is used in its 1980 Model Year 300D and 300SD automobiles certified to the 1.5 g/mi, 100,000 mile California emission standard (Ref. 3-18).

Daimler-Benz has evaluated an advanced hydro-pneumatic EGR system, developed by Bosch, on 10 of its diesel engines (Ref. 3-18). In the Bosch system, both air and fuel flows are sensed and used as system inputs for intake air and EGR flow rates (Ref. 3-19). The tests revealed a number of system problems which are attributed by DB to heating of the fuel in the injection pump, resulting in a power loss due to the lower fuel density, and in difficulties related to metering fuel due to clearance variations as a result of thermal effects. It was felt by DB that correction of the fuel heating problem through the addition of a cooling circuit would require additional equipment on a system which is already very complex. Therefore, no further efforts will be expended by DB on this particular system. Currently, DB's principal efforts involve the development of three electronically controlled systems. The Stage 1 system senses engine speed, load, ambient air conditions, and coolant temperature, while the Stage 2 system adds inputs from air and fuel flow sensing devices. The Stage 3 system provides for total electronic control of fuel injection and EGR, and includes a CO₂ or O₂ sensor in the exhaust to detect fuel-air ratio. Prototypes of the Stage 1 and Stage 2 systems have been built and are being tested. Stage 3 is undergoing preliminary evaluation, although a suitable exhaust gas sensor has not yet been identified.

Current plans for 1982 Model Year 300D and 300SD automobiles to be sold in California call for the use of an advanced version of the 1980 Model Year system, which is currently calibrated to meet 1.5 g/mi NO_x emissions standards for 100,000 miles. The 1982 system will be used initially in California vehicles only, and will be calibrated to meet the 1.0 g/mi NO_x standard.

GM has expended considerable efforts aimed at the development of an EGR system which is modulated by throttle position (Ref. 3-20). This system was tested by GM on the Oldsmobile 260 CID and 350 CID engines, and on the Opel 128 CID engine. On all three engines, it was possible to reduce NO_x to less than 1 g/mi at low vehicle mileage. However, the use of EGR resulted in durability and driveability problems, accompanied by higher HC, CO and particulate emissions, as shown in Table 3-2. Wear in the valve train was especially severe, with intolerable wear being noted in the rocker arms, cam lobes and cam followers. However, these problems may be eliminated by means of design modifications.

TABLE 3-2. EFFECT OF EGR ON EMISSIONS OF GM DIESEL AUTOMOBILES - LOW MILEAGE (Ref. 3-20).

	Inertia Wt, lb.	Emissions, g/mi			
		HC	CO	NO _x	Part.
Emissions Standards	— —	0.41	3.4	1.0	0.60
Experimental Target	— —	0.25	2.5	0.75	0.40
Best 5.7L (Car 96558)	4500				
Baseline		0.26	1.14	1.71	0.30
With EGR		0.30	1.76	0.77	0.64
Best 4.3L (Car 72204)	4000				
Baseline		0.28	0.83	1.59	0.22
With EGR		0.47	1.93	0.74	0.63
Best 2.1L Car (64370)	3000				
Baseline		0.23	0.90	1.22	0.28
With EGR		0.27	1.30	0.81	--
Best 2.1L (Car 66360)	2500				
Baseline		0.22	0.72	1.38	0.41
With EGR		0.22	0.79	0.76	0.44

Peugeot's current plans are to use a hydraulically controlled EGR system for model years 1981 through 1984 (Ref. 3-12). In addition to extensive testing of the Bosch system (Ref. 3-19), Peugeot has been involved in the development of an electro-pneumatic system. However, Peugeot feels that an electronically controlled EGR system might be required, in conjunction with an as yet undeveloped particulate filter, to simultaneously meet NO_x and particulate standards of 1.0 g/mi and 0.6 g/mi, respectively, in its production vehicles. A particulate standard of 0.2 g/mi is not considered by Peugeot to be achievable in 3500 lb inertia weight automobiles at the 1 g/mi NO_x level.

Test data from VW's 2250 lb and 3000 lb inertia weight vehicles, operated with EGR, are presented in Table 3-3 (Ref. 3-21). In the case of the 2250 lb Rabbit the addition of low EGR flow rates resulted in a 17 percent

reduction in NO_x , accompanied by small to moderate increases in HC and particulate emissions. On the Audi, similar trends were observed for low EGR rates, while high rates of EGR resulted in large increases in HC, CO, and particulates. In addition, the use of high EGR rates was associated with a reduction in fuel economy, a degradation in driveability, and an increase in wear of vital engine parts. In light of these problems, VW has serious doubts regarding the viability of EGR as a NO_x control technique in diesel engines.

TABLE 3-3. EFFECT OF EGR ON EMISSIONS OF DIESEL POWERED VOLKSWAGEN AUTOMOBILES (Ref. 3-21).

Vehicle	Inertia Wt, lb.	EGR Rate	Emissions, g/mi			
			HC	CO	NO_x	Part
Rabbit, 1.5L	2250	Zero	0.34	1.34	1.03	0.37
Rabbit, 1.5L	2250	Low	0.42	1.22	0.85	0.39
Audi, 2.0L	3000	Zero	0.39	1.71	1.60	0.68
Audi, 2.0L	3000	Low	0.42	1.26	1.37	0.75
Audi, 2.0L	3000	High	1.31	4.48	1.14	1.00

3.3.1.1 Durability Aspects of EGR

The use of EGR with a diesel engine has been shown to have unfavorable effects on engine durability, primarily due to contamination of the engine oil by particulate matter. GM has evaluated engine wear resulting from the use of EGR in its 2.1 liter Opel and 350 CID Oldsmobile diesels. After completion of 50,000 mile Automobile Manufacturers Association (AMA) durability tests, tear-down of the Opel engine revealed excessive wear of piston rings, ring grooves, cylinder bores, and camshaft lobes. Of the three piston rings, the oil control ring showed the most wear, with the groove clearance 68 percent over the maximum allowable clearance. Conversely, similar Opel engines operating without EGR showed negligible wear in similar tests. In the Oldsmobile diesel the use of EGR resulted in similar piston ring and valve train wear characteristics.

In addition to engine wear, the use of EGR has resulted in the occurrence of inlet system and valve wear. Tests performed by Ricardo Consulting Engineers on turbocharged diesel engines indicate the deposition of oily, sooty matter on the compressor blades and in the intake tract as a result of EGR admission. This accumulation caused a gradual drop in boost pressure with mileage accumulation (Ref. 3-21).

3.3.1.2 Summary

Prototype engine testing has demonstrated that the use of EGR can reduce diesel NO_x emissions to levels below 1 g/mi, even in large vehicles, such as the full size Oldsmobile equipped with a 350 CID engine. However, at this time the use of large amounts of EGR is considered by many experts to be unsuitable for production vehicles, because of related engine durability and driveability problems. In addition, EGR results in higher emissions of HC, CO, and particulate matter. In order to achieve the 1 g/mi NO_x level, careful optimization of injection timing and EGR system operation is required.

3.3.2 Water Addition

The presence of water during the combustion process has been shown to cause changes affecting fuel consumption, output power, and exhaust emissions of diesel engines (Ref. 3-22). Water introduced as an aerosol with the intake air acts as a charge diluent and, due to its high heat of vaporization, results in a reduction of temperatures and pressures at the end of the compression stroke and at the start of combustion. The resultant reduction in peak combustion pressures, temperatures, and oxygen availability during combustion causes a decline in the NO_x formation rates. Water introduced with the fuel in the form of an emulsion causes changes often associated with the so-called "micro-explosion" phenomenon. In the micro-explosion phenomenon, small droplets of water emulsified within the larger droplets of fuel are subject to early vaporization within the droplet's lifetime. This early vaporization process can be sufficiently destructive to shatter the larger droplets into many small fragments. The resultant increase in evaporative surface area, and improved atomization, increases burn rate and reduces the formation of sooty residues (Ref. 3-23). An increase of either water content or mean water particle size was found to enhance the violence of these processes (Ref. 3-24).

While some believe that ignition delay, caused by evaporation of the water, is the primary mechanism affecting the reduction of NO_x , calculations using an elementary kinetic mechanism for methane oxidation suggest that water addition may reduce NO_x formation by chemical inhibition (Ref. 3-25). These analyses indicate that water addition caused an increase in the maximum hydroxyl radical concentration and a corresponding decrease in the oxygen atom concentration. This effect would tend to limit the formation of NO_x , suggesting that a reduction would occur even at constant combustion temperature (Ref. 3-23). It has also been suggested that water incorporated in an emulsion may reduce soot formation by means of chemical mechanisms (Ref. 3-26). One of the benefits of emulsification, in comparison to induction as an aerosol with the air charge, is that the water is carried to the proper locations, where radicals such as OH can attack the soot precursors.

Vehicle tests utilizing water additions for NO_x reduction were conducted by both DB and GM. Water induction via the air intake system was investigated by DB while GM worked with emulsions. Both systems of water addition were used in conjunction with EGR. One of the DB systems studied utilized a variable choke carburetor and an electronically controlled valve to modulate water flow in accordance with engine speed and load. In this case the use of water injection reduced NO_x emissions by about 60 percent (Ref. 3-8). However, as shown in Table 3-4, this technique resulted in large increases in HC and CO emissions, while combined cycle fuel economy decreased by about 7 percent.

The other system investigated by DB utilized water injection upstream of the turbocompressor, with water flow controlled by a throttle valve switch. In this system, there was no water injection during vehicle deceleration, or when engine speed exceeded 3500 rpm. This water injection system also produced large NO_x reductions at the expense of higher HC and CO levels. However, in this case a fuel economy gain of about 5 percent was achieved.

GM investigated emulsions of up to 30 percent water, and found that best results were obtained with 10 to 15 percent water. In these tests, the emulsions were produced by the aid of a surfactant or an emulsifier which was located between the fuel pump and injector pump. Engine dynamometer test data from several engines, operated over a range of load conditions, indicated NO_x

TABLE 3-4. EFFECT OF WATER INJECTION ON DIESEL ENGINE EMISSIONS AND FUEL ECONOMY (Ref. 3-8).

Engine and Water Addition System	Inertia Weight, lb	Config-uration	Emissions, g/mi			Combined Fuel Economy, mpg
			HC ⁽¹⁾	CO	NO _x	
Naturally Aspirated, Carburetion	3500	Baseline plus EGR	0.08	0.78	0.88	31.3
		EGR plus Water	0.35	2.66	0.36	29.11
Turbocharged, Injection	4000	Baseline	0.06	0.76	1.49	28.4
		EGR plus Water	0.16	1.93	0.29	30.0
(1) Non-heated lines to FID.						

reductions of 15 to 40 percent, accompanied by particulate emissions reductions of 25 to 35 percent and increases in HC of about 10 to 100 percent (Ref. 3-3). Interestingly, tests over the Federal Urban Driving Cycle showed NO_x reductions of only 7 percent, while fuel economy decreased by 4 percent. The fuel utilized in these tests contained 10 percent water, formed both with and without the use of a surfactant.

In another series of tests, performed at the Ontario Research Foundation, an onboard emulsification system was investigated (Ref. 3-25). Tests results supported other studies showing that, although water-in-fuel emulsions could reduce NO_x and smoke emissions significantly, success is dependent on the combustion chamber design, injector type, injection pressure, and other general engine design parameters. As shown in Figure 3-16, equivalent NO_x reductions in a 2-stroke DI Detroit Diesel 8V 71N engine required substantially larger amounts of water than did a 4-stroke IDI Deutz Diesel F6L 714 engine (Ref. 3-25). For example, the 8V 71N engine required an addition of about 45 percent water to reduce NO_x by 50 percent, while this was accomplished in the F6L 714 engine with less than 20 percent water. However, in the case of the

FIGURE 3-16. EFFECT OF WATER EMULSIONS ON DIRECT AND INDIRECT INJECTION DIESEL ENGINES (Ref. 3-25).

2-stroke engine, water induction in the form of an aerosol resulted in larger NO_x reductions than with emulsions, as shown in Figure 3-17 (Ref. 3-25).

Although water injection appears to be a powerful NO_x reduction technique, a number of critical problem areas mitigate against its use for automobile engine applications. These problems include potential corrosion of all system parts in contact with water or water vapor, added equipment and complexity, packaging and space requirements of a water storage tank, fillup procedures, freeze protection, and oil dilution (Ref. 3-8).

3.3.3 Aftertreatment Devices

Although particulate removal from the exhaust is not the most desirable approach, as it requires add-on devices and does not alleviate

FIGURE 3-17. EFFECT OF WATER ADDITION METHOD ON NO_x EMISSIONS OF A 2-STROKE DIRECT INJECTION DIESEL ENGINE (Ref. 3-25).

the lube oil contamination problem, this technique has received increasing emphasis because of the difficulties in solving the particulate problem within the combustion chamber. Centrifuges, water scrubbers, electrostatic precipitators, oil bath filters, and molten salt baths have been considered by a number of investigators, but appear to be impractical for automotive applications.

The most promising particulate control technique appears to be the use of exhaust traps and trap oxidizer systems. To date, numerous trap designs have been considered by the automobile manufacturers and other organizations. In these devices, the particulate matter in the engine exhaust is collected in a filter or trap incorporated in the exhaust system, with periodic regeneration of the collection device by cleaning, disposal, or oxidation of the collected matter. However, problems in implementing this approach arise from the large amount of low density particulate matter emitted, which results in rapid loading and clogging of the collection device, with a subsequent loss in

collection efficiency and increase in exhaust backpressure. This is illustrated in Figure 3-18, showing the performance of two oxidizing traps operated over a low mileage range (Ref. 3-17 and 3-27).

FIGURE 3-18. PERFORMANCE OF OXIDIZING PARTICULATE TRAPS AT LOW MILEAGE (Refs. 3-17 and 3-27).

The volume of particulate matter to be collected can be substantial, with GM reporting particulate density values in the range of 0.07 to 0.10 g/cc (Ref. 3-17). For typical light-duty diesel engines with particulate emissions of 0.5 g/mi, the corresponding particulate volume amounts to about 1.3 to 1.9 gallons per 1000 miles. At these levels, disposal traps appear to have limited applicability. While the use of periodic trap regeneration would be a more desirable approach, the development of a practical system of this type is expected to be difficult.

The following paragraphs summarize the efforts of diesel engine manufacturers in developing exhaust aftertreatment devices. GM is evaluating a wide range of aftertreatment techniques, while VW, working with Ricardo, is concentrating its particulate control efforts in the area of trap oxidizers.

Very limited information is available from other manufacturers. Thermal reactors, which have been successfully employed in spark ignition engines, are not considered to be feasible for light-duty diesel engines, because of the relatively low exhaust gas temperatures, and the low HC and CO concentrations characteristic of diesels.

To date, DB has experienced only limited success with particulate filters and trap oxidizers. Although initial particulate reductions up to 80 percent were achieved with clean filters, it was found that filter efficiency and backpressure deteriorated within a few hours of operation as a result of filter clogging (Ref. 3-28). In tests with several trap oxidizers, it was determined that incineration of the collected particulate matter required minimum exhaust gas temperatures of about 850°F for a silver catalyst based trap. These temperatures are well above those usually reached in urban driving, as shown in Table 3-5 for a Mercedes 300D automobile operated over the 1975 FTP test cycle. As indicated, there is only a limited amount of time when the exhaust temperature would be high enough to achieve incineration of the trapped particulate matter. A turbocharged engine would be expected to have even lower exhaust gas temperatures. Thus, the use of trap oxidizer systems of current design appears to be impractical, unless exhaust gas temperature is raised significantly by external means. Initial trap durability tests performed by DB in-

TABLE 3-5. EXHAUST GAS TEMPERATURE VERSUS TIME DISTRIBUTION --
MERCEDES 300D AUTOMOBILE, URBAN CYCLE TEST (Ref. 3-28).

Exhaust Gas Temperature Range, °F	Percent of Time
302 - 392	41.7
393 - 482	17.1
483 - 572	12.4
573 - 752	11.2
753 - 932	6.4
Above 933	1.5

dicade serious problems. A trap oxidizer was mechanically destroyed in a 300D vehicle after only 9300 miles of operation (Ref. 3-29). In this test, particulate emissions rose from 0.04 g/mi at zero mileage to 0.17 g/mi at 9300 miles. Adverse fuel economy effects were noted by DB in some of its tests. In a 240D vehicle, combined cycle fuel economy dropped from 30.6 mpg without a trap oxidizer to 27.2 with the device at low mileage.

At Fiat, a limited amount of testing has been performed to date, using monolithic oxidation catalysts in conjunction with both naturally aspirated (NA) and turbocharged (TC) engines (Ref. 3-15). As shown in Table 3-6, the use of the catalysts A and B resulted in the expected reduction in HC and CO emissions, although total particulate mass emitted increased. However, an analysis of particulate composition revealed a reduction in the organic fraction and an increase in sulfate emissions. Since the fuel employed in these tests had a high sulfur content of 0.6 percent by weight, these results are not typical of data which might be obtained with a low sulfur diesel fuel. Data on system durability and system backpressure are not available.

TABLE 3-6. EFFECT OF OXIDATION CATALYSTS ON EMISSIONS OF NATURALLY ASPIRATED AND TURBOCHARGED FIAT DIESEL VEHICLES (Ref. 3-15).

Engine Type	Catalyst Type	Emissions, g/mi					
		HC	CO	NO _x	Total Part.	Carbon and Organics	Sulfates
NA	None	0.99	1.94	0.94	0.678	0.505	0.169
NA	A	0.55	0.60	0.99	0.750	0.530	0.220
NA	B	0.36	0.33	1.01	1.25	0.445	0.805
TC	None	0.28	1.33	1.47	0.53	--	--
TC + EGR	B	0.20	2.1	1.20	0.78	--	--
European diesel fuel with 0.6 percent sulfur content. 3000 lb inertia weight.							

GM has evaluated a number of different particulate removal devices, including disposable paper filters, electrostatic precipitators, oil-bath filters, washable filters, and traps which employ periodic incineration to eliminate collected particulate matter (Ref. 3-17). Paper filter elements have shown good initial collection efficiencies, in the range of 80 percent. However, after about 700 miles, the filter was loaded up with particulates, and the backpressure increased while collection efficiency declined significantly. In addition to clogging, other problems encountered include rupture of the paper element, and unintended burning and destruction of the filter. Development efforts continue in this area, with emphasis on developing high temperature materials and high volume utilization.

Electrostatic precipitators were tested by GM on an Opel 2100D automobile. The objective of these tests was to concentrate 90 percent of the particulates into 10 percent of the exhaust flow. However, the best performance achieved has been 50 percent of the total particulate mass emitted in 16 percent of the flow. The power requirements for this device were 60 watts at 12,000 volts, but performance was impaired because particulates quickly coated all surfaces exposed to exhaust gas. A technique for particulate removal from the precipitator would be required before the concept has any utility. The use of a modified oil bath air cleaner in the Opel 2100D resulted in a 50 percent increase in particulates. This was apparently due to oil being atomized and carried out with the exhaust stream. In order to identify the maximum potential of an oil bath device, GM used a 30 gallon container to reduce flow velocity. Even with this impractically large device, only a 20 percent particulate reduction was achieved.

GM has experimented also with the use of serviceable filters which would be removed from the vehicle and regenerated. However, cleaning of the filters with soap and water, or with mineral spirits, has not proved to be effective. Ongoing efforts are investigating the feasibility of cleaning the filters with backward pulsed air flow or by chemical dipping. Also being considered is the treatment of the paper filter element with a fine powder, which is intended to block the particulates from entering the pores of the paper, allowing the particulates to be removed more easily.

In-situ regeneration of a trap has been found by GM to be the most effective method of trap regeneration. However, means must be provided to increase the exhaust temperature up to the incineration threshold of about 900°F. This may be accomplished either by inlet throttling or by an electric heating element in the exhaust system. However, both of these methods have an adverse impact on fuel economy.

While oxidation catalysts were found by GM to have some value in reducing HC and CO emissions, test data indicate no reduction in total particulates. This trend, which agrees with Fiat's data shown in Table 3-6, is the direct result of a significant increase in sulfate emissions associated with the use of exhaust catalysts.

VW has employed the services of Ricardo Consulting Engineers in the development and testing of different particulate trap designs (Ref. 3-27). To date, many different traps were tested, some of which use metallic filters similar to steel wool, while others are of the surface scrubber type. In addition, tests were conducted with platinized catalytic coatings, furnished by Johnson-Matthey, to promote incineration of the collected particulate matter. The performance of seven of these traps is summarized in Table 3-7 (Ref. 3-27). Except for Box No. 7, no significant mileage was collected on any of these traps. The best particulate reduction achieved was 59 percent with Box No. 7, which used a platinized catalytic coating on stainless steel wool. Box No. 2, which used steel wool as its filtering medium, had the second highest particulate filtering efficiency at 40 percent. However, the material inside the box ignited while the test vehicle was ascending an 8 percent grade at 60 mph, and the engine compartment was severely damaged from the ensuing fire. In durability testing, Box No. 7 experienced a partial failure before 600 miles, and total failure after 1200 miles. Disassembly of the unit revealed that an internal deflector plate had been destroyed, and that the rear cover had broken away from internal and external tubes in the filter. As a result of these failures the exhaust flow bypassed the filter element. The test unit was fabricated from mild steel, and the use of stainless steel or some other temperature resistant alloy might alleviate this problem.

As reported by VW, Johnson-Matthey Research has performed vehicle testing of two catalytic particulate filter systems (Ref. 3-27). According to

TABLE 3-7. SUMMARY OF VW PARTICULATE TRAP DATA AT LOW MILEAGE
(Ref. 3-27).

Box No.	Filter Type	Back-Pressure	Parti- culates	Organics	Sulfates
1	Surface Scrubber, ICE Saffil	191	-15	-31	--
2	Radial Flow Filter, Medium-Grade Steel Band Wool	55	-40	-38	--
3	Surface Scrubber, Platinized Catalyst	208	-16	-33	93
4	Surface Scrubber, Low Backpressure Design	50	- 5	- 9	-34
5	Radial Flow Filter, Fecraloy Wire Mesh	17	-11	- 3	-28
6	Radial Flow Filter, Grade 2 Stainless Steel Band Wool	8	-32	- 9	-45
7	Radial Flow Filter, Grade 2 Stainless Steel Wool, Platinized Coating	-15	-59	-70	0

Table 3-8, Filter A achieved a reduction in particulates of 11 percent at low mileage, and some reduction in HC and CO. However, these improvements were accompanied by a dramatic increase in system backpressure and sulfate emissions, and an 8 percent loss in fuel economy. Filter B, which is larger than Filter A but has the same precious metal loading, shows significantly higher initial particulate removal effectiveness. However, after completion of 1800 miles of durability testing under severe conditions, examination of the unit showed that the observed performance degradation was due to mechanical failure of the catalyst, and not due to fouling or poisoning of the active surfaces.

Based on a comprehensive examination of available information, it is concluded that paper filters, servicable filters, electrostatic precipi-

TABLE 3-8. EMISSIONS RELATIVE TO BASELINE OF AUDI 100 AUTO-MOBILE TESTED WITH JOHNSON MATTHEY CATALYTIC PARTICULATE FILTERS (Ref. 3-27).

Filter System	A	B		
Catalyst Age, mi	Low	0	50	1800
Total Particulates	-11	-41	-39	-21
HC	-42	-68	-66	-46
C	- 4	-25	-22	- 6
Sulfates	+318	- 9	-29	- 5
Gaseous HC	-36	-43	-28	-38
CO	-35	-68	-45	-48
NO _x	+ 8	+17	- 1	-10
Fuel Economy	- 8	+ 1	+ 5	-
Backpressure	+621	- 2	+ 5	-

tators, and oil bath filters have not yet been demonstrated to be practical or effective in reducing particulate emissions from diesel engines. Conversely, particulate trap oxidizer systems with in-situ regeneration through oxidation have shown promise. However, a number of currently severe problem areas must be resolved before catalytic traps can be seriously considered for use in production vehicle applications. These include (1) demonstration of 50,000 mile durability, (2) management of uncontrolled particulate combustion, (3) modification of test procedures, (4) reduction of sulfate emissions, (5) reduction of catalyst light-off temperature, and (6) development of a viable control system.

3.3.4 Turbocharging

The power output of naturally aspirated diesel engines is generally limited by smoke. The smoke problem can be alleviated by means of a turbocharger, which permits an increase in the air-fuel ratio as a result of an increase in the air flow rate supplied to the engine. In this case, HC

emissions reductions up to 30 percent have been achieved, at the expense of moderate increases in NO_x emissions and fuel consumption (Refs. 3-1 and 3-20). Conversely, the use of turbocharging in conjunction with an increase in the capacity of the fuel injection system increases the power output capability of the engine to levels typical of naturally aspirated spark ignition engines.

Test data from a number of experimental and production diesel automobiles are presented in Table 3-9, showing the effects of turbocharging, combined with variations in engine displacement and rear axle ratio, on vehicle fuel economy and 0-60 mph acceleration time. As indicated, the acceleration performance of the turbocharged Mercedes-Benz and Peugeot production vehicles is significantly higher than for the corresponding naturally aspirated vehicles, accompanied by small variations in fuel economy. Data from experimental Fiat and Volkswagen vehicles show substantial performance and fuel economy improvements and, at equal performance, the VW/Audi data show an even larger improvement in fuel economy. It should be noted, however, that additional design changes were incorporated in some of the turbocharged engines, including modi-

TABLE 3-9. PERFORMANCE OF TURBOCHARGED DIESEL VEHICLES WITH MODIFIED FUEL INJECTION SYSTEMS AND REAR AXLE RATIOS.

VEHICLE	IW, lb	NA/TC	HORSE-POWER	CID	COMBINED mpg	0-60 mph, sec
VOLKSWAGEN	2250	NA	50	90	41	18.3
		TC	70	90	45	12.7
VW/AUDI	3000	NA	66	130	33	17.6
		TC	70	90	40	17.4
FIAT	3000	NA	70	149	35	17.7
		TC	85	149	40	13.9
GM PRE-X CAR	3000	NA	--	120	36	19.9
		TC	--	128	38	18.0
PEUGEOT	3500	NA	69	140	30	20.2
		TC	81	140	29	17.8
MERCEDES	4000	NA	77	183	25	17.1
		TC	110	183	26	12.7
OLDSMOBILE	4500	NA	120	350	22	18.5
		TC	--	260	22	17.3

fied valve timing, compression ratio, fuel injection timing, injection pressure and injection rate. The effects of these modifications on vehicle fuel economy must be taken into account before a meaningful assessment can be made of the energy conservation benefits associated with turbocharging.

In general, the transient response of a turbocharged engine is inferior to that of a naturally aspirated engine of equivalent power. This is due to the time required to accelerate the turbocompressor before an increase in boost pressure can be realized. Two different approaches are available to improve the response of a turbocharger: employing a waste gate or using variable geometry turbine nozzles (Ref. 3-30). For an engine which spends most of its time operating at light loads, the waste gate is a simple and attractive method of matching the turbocharger to the engine. It does result in a loss of efficiency at high power levels, when a portion of the exhaust stream is diverted around the turbine. A variable geometry nozzle assembly for the turbine avoids this loss of efficiency at high power, but results in a more complex and expensive turbine housing.

While turbocharging is an effective means of upgrading an existing engine line to a higher power rating, it does require many engine and vehicle changes. For example, turbocharging imposes higher mechanical loads on the engine, which will generally require strengthening of the crankshaft, connecting rods, bearings, and possibly the cylinder block and head. Increased thermal loads require the use of a larger radiator, and may also require cooling of the pistons with oil, and the addition of an oil cooler. This discussion clearly shows that the incremental cost of a reliable, well designed turbocharged engine system is considerably more than the cost of a turbocompressor.

According to GM the cost of turbocharging a V-6 or V-8 diesel engine is about \$330, including dealer markup but excluding manufacturer profits (Ref. 3-17). Peugeot believes that the premium for its supercharged 2.3 liter diesel engine will be from \$500 to \$1000, because the cost of turbocharging the 2.3 liter engine is considered by Peugeot to be comparable to that of developing a new naturally aspirated engine, which would have a displacement of about 3.0 liters (Ref. 3-31).

Current development efforts in the area of diesel turbocharging conducted by the automobile industry are briefly described in the following two subsections.

3.3.4.1 Conventional Turbocharger Configurations

According to DB, the use of turbocharging alone has no beneficial effect on particulate emissions. However, particulate data from the certification models of the Mercedes 300D and 300SD vehicles have been interpreted by the EPA to indicate that turbocharging caused a reduction in particulate emissions. DB explains the observed reduction in particulates with turbocharging as the direct result of modifications in prechamber geometry, injection timing, and other injection system characteristics, as well as due to atypical particulate emissions levels in the 300D certification vehicle (Ref. 3-27).

Fiat has investigated the effects of turbocharging its 2445 cc light-duty diesel engine (Ref. 3-2). In addition to adding a Garrett T3 turbocharger, a larger capacity injector pump was fitted, injection timing was retarded, and the rear axle ratio was lowered. Emissions and performance data of this engine, when installed in a 3000 lb inertia weight automobile, are presented in Table 3-10. The data points showing particulate emissions were taken on the chassis dynamometer in accordance with the 1975 Federal Test Procedure, while the other data simulate this procedure by using a weighted average of several steady-state points. The turbocharged engine produced lower levels of particulates, HC, CO, and surprisingly, NO_x. The lower level of NO_x is probably due to retarded injection timing used in the calibration. Fuel economy was marginally better with the turbocharged engine, which may be attributed to the use of a lower axle ratio. In spite of the lower axle ratio, the acceleration performance of the turbocharged engine was superior to that of the naturally aspirated baseline version. In addition, Fiat investigated the effects of EGR and oxidation catalysts on the emissions of these engines, as shown in Table 3-11 (Ref. 3-2). As expected, particulate emissions increased with the introduction of EGR. It is interesting to note the large increase in particulates emissions resulting from the addition of an oxidation catalyst. This increase is attributed to the increased conversion of sulfur dioxide to sulfates in the presence of the catalyst. However, the use of the catalyst resulted in a reduction in the organics adsorbed on the particulate matter.

TABLE 3-10. EMISSIONS, FUEL ECONOMY, AND PERFORMANCE PROJECTIONS FOR NATURALLY ASPIRATED AND TURBOCHARGED DIESEL VEHICLES -- 3000 LB INERTIA WEIGHT (Ref. 3-2).

Engine	Rear Axle Ratio	Emissions, g/mi				Fuel Economy, mpg		Top Speed, mph	0-60 mph Accel, sec
		HC	CO	NO _x	Partic.	Combined	Urban		
Naturally Aspirated	2.8	0.29	1.48	1.50	--	37.9	34.5	97	18.1
	3.0	0.30	1.58	1.50	--	36.4	33.2	95	17.9
	3.2	0.31	1.68	1.60	0.55	35.0	32.0	91	17.7
	2.4	0.27	1.28	1.36	--	39.8	37.1	105	13.9
Turbocharged	2.6	0.28	1.33	1.47	0.36	37.7	35.0	105	13.8
	2.8	0.29	1.36	1.59	--	35.7	33.1	102	13.7

TABLE 3-11. EXHAUST EMISSIONS AND FUEL ECONOMY OF DIFFERENT ENGINE CONFIGURATIONS - 3000 LB INERTIA WEIGHT VEHICLES, EUROPEAN DIESEL FUEL (Ref. 3-2).

Engine Configuration	Rear Axle Ratio	Emissions, g/mi				Combined Fuel Econ, mpg
		HC	CO	NO _x	Partic.	
Naturally Aspirated (NA)	3.2	0.31	1.68	1.60	0.55	34.6
NA Plus Oxidation Catalyst (OC)	3.2	0.36	0.33	1.01	1.25	34.5
Turbocharged (TC)	2.6	0.28	1.33	1.47	0.36	36.3
TC Plus OC	2.6	0.31	2.67	1.19	0.53	35.6
TC + OC + EGR	2.6	0.20	2.10	1.20	0.78	35.6

Experiments performed by GM indicate that the use of a turbo-charger has little effect on fuel economy and emissions of diesel automobiles. As shown in Table 3-12, the addition of a turbocharger without a simultaneous change in fuel injection pump capacity and rear axle ratio resulted in a 6 per-

TABLE 3-12. EFFECTS OF TURBOCHARGING, FUEL SCHEDULES, AND AXLE RATIO ON THE PERFORMANCE OF A DIESEL AUTOMOBILE (Ref. 3-17).

Engine Configuration ⁽¹⁾	Axle Ratio	Emissions, g/mi				Fuel Economy, mpg	0-60 mph Acceleration, sec
		HC	CO	NO _x	Part		
NA ⁽²⁾	4.15	0.49	1.32	0.95	0.23	35.7	19.9
TC ⁽²⁾	4.15	0.47	1.33	1.14	0.24	33.6	19.7
TC ⁽³⁾	4.15	0.47	1.36	1.13	0.28	33.3	14.7
TC ⁽³⁾	3.74	0.37	1.07	1.10	0.25	34.6	17.2
TC ⁽³⁾	3.34	0.35	1.17	0.94	0.23	37.8	18.0
<p>(1) Combined cycle.</p> <p>(2) Injection pump calibrated for naturally aspirated engine.</p> <p>(3) Injection pump with higher delivery rate per stroke; calibrated for turbocharged engine.</p>							

cent loss in fuel economy and a 20 percent increase in NO_x emissions (Ref. 3-17). However, incorporation of a larger injection pump provided a substantial improvement in vehicle acceleration performance, at the expense of moderate increases in NO_x, particulates, and fuel consumption. Simultaneous reduction in the rear axle ratio from 4.15 to 3.34 resulted in exhaust emission levels similar to those of the naturally aspirated baseline configuration, accompanied by a 6 percent reduction in fuel consumption. Based on these particular tests, turbocharging provides no benefits in terms of gaseous and particulate emissions control. However, it is not known to what degree injection timing, manifold pressure/wastegate setting, or transmission ratios were optimized by GM in the different vehicle configurations.

Peugeot has recently introduced its turbocharged 2.3 liter diesel powered 604 series automobile in the United States. According to Peugeot, many modifications were required to the original 2.3 liter naturally aspirated

engine. For example, oil cooling of the pistons was added, along with a piston alloy with higher conductivity, and a cast iron insert was incorporated to hold the upper compression ring. An oil cooler was also added, and the radiator area was increased by 25 percent. The oil flow rate was increased by 70 percent to provide for the increased demands of piston cooling and turbocharger lubrication. Also, several structural changes were made to the engine, including an increase in crankpin diameter, a wider crank arm, and a strengthened connecting rod. The addition of the turbocharger did not reduce particulate emissions, as shown in Table 3-13, although HC and CO emissions are lower for the TC engine, while NO_x is considerably higher, and fuel economy slightly lower.

TABLE 3-13. EXHAUST EMISSIONS AND FUEL ECONOMY OF PEUGEOT DIESEL AUTOMOBILES (Refs. 3-10 and 3-32).

Vehicle	Engine	IW, lb	Emissions, g/mi				Fuel Economy ⁽¹⁾ , mpg
			HC	CO	NO _x	Part	
504D	2.3L NA	3500	0.87	1.69	1.16	0.29	27.3
604D	2.3L TC	4000	0.30	1.5	1.8	0.35	26
(1) Urban Cycle.							

Ricardo Consulting Engineers have retrofitted a Mercedes 300D diesel automobile with a turbocharger and EGR system to determine the emissions and fuel economy characteristics of such a vehicle (Ref. 3-1). Special manifolds were fitted to accommodate the modifications, but otherwise there were no changes made to the engine. Consequently, the experimental vehicle was unlike the Mercedes Benz 300SD, which uses a higher capacity injection pump, different injector nozzles, a modified prechamber configuration, a numerically lower axle ratio, and specific engine modifications to better withstand the higher structural and

thermal loads resulting from turbocharging (Ref. 3-33). Some of the Ricardo data are presented in Table 3-14, showing higher NO_x and lower HC and particulates emissions for the turbocharged configuration. The addition of EGR resulted in large increases in particulate emissions, fuel consumption, and 0-60 mph acceleration time, while NO_x was reduced significantly, particularly when combined with fuel injection retard.

TABLE 3-14. EFFECTS OF TURBOCHARGING AND EGR ON THE PERFORMANCE OF A MERCEDES 300D AUTOMOBILE (Ref. 3-1).

Vehicle	Emissions, g/mi				Urban Mpg	0-60 mph Acceleration, sec
	HC	CO	NO _x	Part.		
Standard 300D	0.183	0.94	1.66	0.8	24.3	21.2
Turbocharged	0.14	0.94	1.75	0.5	23.8	22.4
TC, EGR Mod C ⁽¹⁾	1.053	2.956	0.379	1.228	18.86	25.3
TC, EGR Mod D	0.226	1.563	0.961	1.59	20.08	22.6
TC, EGR Mod D ⁽²⁾	0.171	1.329	1.52	0.964	20.28	20.5
(1) Injection retarded 4 deg.						
(2) 2 mm EGR valve lift.						

Test data provided by VW and reproduced in Table 3-15, show that turbocharging alone is not effective as a particulate control technique (Ref. 3-27). It should be noted, however, that no information was provided by VW regarding any other changes that might have been incorporated in the fuel injection system and power train. Theoretical studies performed by VW indicate that turbocharging can reduce particulate emissions levels in those cases where the naturally aspirated version of the engine is underpowered. The addition of a turbocharger would then raise the smoke-limited power level above the requirements of the urban cycle.

3.3.4.2 Advanced Turbocharging Concepts

In addition to ongoing efforts in the area of improved conventional turbochargers for potential use in both light-duty and heavy-duty diesel engines, a number of organizations are involved in the development of novel

TABLE 3-15. EMISSIONS OF NATURALLY ASPIRATED AND TURBOCHARGED VW DIESEL RABBIT VEHICLES - 2250 LB INERTIA WEIGHT, 4-SPEED MANUAL TRANSMISSION (Ref. 3-27).

Engine Type	Emissions, g/mi			
	HC	CO	NO _x	Part.
Preproduction, Naturally Asp.	0.35	1.50	1.21	0.30
Developmental Turbocharged	0.32	1.42	1.21	0.36

turbocharger concepts. The Compres Pressure Wave Supercharger, under development by Brown Boveri primarily for heavy-duty diesels, falls in that category. In this device, shown schematically in Figure 3-19, energy from the exhaust gas is transfered to the incoming air by means of pressure waves generated

FIGURE 3-19. THE BROWN BOVERI COMPRES PRESSURE WAVE SUPERCHARGER (Ref. 3-34).

within its rotor (Ref. 3-34). The principal advantage of the Comprex concept relative to a conventional turbocharger is its ability to produce higher boost pressures at low engine speeds. In addition, transient response to increased power demand is considerably higher than that of conventional turbochargers since acceleration of the Comprex rotor is not required to produce increased boost pressure.

The performance characteristics of a Comprex Supercharger in an Opel 2100D vehicle was determined by Ricardo Consulting Engineers and compared with the performance of the naturally aspirated vehicle and a vehicle equipped with a Garrett AiResearch T3 turbocharger (Ref. 3-35). Pertinent test data from the three configurations are presented in Figure 3-20, showing the effects

FIGURE 3-20. PERFORMANCE OF TURBOCHARGED, COMPREX BOOSTED, AND NATURALLY ASPIRATED ENGINES (Ref. 3-35).

of engine speed on boost pressure, brake mean effective pressure, smoke emissions, and brake specific fuel consumption. Vehicle test data are listed in Table 3-16, presenting fuel economy, emissions, acceleration, and noise data for the three techniques investigated (Ref. 3-35). Although the fuel injection schedule was altered for the two supercharged configurations, the power trains

TABLE 3-16. TEST DATA FROM NATURALLY ASPIRATED, TURBOCHARGED, AND COMPREX EQUIPPED OPEL 2100D VEHICLES -- EUROPEAN DIESEL FUEL (Ref. 3-35).

	Naturally Aspirated	Turbo-charged	Comprex Boosted
<u>Fuel Economy, mpg</u>			
Urban Cycle	33.5	29.7	25.8
Highway Cycle	35.8	33.7	33.1
Steady 50 km/hr	49.3	43.3	42.0
Steady 90 km/hr	32.7	30.5	33.0
Steady 120 km/hr	19.6	18.0	23.2
<u>Gaseous Emissions, g/mi</u>			
HC	0.145	0.25	1.16
NO _x	0.99	1.24	0.66
CO	0.79	0.95	3.70
<u>Acceleration Times, sec</u>			
0-100 km/hr All gears	23.0	14.0	12.5
50-90 km/hr 3rd gear	10.0	7.0	5.9
90-100 km/hr 4th gear	19.7	10.2	7.9
<u>Noise, dB(A)</u>			
Internal; Steady 50 km/hr	65	68	64.5
Internal; Steady 80 km/hr	70	72	70.5
ISO R362 Driveby	77	79	80
Idle - Front	63	63.5	66.5

of the supercharged vehicles were not optimized by Ricardo for fuel economy. The Comprex equipped vehicle provided better acceleration and transient response than the turbocharged version, but at the expense of higher HC and CO emissions, lower fuel economy, and higher noise levels. NO_x emissions were quite low for the Comprex, suggesting that the Comprex might have "built-in" EGR, since the inlet and exhaust systems are directly connected through the rotor. In its current configuration, the Comprex is heavier, bulkier, and about twice the cost of a conventional turbocharger. While earlier versions of the Comprex emitted high siren-like noise, a new rotor configuration developed by Brown Boveri shows noise levels about equal to that of turbocharged engines.

Turbocompounding represents another advanced engine waste heat utilization technique, which is currently being developed by Cummins Engine Company under contract to the Department of Energy (Ref. 3-36). The system consists of a second turbine stage, which is added downstream of the conventional turbocharger. This turbine stage is geared directly to the engine crankshaft to supplement the shaft power output of the engine. Test data indicate an 8 percent improvement in specific fuel consumption at full power, declining to 1 percent at 30 percent load. This trend indicates that turbocompounding might be of greatest value in intercity trucks and buses, rather than automobiles or other light-duty vehicles.

3.4 FUEL MODIFICATIONS AND ADDITIVES

3.4.1 Fuel Effects

In addition to combustion chamber geometry, injection system characteristics, and engine operating parameters, the molecular structure of the fuel has a significant effect on the combustion process and the production of exhaust emissions (Ref. 3-37). Fuel composition is generally described by a number of physical characteristics, including (1) specific gravity or API gravity number, (2) viscosity, (3) boiling range or a number of boiling points, (4) cetane number, (5) sulfur and other impurities content, and (6) hydrocarbon family content, such as percentage paraffins, olefins, naphthenes, and aromatics (Refs. 3-37 and 3-38). As for hydrocarbon make-up, it is noted that the ring structured aromatics are very stable chemically (Ref. 3-39). Indeed, one member

of the aromatic family, alpha-methyl naphthalene, was once used as one of the primary reference fuels for diesel fuel testing, having an arbitrarily assigned value of zero cetane (Ref. 3-39). Of course, a number of these parameters are inter-related. For example, a high aromatic content produces low cetane fuels, and also results in high boiling points and high density (Ref. 3-37).

The response to changes in fuels characteristics cannot always be predicted, and is often affected by engine design and operating conditions. For example, tests of two different diesel automobiles, using five different fuels and eight different driving cycles, revealed that differences between vehicles and operating schedules can be greater than those between fuels (Ref. 3-40). These differences are illustrated in Tables 3-17 and 3-18 for particulate mass and benzo(a)pyrene (BaP) emissions. As shown, particulate mass emissions of the VW Rabbit, when tested over the cold FTP driving cycle, are lower than for the Mercedes 240D, for all fuels except the Minimum Quality No. 2 diesel fuel. Conversely, over the cold FTP the BaP content of the particulates was considerably lower for the Mercedes than for the VW, for any of the fuels tested. Also, while the Minimum Quality No. 2 diesel fuel produced the highest BaP level in the case of the Rabbit and cold FTP cycle, this fuel produced significantly less BaP at 50 km/h than the 2D Emissions Fuel and the

TABLE 3-17. PARTICULATE MASS EMISSIONS OF TWO VEHICLES, FOR FIVE FUELS AND EIGHT DRIVING CYCLES AND MODES (Ref. 3-40).

VEHICLE	FUEL	GRAMS PARTICULATE PER KILOMETER BY OPERATING CYCLE OR MODE								
		COLD FTP	HOT FTP	(CALCULATED) 1975 FTP	CFDS	FET	NYCC	STEADY STATES		
								IDLE ⁽¹⁾	50 kph	85 kph
MERCEDES 240D	EMISS. 2D	0.335	0.324	0.329	0.261	0.212	0.680	2.99	0.150	0.196
	NA (2D)	0.319	0.311	0.314	0.226	0.192	0.565	3.16	0.142	0.165
	JET A (1D)	0.251	0.223	0.235	0.166	0.140	0.317	1.50	0.114	0.136
	MIN 2D	0.408	0.358	0.380	0.257	0.258	0.808	4.00	0.150	0.231
	PREM 2D	0.299	0.286	0.292	0.203	0.181	0.563	2.71	0.131	0.195
VW RABBIT DIESEL	EMISS. 2D	0.252	0.204	0.225	0.206	0.173	0.363	1.93	0.090	0.167
	NA (2D)	0.250	0.194	0.218	0.194	0.143	0.384	2.12	0.068	0.148
	JET A (1D)	0.209	0.152	0.177	0.149	0.138	0.295	0.742	0.047	0.103
	MIN 2D	0.565	0.231	0.375	0.222	0.174	0.450	2.84	0.197	0.189
	PREM	0.221	0.174	0.194	0.156	0.175	0.402	2.10	0.052	0.164
(1) Grams per hour instead of g/km.										

TABLE 3-18. BENZO(A)PYRENE EMISSIONS OF TWO VEHICLES, FOR FIVE FUELS AND EIGHT DRIVING CYCLES AND MODES (Ref. 3-40).

VEHICLE	FUEL	MICROGRAMS PER KILOMETER BY OPERATING CYCLE OR MODE							
		COLD FTP	HOT FTP	CFDS	FET	NYCC	STEADY-STATE MODES		
							IDLE ⁽¹⁾	50 kph	85 kph
MERCEDES 240D	EMISS. 2D	0.38	0.39	0.13	0.076	1.9	12.0	0.14	0.979
	NAT'L AV. 2D	0.54	0.40	0.19	0.067	2.7	19.0	0.12	0.033
	JET A (1D)	0.38	0.28	0.17	0.16	0.75	9.2	0.048	0.14
	MIN QUAL 2D	0.74	0.53	0.16	0.086	4.0	55.0	0.15	0.035
	PREM QUAL 2D	0.23	0.23	0.13	0.15	0.75	4.1	0.38	0.028
VW RABBIT DIESEL	EMISS. 2D	1.9	0.55	0.36	0.39	1.7	4.5	0.34	0.25
	NAT'L AV. 2D	2.3	0.60	0.39	0.25	1.6	5.3	0.33	0.22
	JET A (1D)	2.0	0.56	1.2	0.87	0.35	...	0.019	0.74
	MIN QUAL 2D	7.0	1.1	0.73	0.41	1.5	4.8	0.096	0.32
	PREM QUAL 2D	1.8	0.48	0.30	0.40	1.4	3.5	0.18	0.10
⁽¹⁾ $\mu\text{g/hr}$ instead of $\mu\text{g/km}$. ⁽²⁾ Below minimum detectable limit; in this case, under $0.35 \mu\text{g/hr}$.									

Premium Quality No. 2 diesel fuel. This lack of correspondence between particulate mass and adsorbed BaP indicates that future particulate regulations should control not only total particulate mass emissions, but also the emitted mass of undesirable constituents, such as BaP.

In cooperation with a number of major petroleum suppliers, GM has experimented with 46 different fuel blends to determine their emissions reduction potential (Refs. 3-3 and 3-38). These fuels were evaluated in steady-state dynamometer tests, using GM's 5.7 liter V-8 light-duty diesel engine. Weighting factors were then utilized to convert test measurements into an index representative of the emissions corresponding to the 1975 FTP cycle. Since injection timing requirements vary from fuel to fuel, timing sensitivity curves utilizing standard, advanced, and retarded settings were used in this procedure.

Particulate emissions data for the various fuels tested are shown in Figure 3-21 as a percentage of the emissions for a baseline D-2 fuel. As indicated, particulate emissions utilizing the baseline fuel varied with time, expressed in terms of data set number, amounting to as much as 22 percent above the minimum value obtained in Data Set No. 18. While this may seem to be a

FIGURE 3-21. PARTICULATE EMISSIONS FROM TESTS USING DIFFERENT FUELS (Ref. 3-38).

large variation, results are considered good in light of the wide variety of fuels tested and the fact that the test series lasted two months, with the engine operated around the clock. Based on the results of a regression analysis, particulate emission levels are most closely related to fuel aromatics content, and 90 percent boiling point, as shown in Figures 3-22 and 3-23. Fuel samples utilizing a cetane improver are denoted by an underlined fuel sample number. The 90 percent points of gasoline, JP-4, kerosene, D-1 and D-2 fuels are also indicated in Figure 3-23. In general, particulate emissions decline with de-

FIGURE 3-22. PARTICULATE EMISSIONS FOR DIFFERENT FUELS AS A FUNCTION OF AROMATICS CONTENT (Ref. 3-38).

FIGURE 3-23. PARTICULATE EMISSIONS FOR DIFFERENT FUELS AS A FUNCTION OF 90 PERCENT BOILING POINT (Ref. 3-38).

creasing fuels aromatics content and boiling point. As shown in these figures, particulate emissions were high in every case where a cetane improver was used. Elimination of fuels with cetane improvers from the regression analysis improved correlation results and permitted computation of the particulate index by means of the following mathematical expression (Ref. 3-38).

$$\begin{aligned} \text{Particulate Index} = & 0.57 + 0.00343 \times 90\% \text{ Boiling Point } (^{\circ}\text{C}) \\ & + 0.0102 \times \% \text{ Aromatics Content} \end{aligned}$$

Test data from a heavy-duty diesel engine are presented in Figure 3-24 (Ref. 3-41). These data are in general agreement with the previously established trends of increasing particulates as aromatic content of the fuel increases.

With regard to NO_x and soluble organics extractable from the particulates, statistical analyses performed by GM indicate an almost insignificant correlation of those species with fuel composition (Ref. 3-38). However, in the case of NO_x this lack of correlation is not consistent with results published by other investigations. For example, DB reports that high NO_x emissions are obtained as a result of an increase in the ignition delay and combustion chamber pressure rise rate associated with the use of fuel having high aro-

FIGURE 3-24. EFFECTS OF FUEL AROMATICS CONTENT AND DILUTION RATIO ON PARTICULATE EMISSIONS OF A DIRECT INJECTION DIESEL ENGINE (Ref. 3-41).

maticity and consequently low cetane number (Ref. 3-37). Supplemental dynamometer tests conducted by GM tend to confirm the findings by DB. In these tests, blends of fuels with high and low aromatics content were used to obtain the desired aromaticity (Ref. 3-38). Test results are presented in Figures 3-25 and 3-26. In Figure 3-25 aromaticity was varied by blending No. 2 diesel fuel with a highly aromatic solvent, while mixtures of a narrow cut fuel with low aromaticity and a highly aromatic solvent were used in the tests represented by Figure 3-26. As indicated, NO_x and fuel economy increase steadily with fuel aromatics content, while HC and particulate emissions are obviously affected by other fuel parameters as well.

Other test data indicate that fuel composition, characterized in terms of the 90 percent boiling point, has less of an effect on gaseous emissions than does engine type. This is illustrated in Figure 3-27, which presents test data from four fuels and two engines tested over the 13-Mode Cycle. The gaseous emissions of the indirect injection diesel engine shows

FIGURE 3-25. EFFECT OF FUEL AROMATICS CONTENT ON EMISSIONS AND FUEL ECONOMY OF AN INDIRECT INJECTION DIESEL ENGINE -- SOLVENT AND NO. 2 DIESEL FUEL BLENDS (Ref. 3-38).

little fuel sensitivity. However, the NO_x emissions of the direct injection diesel are more strongly affected by variations in fuel composition than is the indirect injection engine (Ref. 3-42).

The contribution of specific fuel hydrocarbon compounds to the formation of particulates was determined experimentally using one cylinder from one of Opel's production diesel engines as the test bed (Refs. 3-3 and 3-38). In these tests, which were conducted on the dynamometer under steady state conditions, representing road loads at 25 and 55 mph, seven of the fuel hydrocarbon compounds were tagged with radioactive Carbon-14. An analysis of the radioactivity of the collected particulates then served as a measure of the

FIGURE 3-26. EFFECT OF FUEL AROMATICS CONTENT ON EMISSIONS AND FUEL ECONOMY OF AN INDIRECT INJECTION DIESEL ENGINE -- SOLVENT AND NARROW CUT FUEL BLENDS (Ref. 3-38).

relative contribution of each compound to particulate formation. Test results clearly indicate that (1) all compounds tested contribute to the formation of particulates, (2) particulate emissions of the paraffins are independent of boiling point, and (3) the aromatic group is the largest contributor to particulate formation. Of particular significance is the latter finding, since an increasing trend in the aromatics content is projected for diesel fuel as a result of an increased use of catalytic cracking processes to raise the yield of diesel fuel production in the refinery (Ref. 3-37). In addition, the available fraction of diesel fuel in the crude oil may be increased by increasing the allowable 90 percent boiling point temperature (Ref. 3-43). An increase in the 90 percent boiling point from 640°F to 680°F could increase the distillate fuel fraction by about 4 percent (Ref. 3-43).

FIGURE 3-27. GASEOUS EMISSIONS OF TWO DIESEL ENGINES -- 90 PERCENT BOILING POINT FUELS WITH DIFFERENT COMPOSITION (Ref. 3-42).

DB and Peugeot have expressed concern regarding the effects of fuel quality on emission certification test results and requirements (Refs. 3-37 and 3-44). DB feels that engine manufacturers cannot meet stringent fuel economy and emissions regulations if diesel fuel quality is permitted to deteriorate. An example of the effects of fuel quality variations on emissions was provided by Peugeot. Tests conducted by the EPA on a 1979 Peugeot 504 diesel vehicle showed HC emissions of 0.61 g/mi with 42 cetane U.S. diesel fuel, and 0.38 g/mi HC with 50 cetane European diesel fuel (Ref. 3-44).

3.4.2 Fuel Additives

High performance diesel engines place increasing demands on diesel fuel quality, with additives playing an important role in achieving required performance standards. Typical chemical compounds used as additives, and their functions, are listed in Table 3-19, including combustion modifiers, cetane

TABLE 3-19. TYPICAL DIESEL FUEL ADDITIVES (Ref. 3-45).

Function	Typical Compounds
Combustion Modifier	Barium and Calcium Salts in Amine or Sulfonate Complexes Metal Alkyls of Manganese, Iron, Cobalt, or Nickel
Cetane Improver	Amyl and Hexyl Nitrates Alkyl Carbonates
Antioxidant	N,N'-dialkyl Paraphenylene Diamines, Para-amino phenols
Metal Deactivator	N,N'-disalicylidene-1,2-diamino Propane
Corrosion Inhibitor	Phosphorus Acids Ammonium Mahogany Sulfonates
Detergent and Dispersant	Ethoxylated Alkyl Phenols, Polyisobutylene Alkylated Succinimides
Pour Point Depressant	Polymethacrylates Polyolefins
Biocide	Quaternary Ammonium Salts of Salicylic Esters
Color Stabilizer	Tertiary Amines, Imidazolines
Dye - Red Blue	Azobenzene-4-azo-2-naphthol 1,4-di(isopropylamine)anthraquinone

improvers, anti-oxidants, metal deactivators, corrosion inhibitors, detergents and dispersants, pour point depressants, biocides, color stabilizers, and dyes. These additives are briefly examined in the following subsections.

3.4.2.1 Combustion Modifiers

Combustion modifiers are designed to suppress the formation of black smoke during combustion through enhancement of the carbon to carbon dioxide conversion process. Barium and calcium salts in amine or sulfonate complexes, as well as metal alkyls of transition elements, particularly manganese, are effective smoke depressants. Because of the alkaline nature of the barium-based additives, these compounds provide additional benefits including antiwear protection for piston rings and injectors, better storage stability, anti-static properties, and anti-bacterial action. However, there is concern regarding the toxicity of some of the end products generated during combustion of these additives, and the potential increase in total particulate emissions.

The use of special additives as a means of providing particulate emission control has been investigated by a number of organizations. Generally, these additives are intended to reduce ignition delay, catalyze the combustion of carbon, and improve the air-fuel mixing process by assisting fuel droplet dispersion (Ref. 3-3). In conjunction with several additive suppliers, GM has screened a number of commercially available and experimental additives using a 5.7 liter GM diesel engine and operating it at 40 mph road load. Tests of 19 different additives resulted in particulate emission variations ranging from a 25 percent reduction to a 48 percent increase. Further screening of three of these additives indicate that the level of particulate reduction is load dependent. For example, one additive showed an 11 percent reduction in particulate emissions at 55 mph, and a 13 percent increase at 40 mph. Tests of another additive over the FTP driving cycle showed a 16 percent reduction in particulates, with little or no change in gaseous emissions and fuel economy.

3.4.2.2 Cetane Number Improvers

Fuel cetane number, which is dependent upon the hydrocarbon composition of the fuel, is a most important parameter affecting diesel engine operation. A number of compounds have been shown to be excellent cetane improvers,

including mixtures of primary amyl nitrates or primary hexyl nitrates. Typically, additive concentrations of 1000 ppm provide an increase in cetane number by about 4 units. Despite this proven capability, cetane improvers are currently not widely used, probably because of their relatively high cost and the fact that today's diesel fuels have sufficiently high cetane ratings to satisfy engine manufacturers and users needs.

3.4.2.3 Other Additives

A number of other diesel fuel additives have been used in the past in specialty applications, including low-temperature flow improvers, biocides, antistatic additives, and deodorants.

The low-temperature handling properties of a given fuel blend can be improved in several ways, including the addition of a low pour point stock such as kerosene, reduction of the fuel wax content, and by the use of a pour point depressant. Chemically, pour point depressants are polymers, consisting of polyolefins, polymethacrylates, ethylene-vinyl acetate copolymers, aliphatic amine oxides, and fumarate-vinyl acetate copolymers. Typical additive concentrations range from 200 to 1000 ppm. Currently, pour point depressants are used more frequently in Europe than in the United States.

Bacterial growth has been observed in diesel fuel storage tanks, leading to clogging of filters, fuel degradation, and a marked acceleration of corrosion in the storage tanks. Compounds such as quarternary ammonium salts of salicylic esters and diamine complexes of nickel have the capability of alleviating these problems. Also, certain barium-based compounds, such as those identified as smoke suppressants, provide biocidal properties.

3.4.3 Alcohols

Recent investigations have considered the use of ethanol and methanol alcohol as a means of supplementing available supplies of diesel fuel (Ref. 3-22). However, a major difficulty associated with the use of alcohols as a diesel fuel is their high heat of vaporization, which results in excessive mixture cooling and large ignition delays. For example, vaporization of a stoichiometric mixture of methanol in air lowers the adiabatic mixture temperature by 356°F, while ethanol produces a drop of 200°F (Ref. 3-46). In com-

parison, vaporization of a stoichiometric mixture of cetane and air causes mixture temperature to drop by only about 30°F. To overcome this characteristic of the alcohols, higher engine compression ratios, combined with charge preheating, may be required to achieve satisfactory combustion (Ref. 3-5). Additionally, the stoichiometric mixture ratio of alcohols is considerably lower than for diesel fuel, amounting to about 6:1 for methanol and 9:1 for ethanol, compared to about 15:1 for diesel fuel (Ref. 3-46). Therefore, the capacity of the fuel injection system must be increased to deliver the larger quantities of alcohol fuels required at each engine power setting. However, injection of the alcohol into the intake manifold, generally called fumigation, might negate the requirement of increased injection system capacity (Ref. 3-46).

Because of the poor ignition characteristics of neat alcohols, experimental work involving the use of these fuels in diesel engines has been rather limited in the past. In some instances a spark ignition system was added to enhance alcohol ignition, while other experimenters have relied on the use of large quantities of ignition improvers, such as hexyl nitrate or Cetonox (Refs. 3-47 through 3-49). Based on engine tests, the use of an alcohol-hexyl nitrate mixture indicates an increase in HC, CO, and NO_x emissions relative to diesel fuel (Ref. 3-49). The observed increase in CO is attributed by the author to deficiencies in the fuel injection system, which apparently was not modified for use with alcohols, while the increase in NO_x may be related to the nitrogen-based ignition improver. Other engine tests with neat ethanol indicate Bosch Smoke Meter readings of zero throughout the load range (Ref. 3-43). Similar observations were made in diesel engine tests using methanol as the fuel (Ref. 3-46).

In the case of alcohol fumigation, the diesel fuel injected into the combustion chamber acts as a pilot ignition source for the homogeneous alcohol-air mixture. Since the combustion process is comprised of both diffusion flame burning of the diesel fuel droplets and homogeneous combustion of the alcohol-air mixture along the flame front, the exhaust emissions of fumigated diesel engines show patterns that are characteristic of both diesel and spark ignition engines (Ref. 3-46). Flame quenching at the cylinder walls, and bulk quenching of the slow burning lean alcohol-air mixture during the expansion

stroke indicate that fumigation may always be associated with the formation of higher HC emissions relative to engine operation with diesel fuel. In general, CO emissions remain low, providing a lean overall mixture ratio is maintained. NO_x emissions trends are similar to those obtained for diesel fuel, with peak values obtained at slightly lean overall mixture ratios (Ref. 3-46).

The use of alcohol-diesel fuel emulsions in diesel engines is being considered by a number of investigators. However, surfactants are required to improve the miscibility characteristics of the mixtures, and the altered vaporization and combustion characteristics of the alcohol-diesel fuel mixture relative to diesel fuel are expected to affect ignition delay, combustion efficiency, peak combustion temperatures and pressures, and pollutant formation (Ref. 3-46). Test data from a heavy-duty direct injection diesel engine, utilizing a non-stabilized methanol emulsion in conjunction with an on-board emulsification system, are presented in Table 3-20 (Ref. 3-25). As shown, the use of 25 percent methanol resulted in particulate emissions and cyclohexane insolubles reductions of 50 percent and 74 percent, respectively, while conden-

TABLE 3-20. EFFECT OF A DIESEL-METHANOL FUEL BLEND ON EXHAUST EMISSIONS OF A HEAVY-DUTY DIRECT INJECTION DIESEL ENGINE⁽¹⁾ (Ref. 3-25).

Exhaust Species	Emissions, mg/m ³		
	D2 Diesel Fuel	D2 + 25 Percent Methanol	Change, Percent
Particulates	51.6	25.8	-50
Cyclohexane Insoluble	35.9	9.3	-74
Condensable Organics	15.7	16.5	+5
(1) DDA 8V-71 Diesel Engine, maximum continuous rating 220 kW, 2100 rpm, 563 ft/lb.			

sible organics increased slightly. Indirect injection diesel engine test data are listed in Table 3-21 for emulsions containing 18 percent and 21 percent methanol. For unknown reasons, the 18 percent emulsion provided more favorable emissions results. In general, particulate emissions declined significantly with the addition of methanol, at the expense of marked increases in HC and NO_x emissions.

Other investigators have made use of dual injection systems. However, alcohol has unfavorable lubricity characteristics, and its use may require the need for an additive to minimize fuel injection pump wear. In a test program involving a heavy duty truck engine, the standard fuel injection system was converted to a dual system, and 1 percent castor oil was added to the alcohol (Ref. 3-48). The diesel fuel was injected first to provide pilot ignition

TABLE 3-21. EFFECT OF DIESEL-METHANOL FUEL BLENDS ON EXHAUST EMISSIONS OF A HEAVY-DUTY INDIRECT INJECTION DIESEL ENGINE⁽¹⁾ (Ref. 3-50).

Exhaust Species	Engine Speed rpm	Emissions, g/bhph				
		D2 Diesel Fuel	D2 + 18 pct Methanol ⁽²⁾	Change, pct	D2 + 21 pct Methanol ⁽³⁾	Change, pct
HC	1600	0.057	0.111	+95	0.149	+161
	2200	0.139	0.201	+45	0.207	+ 94
CO	1600	0.990	0.818	-17	1.18	+ 19
	2200	1.270	1.20	- 6	1.46	+ 15
NO _x	1600	1.77	2.82	+59	3.95	+123
	2200	2.17	3.17	+46	3.42	+ 58
Particulates	1600	0.445	0.116	-74	0.167	- 63
	2200	0.237	0.089	-62	0.140	- 41

(1) Deutz F6L714 V-6 Diesel Engine maximum continuous rating 130 bhp.

(2) Standard injection timing.

(3) Timing advanced 5 degrees.

for the alcohol. Test results indicated increased power over the entire speed range, although thermal efficiency at full load declined. HC emissions remained at the diesel fuel levels, while smoke was reduced by 80 percent.

3.4.4 Implementation Problems

The use of diesel fuel blends, additives, and alcohols as a means of particulate emission control imposes a number of operational problems which would have to be resolved before these products could be made available in sufficient quantities. The manufacture of such fuel blends, which should have low boiling points and low aromatic content, requires extensive refinery modifications, while increased plant capacity would have to be provided for the production of alcohols and surfactants. In addition, a national distribution system would have to be developed to make these fuels available along with the existing fuels, since the new fuel blends would not necessarily be applicable to existing engines without costly modifications.

The use of additives could be implemented quite easily by adding these compounds in the refinery, unless they would be incompatible with in-use engines. As an alternative approach, the additives could be stored on-board and added to the fuel by a special metering system. This technique might also be applicable to the alcohols, as the use of an on-board emulsification system would negate the requirements for stable diesel fuel-alcohol emulsions and separate distribution systems.

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SECTION 4

DIESEL EXHAUST EMISSIONS MEASUREMENT TECHNOLOGY

Existing Federal Test Procedures (FTP) for exhaust emissions certification of light-duty diesel and spark ignition (SI) vehicles are similar, since only gaseous emissions species are currently regulated (Ref. 4-1). However, the Environmental Protection Agency (EPA) has promulgated major changes in those sections of the FTP applicable to testing of diesel vehicles. These modifications are intended to accommodate measurement and regulation of particulate emissions from light-duty diesel vehicles mandated for 1982 and subsequent model years. The test procedure requires a dilution tunnel and constant volume sampler (CVS) to physically simulate the dilution process undergone by diesel engine exhaust subjected to normal atmospheric dilution (Ref. 4-2). A brief description of the dilution tunnel concept used for the measurement of particulates is presented in the following subsection.

4.1 PARTICULATE EMISSIONS MEASUREMENT

A dilution tunnel approach to particulate measurement is required by the EPA because of the complex manner in which diesel particulates enter the atmosphere. For a diesel powered vehicle three distinct pollutant phases can be identified, including (1) the combustion process, (2) the flow of undiluted exhaust in the muffler and exhaust pipe, and (3) the dilution process in the atmosphere (Ref. 4-3). While gaseous pollutants can be accurately measured in the undiluted exhaust, physical and chemical processes involving particulates are still in progress in the exhaust before as well as after dilution in the atmosphere. For this reason, it is important that a system used for the determination of diesel particulate emissions incorporate a physical simulation of the atmospheric dilution process, and this is accomplished in an approximate manner by a dilution tunnel.

Figure 4-1 depicts a dilution tunnel used for the measurement of diesel particulates. As illustrated, a fraction of the raw, undiluted exhaust from the diesel engine is split off at the muffler and fed to the dilution tunnel to approximate atmospheric dilution processes.

FIGURE 4-1. DILUTION TUNNEL SCHEMATIC (Ref. 4-3).

The time scale over which dilution takes place in a dilution tunnel cannot exactly simulate atmospheric dilution time scales. As shown in Figure 4-2, the time scale of the different processes contributing to the formation of particulates ranges from milliseconds, for combustion of the fuel in the cylinder, to days, for disposal of the particulates in the atmosphere. While the longer time frames are impossible to duplicate in practical test procedures, the diluted test sample is more representative of the actual diesel exhaust contribution to particulates in the atmosphere than a sample taken directly from the raw, undiluted exhaust gas.

FIGURE 4-2. DIESEL PARTICULATE TIME SCALE (Ref. 4-3).

Figure 4-3 further compares the history of atmospheric dilution of exhaust gases with dilution achieved in a typical dilution tunnel (Ref. 4-4). Relative exhaust gas/air mixture temperature history is also shown in Figure 4-3.

FIGURE 4-3. VOLUME DILUTION RATIO FOR ATMOSPHERIC VERSUS DILUTION TUNNEL DILUTION (Ref. 4-4).

It should be noted that the curve representing atmospheric dilution is an average or mean dilution curve, since each elemental mass of vehicle exhaust undergoes its own unique dilution history in the atmosphere. Conversely, the sampled exhaust is relatively homogeneous in a dilution tunnel with good mixing prior to sampling. This, along with the difference in dilution ratio, may lead to differences in particulate character for particulates sampled in a dilution tunnel, relative to those in the free atmosphere. These differences may, in turn, impact more basic issues such as health effects.

While dilution tunnels are capable of achieving higher dilution ratios which are more representative of atmospheric dilution processes, the associated increase in the time required for collection of a particulate filter sample

suitable for subsequent characterization has, in the past, rendered higher dilution impractical. To alleviate this problem, a number of researchers have investigated numerous other methods for collecting particulates in the dilution tunnel environment. These methods include the use of impaction devices, electrical aerosol analyzers, centrifuges, thermal precipitators, electrostatic precipitators, and impingers (Refs. 4-1, 4-3, and 4-5 through 4-13). Unfortunately, these methods have not met with any substantial success. However, recent research by General Motors (GM) has led to an opto-acoustic approach for measuring particulate mass, which may totally eliminate the time constraints imposed by filter collection of particulates (Ref. 4-14). The GM technique has a response time of a half second, is more accurate than existing optical methods, which are sensitive to particulate size and composition, and is sensitive enough to measure ambient dust in room air. In principal, the GM method uses an infrared laser beam to heat exhaust particulates in a test cell which, in turn, heats the surrounding air and increases air pressure. By cycling the laser beam on and off at a rapid rate, pressure changes of acoustic frequency are created which are sensed by a microphone in the cell. These acoustic signals are then used to calculate particulate mass concentrations.

In the EPA procedure, a dilution tunnel filter maintained at 125°F or lower is specified as the method for particle collection. While exhaust smoke opacity is an alternate technique for measuring total emitted particulate mass, according to the EPA this method is only viable under certain operating modes in which sufficient smoke is emitted to assure accurate measurement (Ref. 4-15). Thus, at lower smoke levels, appreciable amounts of particulate mass might go undetected if smoke opacity were used as a measure of particulate emissions.

4.2 GASEOUS EMISSIONS MEASUREMENT

While current EPA measurement procedures for gas phase pollutants emitted by diesel vehicles are conceptually the same as for gasoline vehicles, the details of the two procedures differ slightly (Ref. 4-15). Currently, gasoline vehicle exhaust is diluted in a constant volume sampler (CVS), filtered, and collected in sample bags for subsequent determination of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x). For diesel vehicles the procedure is identical, with the exception that (1) a heated flame ionization detector (HFID)

used to prevent condensation of the heavier HC species emitted from diesels, and (2) emissions are measured continuously and integrated electronically to determine total HC mass. This method results in more accurate HC measurements than the bag method because the low volatility, high molecular weight HC species can not be trapped on the wall of the sampling system.

The equivalency of the bag and electronic integration methods was tested in a short series of experiments, using a gasoline fueled vehicle and both bag and electronic integration of the exhaust. Over six tests, continuous electronic integration averaged 73.5 ± 3.0 parts per million (ppm) carbon, while bag integration yielded 72.4 ± 2.8 ppm carbon (Ref. 4-16). This represents an error in the continuous measurement scheme of only 1.5 percent relative to the bag integration method.

In the dilution tunnel and CVS method of collecting the HC gas phase sample, the EPA will use the HFID/continuous integration technique with the sample probe positioned in the dilution tunnel at a downstream location to assure thorough mixing of the diluted gas stream (Ref. 4-2). Gas samples collected by the probe will be passed through a filter to remove all particulate matter from the gas stream prior to detection by the HFID. The entire system, including the probe, filter, and HFID, will be heated to maintain a wall temperature of $375^{\circ} \pm 20^{\circ}\text{F}$.

It should be noted that the filter in the gas phase collection system is distinct from the previously mentioned particulate collection filter, with the gas phase filter maintained at $375^{\circ} \pm 20^{\circ}\text{F}$ and the particulate filter constrained to a temperature no higher than 125°F . This approach is considered by some investigators to have a potential for overestimating the total hydrocarbon content emitted by diesel vehicles, as discussed in the next section along with other EPA test procedure requirements.

4.3 EMISSIONS MEASUREMENT CONSIDERATIONS

4.3.1 EPA System

A potential difficulty associated with the particulate/gaseous measurement system required by the EPA has been noted by GM, and is centered on maintaining particulate collection filter temperatures of 125°F or lower, while holding the filter in the gas phase collection system at $375^{\circ} \pm 20^{\circ}\text{F}$ (Ref. 4-17).

According to GM, the disparity in filter temperatures causes a double-counting of hydrocarbons. This is said to result because hydrocarbons adsorbed on particulates and retained on the particulate collection filter at 125°F or less, have HC counterparts that are desorbed and converted to gas phase species in the separate gas phase collection stream which maintains its particulate blocking filter at the much higher temperature of $375^{\circ} \pm 20^{\circ}\text{F}$. GM believes that this unfairly raises the measured HC level due to the volatilization of HC that should remain adsorbed on particulates and that is counted as particulate mass on the lower temperature filter. According to GM, a more realistic system would hold both filters at a nearly ambient temperature (Ref. 4-17). This would define particulate and gas emissions at the same temperature; particulates being species that are caught by the filter, and gases being species that pass through a similar filter at the same temperature.

GM researchers note that some investigators believe that double-counting of HC species is justifiable, since the HC species attached to the particulates in the exhaust will eventually become free HC compounds upon dilution in the atmosphere. However, GM's experimental evidence shows that this is not the case (Ref. 4-17). In experiments which examined particulate composition by comparing dilution tunnel results at dilution ratios of 14 and 26 with atmospheric dilution ranging from 5 to 150, it was shown that the extractable organic fraction and the benzo(a)pyrene (BaP) content of the tunnel and atmospheric experiments correlated quite well. These results, which are shown in Figures 4-4 and 4-5, indicate that HC is strongly bound to the particulates. In fact, Figure 4-5 shows that particulate BaP content actually increases with increasing dilution, because concentrated exhaust converts BaP to other products, probably by reaction with NO_2 (Ref. 4-17). Results similar to those of Figures 4-4 and 4-5 at dilution ratios up to 275 have been observed by the EPA, as noted by GM (Ref. 4-17).

To verify that the organic fraction does not volatilize over longer periods of time, GM monitored the content of filters containing particulate matter for up to 7 months at ambient conditions. The average particulate weight loss was only 0.4 percent in these experiments, which encompassed particulate extractable fractions ranging from 15 to 45 percent of particulate mass. Detailed results are given in Table 4-1, further verifying the stability of the particulate organic fraction at ambient temperatures. The desorption of particle-bound

FIGURE 4-4. DIESEL PARTICULATE EXTRACTABLE ORGANIC FRACTION IN OPEN AIR AND IN A DILUTION TUNNEL (Ref. 4-17).

FIGURE 4-5. DIESEL PARTICULATE BaP CONTENT IN OPEN AIR AND IN A DILUTION TUNNEL (Ref. 4-17).

TABLE 4-1. EVAPORATION OF HC FROM DIESEL PARTICULATES AGED ON FILTERS - ROOM TEMPERATURE STORAGE (Ref. 4-17).

Days After Collection	Particulate Mass on Filter, mg	Particulate Mass Evaporated, percent	Particulate Mass Extractable, percent
80	17.7	0.29	28
80	19.5	2.05	37
80	18.6	0.84	36
80	39.2	0.02	16
80	32.4	0.19	17
190	52.8	-0.10	15
190	38.7	-0.07	17
190	37.4	-0.05	22
190	42.6	-0.41	18
190	29.1	0.97	41
210	16.8	0.35	29
210	17.5	0.10	30
210	34.8	0.80	42
210	34.5	0.58	45

organics is under active investigation by the Coordinating Research Council (Ref. 4-16).

Another difficulty arises during certain portions of the Federal Driving Cycle. As noted by Daimler-Benz (DB), the "second hill" of the hot transient phase of the Urban Cycle can cause the filter temperature to exceed 125°F (Ref. 4-18). However, DB notes that peak temperatures as high as 170°F have little effect on total particulate weight collected, according to tests performed by the EPA.

Other GM concerns with EPA particulate measurement methods include the requirements that (1) a critical flow venturi (CFV) sampler not be used without a heat exchanger, (2) temperatures be maintained which preclude the use of commercially heated lines, and (3) particulate filters be stabilized for at least

eight hours prior to use. GM believes that these requirements constitute unnecessary restrictions on facilities design and the efficient accumulation of test-vehicle mileage, as well as excessive cost for facilities modifications (Ref. 4-17).

4.3.2 Emissions Measurement Sensitivities

Recent research has quantified the measurement sensitivity of gaseous and particulate emissions to variations in a number of dilution tunnel and other test system parameters. These include (1) the comparison of baffle versus tunnel mixing of exhaust and diluent air, (2) the interactions between filter material and gaseous organics, (3) the effects of probe line length and CVS flow rate on measured emissions, (4) the effects of filter temperature on measured emissions, (5) the choice of isokinetic versus non-isokinetic sampling, and (6) the effects of dilution fraction and fuel type on measured emissions.

Baffle versus tunnel mixing of exhaust and diluent air is compared in Table 4-2, showing gaseous and particulate emissions data obtained in a series of FTP tests. In these test, a Nissan diesel engine was used in conjunction with baffle mixing and turbulent flow tunnel mixing at Reynolds numbers of about 30,000, and a flow rate of 350 cfm (Ref. 4-16). The results in Table 4-2 show a loss of about 6 percent in measured particulate mass using baffle mixing rather than tunnel mixing of exhaust and diluent air. This loss is probably due to collection of particulates on the baffle plate.

TABLE 4-2. BAFFLE VERSUS TUNNEL MIXING SYSTEMS
(Ref. 4-16).

Emission Specie	Sampling System "A" (Baffle)	Sampling System "B" (Tunnel)
THC	0.347 ± 0.004	0.349 ± 0.004
CO	1.88 ± 0.04	1.89 ± 0.16
NO _x	1.98 ± 0.05	1.96 ± 0.16
Particulate	0.370 ± 0.024	0.394 ± 0.021

Table 4-3 presents data showing how the use of glass fiber filters can lead to the measurement of larger amounts of particulate mass relative to the

use of teflon-coated glass fiber filters. This effect is a result of gaseous organics being absorbed by the glass fiber filter, as shown by the difference in particle extracts obtained from the two types of filters. The teflon filter also has the advantage of being less hygroscopic and more rugged than the glass fiber filter.

TABLE 4-3. GLASS FIBER VERSUS TEFLON-COATED GLASS FIBER FILTER MEDIA (1) (Ref. 4-16).

Vehicle	Filter Media ⁽²⁾	Total Particulate, g/mi	Particle Extracts, g/mi	Extracts of Total Particulate, percent
Rabbit	TEF/Glass	0.169	0.046	27.2
Rabbit	GF/AE	0.200	0.072	36.0
Difference		0.031	0.026	
Nissan	TEF/Glass	0.389	0.056	14.4
Nissan	GF/AE	0.408	0.074	18.1
Difference		0.019	0.018	
(1) Average of four or more runs.				
(2) Located outside of tunnel.				

The sensitivity of particulate mass measurements as a function of probe line length and CVS flow rate is presented in Table 4-4 (Ref. 4-16). These results do not show variations of significance, indicating that probe line length and CVS flow rate are probably not critical factors in the measurement of particulates. In addition to probe sensitivity and flow rate tests, the experiments conducted to obtain the data of Table 4-4 allowed experimentation over a limited filter temperature range. Based on tests at a flow rate of 350 cfm, it was concluded that there is no significant impact on particulate mass collected for filters at a constant 85°F temperature as opposed to a 104°F average, with excursions to 136°F. Similar results were obtained at 560 cfm and with filters inside the tunnel averaging 99°F with excursions to 122°F, compared to the constant 85°F temperature of filters mounted external to the tunnel.

TABLE 4-4. PARTICULATE PROBE SENSITIVITY TESTS
(Ref. 4-16).

Vehicle	CVS Rate, cfm	Test Cycle	Total Part., g/mi	Particle Extracts, g/mi	Percent of Particle Extracts	Filter Probe Length, ft
Olds	560	FTP	0.96	0.20	20.8	0.15
Olds	560	FTP	0.94	0.18	19.2	3.0
Olds	350	FTP	0.92	0.19	20.7	0.15
Olds	350	FTP	0.91	0.18	19.8	3.0
Olds	560	LA-4 ⁽¹⁾	0.80	0.16	20.0	0.15
Olds	560	LA-4	0.79	0.16	20.3	3.0
Olds	350	LA-4	0.76	0.15	19.7	0.15
Olds	350	LA-4	0.78	0.15	19.2	3.0
Rabbit	350	FTP	0.18	0.047	26.1	0.15
Rabbit	350	FTP	0.18	0.054	30.0	3.0
Rabbit	350	LA-4	0.17	0.046	27.1	0.15
Rabbit	350	LA-4	0.17	0.046	27.1	3.0
(1) Hot-start tests.						

Insensitivity to isokinetic versus non-isokinetic flow at the particulate sampling probe tip is demonstrated by the data of Table 4-5 (Ref. 4-16). These data were taken during the FTP tests with a Nissan diesel engine described previously in connection with tests used to compare baffle versus tunnel mixing of exhaust and air.

In experiments to determine the effect of variations in dilution fraction on emissions it was found that no significant differences in either gaseous or particulate emissions were observed for FTP cyclic tests, using dilution fractions ranging from approximately 9 to 18 (Ref. 4-16). Further experiments to examine desorption of particulate bound organics at high dilution showed insignificant variations with dilution ratio. Furthermore, no significant variations in the molecular weight of extracted organics were observed at different dilution ratios (Ref. 4-16). Typical test data are presented in Table 4-6.

TABLE 4-5. ISOKINETIC VERSUS NON-ISOKINETIC SAMPLING
(Ref. 4-16).

Sampling Method	Sampling System "A" (Baffle), g/mi	Sampling System "B" (Tunnel), g/mi
Isokinetic	0.371 ± 0.028	0.397 ± 0.021
Non-isokinetic ⁽¹⁾	0.370 ± 0.025	0.391 ± 0.023
(1) Average of two runs $\frac{1}{4}$ isokinetic rate and two runs $\frac{1}{2}$ isokinetic rate.		

TABLE 4-6. CATERPILLAR VARIABLE DILUTION TEST DATA
(Ref. 4-16).

Dilution Ratio	Percent of Total Mass Extractable
10:1	31.3 ± 0.2
20:1	29.0 ± 0.7
275:1	32.9 ± 1.4

Additional test data showing the effects of dilution ratio on particulate mass emissions are presented in Figure 4-6, for a naturally aspirated, direct injection V-8 truck diesel engine operated on three different fuels (Ref. 4-4). As illustrated, particle mass emissions are strongly affected by fuel type, but are rather insensitive to volume dilution ratio, for ratios above five. Very low particulate emission levels are obtained with fuel 1, which is a blend of several production runs of No. 1 diesel fuel and is representative of the lightest fuel used in diesel engines. Fuel 2 is an American Society for Testing and Materials (ASTM) No. 2 fuel and is considered a "baseline" diesel fuel. Fuel 3 is a gas-oil blend representing the heaviest fuel used in automotive applications.

FIGURE 4-6. TOTAL PARTICLE EMISSIONS VERSUS VOLUME DILUTION RATIO FOR THREE FUELS (Ref. 4-4).

4.4

ANALYSIS OF PARTICULATE CONTENT

While the EPA particulate regulations, which become effective in Model Year 1982 are limited to the control of particulate mass, it is conceivable that future regulations will be developed which control both particulate mass and organic content. Ultimately, these regulations will depend on the outcome of large-scale health effects studies currently in progress by the EPA and other organizations. These studies have given rise to a good deal of research and development into methods for characterizing the soluble organic fractions and sulfates. Some of these techniques are briefly discussed in the following paragraphs.

Figure 4-7 presents a flow chart of a method developed to determine total HC emissions contained in diluted diesel exhaust, using the two-temperature filter system proposed by the EPA and discussed in Subsection 4.3. As shown in Figure 4-7, the diluted exhaust is split into species collected at temperatures less than 125°F and at a nominal 375°F. Solvent extraction of the hot filter is then used to estimate organics not desorbed at 375°F. These are combined with continuous total gaseous HC data obtained by FID to determine total HC emissions, which are equivalent to A plus C in Figure 4-7. The total

particle bound organics are estimated by solvent extraction of the cool filter, D, and total gaseous organics are estimated by subtracting D from A plus C.

FIGURE 4-7. HYDROCARBON ANALYTICAL SCHEME
(Ref. 4-3).

Particulate and gaseous organic molecular weights are estimated using gas chromatography analysis of samples B, D and E, with the particulate distribution obtained directly from sample D and the gaseous distribution from samples B and E from which sample D is subtracted. Low carbon number organics (C_1 to C_{10}) are obtained from a cool filtered sample collected in a teflon bag, while higher carbon number organics (C_{10} to C_{40}) are collected on porous polymer traps (gaseous compounds) or teflon-coated glass fiber filters (particulates). Methylene chloride is used to extract the organics from the trap or filter.

In the analysis of sulfates, particulates can be collected on a dilution tunnel filter and extracted using the barium chloranilate method. The final sulfate determination is colorimetric. Typically, less than 4 percent of fuel sulfur is converted to sulfates, and it is usually assumed that sulfur dioxide (SO_2) accounts for the remainder of the fuel sulfur (Ref. 4-3).

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SECTION 5

DIESEL ENGINE NOISE CHARACTERISTICS

5.1 INTRODUCTION

This section deals with the noise emissions from light-duty diesel engines. However, the noise characteristics of peripheral engine components such as exhaust, fan, transmission, and chassis are not considered, except for instances where they directly affect engine noise emissions. Subsection 5.2 compares the noise characteristics of various diesel and spark ignition (SI) engines, and examines the current status of legislation affecting light-duty vehicles. Subsection 5.3 addresses the sources and causes of diesel engine noise, and Subsection 5.4 discusses diesel engine noise abatement techniques and their impact on fuel economy, emissions, and engine durability. Noise reduction research needs are identified in Subsection 5.5.

Historically, the diesel engine has been used to power large trucks and buses rather than automobiles. One legacy of this heritage is the perception of the diesel engine as being more noisy than the SI engine. While this is true to some extent, diesel engines do not inherently emit more noise than equivalent SI engines in every instance. In general, diesel noise is of a different constitution as a result of different circumstances of generation.

5.2 NOISE MEASUREMENT AND PERCEPTION

Because of the subjective nature of human perception, an objective measure of sound levels has been devised which is based on the measurement of sound pressure energy with respect to a specific reference. Ten times the common logarithm of this ratio is defined as the sound pressure level (SPL) in decibels (dB). The reference level is frequently chosen as the faintest sound the average person can hear, the so-called "Threshold of Hearing". The international standard for this level is $20 \mu\text{Pa}$, which is used throughout this discussion (Ref. 5-1). When considering separate noise sources, the sound energy levels are added to yield the overall SPL, not the decibels. Thus two sources, each emitting 90 dB together emit 93 dB, not 180 dB. Figure 5-1 shows dB ratings for typical activities.

FIGURE 5-1. DECIBEL LEVELS OF TYPICAL NOISE SOURCES (Refs. 5-1 and 5-2).

In addition to intensity level, sound is characterized by its frequency. The human ear is able to perceive sounds between about 20 and 20,000 Hertz (Hz), with maximum sensitivity in the range of 800 to 5,000 Hz (Ref. 5-3). To correct the sound pressure level for the frequency dependence of the ear, a weighting network is often applied. The most common weighting network is the "A" rating (dB(A)), which is used throughout this report.

Some sounds seem more annoying than others. While attempts have been made to quantify annoyance, it still remains somewhat subjective. One important source of annoyance is the masking of speech. The frequency range of 800-1900 Hz is most important for ensuring intelligible speech (Ref. 5-4).

5.2.1 Diesel Noise Emission Characteristics

A typical diesel engine noise spectrum is depicted in Figure 5-2. Ninety percent of the perceived noise is being radiated between 500 and 5000 Hz at all engine speeds, with maximum perceived noise being radiated between 800 and 2000 Hz. These two ranges correspond, respectively, to the frequencies of maximum hearing sensitivity and to the frequencies of maximum importance to

speech. A 95.5 dB(SPL) curve is also shown in Figure 5-2 to allow comparison with the unweighted sound pressure levels. The SPL curve demonstrates that, although the perceived sound level below 500 Hz is not significant in itself, it still has a great deal of energy. This energy contributes to the perceived noise level indirectly by exciting structural resonances in the 500-4000 Hz region. During engine warmup, and at idle, primarily the components of the noise spectrum between 800 and 4000 Hz are perceived as "diesel knock" (Ref. 5-5).

FIGURE 5-2. NOISE SPECTRUM OF INDIRECT INJECTION DIESEL ENGINE AT VARIOUS ENGINE SPEEDS - 1 METER DISTANCE BETWEEN UNSHIELDED ENGINE AND MICROPHONE (Ref. 5-6).

Figure 5-3 compares the overall noise levels of typical diesel, SI, and Stirling engines. As indicated, the noise levels of the naturally aspirated diesels at their rated speeds are nearly identical. At a given speed, the noise level of the high-speed indirect injection (IDI) diesel engine is lower than that of the larger direct injection (DI) truck engine. The addition of a turbocharger results in a reduction in the noise level of the DI engine in the upper speed region. The effects of chamber design variation on noise are also shown in Figure 5-3, indicating that the low swirl, shallow "dish" chamber is less noisy than the toroidal chamber. For comparison, data from a small prototype double-acting Stirling engine, suitable for use in a compact automobile, are also shown, indicating very low noise levels for that engine type.

FIGURE 5-3. ENGINE NOISE VERSUS SPEED OF DIESEL, SPARK IGNITION, AND STIRLING ENGINES (Refs. 5-7 through 5-9).

The noise spectrum at rated speed of a small naturally aspirated IDI diesel engine is compared in Figure 5-4 with that of an equivalent SI engine. While there is little difference in the overall noise levels of the two engines, amounting to about 103 dB(A) for the diesel and 101.5 dB(A) for the SI engine, there are noticeable differences in the composition of the noise spectrum. In the case of the diesel, 70 percent of the noise lies in the 500-4000 Hz range, with an additional 30 percent contributed by the 125 Hz peak. The SI engine shows just the opposite effect, with 76 percent of its noise in the 160-315 Hz range, and only 22 percent in the 500-4000 Hz region. Even though the overall noise levels are similar, the diesel will probably be subjectively judged more annoying, because of the speech masking effect of its noise spectrum. The large maximum at 500 Hz is the 3rd harmonic of the large 125 Hz peak, and may be partially excited by the fundamental. Also, the distinct 2500 Hz peak is probably due to the excitation of a structural resonance.

5.2.2 Noise Reduction Legislation

At present, there is no federal legislation or regulation dealing specifically with the noise emissions of automobiles and light-duty trucks.

FIGURE 5-4. COMPARISON OF SPARK IGNITION AND DIESEL ENGINE NOISE SPECTRA- FULL LOAD, RATED SPEED, 1 METER, UNSHIELDED (Ref. 5-10).

The Environmental Protection Agency (EPA) is currently investigating such noise emissions and has already issued emission standards for medium- and heavy-duty trucks. In its investigations, the EPA determined that two 24 hr noise exposure levels were necessary for protection of the long-term health and welfare of the public. The equivalent of exposure to 70 dB(A) for 24 hr (the Leq level) was determined to be the permissible maximum for prevention of hearing loss. A night-weighted equivalent exposure of 55 dB(A) for 24 hr while outdoors in a residential area (the Ldn level) was established as the permissible maximum for interference and annoyance (Ref. 5-2). EPA further determined that 40-70 million people are currently subjected to Ldn noise levels of 60 dB(A) or more due to urban traffic. The major classes of urban vehicles are medium- and heavy-duty trucks, light-duty vehicles, buses, and motorcycles. In terms of both the specific emission levels of individual vehicles and the overall vehicle class noise contributions to the total noise, much of the traffic noise was found to be due to medium- and heavy-duty trucks. However, the other vehicle classes were found to be significant contributors, as well. The automobile and light-duty truck classes were subsequently identified as candidates for further study, to determine if they should be designated as major noise sources which warranted

regulation. Such regulation would consider the vehicle type's contribution to overall noise in addition to specific emission levels (Ref. 5-2).

Beyond the noise impact of current light-duty vehicles, the EPA is also concerned that the mandated fuel economy standards will result in larger percentages of 4-cylinder SI and diesel powered light-duty vehicles in the future. These vehicles are noisier than the average SI vehicle, with the diesels being 5 dB(A) noisier during acceleration. Unchecked, the growth in light-duty vehicle traffic noise would negate anticipated savings resulting from control of motorcycle noise (Ref. 5-11). To fully assess the impact of light-duty vehicles on traffic noise, the EPA has proposed a new light-duty vehicle noise test procedure.

5.2.2.1 Light-Duty Vehicle Noise Test Procedures

Two vehicle noise test procedures which have been widely used are the Society of Automotive Engineers (SAE) J986a Procedure in the United States and the International Standardization Organization (ISO) R362 Procedure in Europe. These are full throttle driveby tests, wherein the vehicle under test approaches the test area in a low gear and then accelerates at full throttle to rated engine speed (RES). It should be noted that, due to differences in the test procedures, results from tests with one procedure cannot be applied generally to predict the results from other procedures. Generally, the SAE procedure produces higher noise levels (Ref. 5-12). The EPA has experimented with another noise measurement procedure which is more representative of light-duty vehicle operation in the urban environment. In this test, the vehicle is operated at part throttle (Ref. 5-13). Table 5-1 compares the EPA test procedure and a new procedure recommended by General Motors (GM) with the earlier SAE and ISO full throttle procedures. One basic difference between the EPA and GM procedures is that the latter specifies a gear/axle ratio factor in computing engine speeds and test section distances. Also, the GM procedure specifies vehicle speed at the start and conclusion of the test, and specifies a designated test section length, while the EPA procedure specifies a given acceleration rate at 22 mph and an experimentally determined test section length.

TABLE 5-1. LIGHT VEHICLE NOISE TEST PROCEDURES.

Test Parameter	Proposed EPA Urban Noise Acceleration Test	Proposed GM Speed-Distance Test	SAE J986a	ISO R362
Throttle Setting	Partial. Adjust stop to yield $0.15 \pm 0.01g$ acceleration at 22 mph or 70% rated engine speed (RES).	Partial. Adjust stop to yield 70% RES on 40 km/hr (25 mph) at End Point, ± 1 km/hr.	Full	Full
Gear Selection	1st gear, or the lowest numerical gear ratio which produces 70% RES at or below 25 mph.	1st gear, or the highest numerical gear ratio "normally used in urban traffic."	Low Gear Range	2nd gear if less than 5 gear ratios. 3rd gear if 5 or more gear ratios.
Test Section Starting Point	Adjusted to yield 70% RES or 25 mph within End Zone during test.	Determined by gear/axle ratio, RES, from a chart.	Point on vehicle path 7.5 m (25 ft) before a perpendicular to microphone location.	Point on vehicle path 10 m (33 ft) before a perpendicular to microphone location.
Test Ending Point	20 ft section of vehicle path centered on a perpendicular to microphone location.	Point on vehicle path 7.5 m (25 ft) beyond a perpendicular to microphone location.	Point on vehicle path 7.5 m (25 ft) beyond a perpendicular to microphone location.	Point on vehicle 10 m (33 ft) beyond a perpendicular to microphone location.
Microphone Response and Location	A-weighted, fast response. Located 25 ft from vehicle path, 4 ft above test surface.	A-weighted, fast response. Located 7.5 m (25 ft) from vehicle path, 1.2 m (4 ft) above test surface.	A-weighted, fast response. Located 15.2 m (50 ft) from vehicle path.	A-weighted, fast response. Located 7.5 m (25 ft) from vehicle path 1.2 m (4 ft) above test surface.
Approach to Test Area	At 25% RES	At 25% RES, maintaining constant speed for 15 m (50 ft) before test area.	At 50 km/hr (30 mph).	At 50 km/hr (30 mph), or 75% RES, or 75% governed speed.
Test Procedure	Open throttle to stop. Hold until front edge of auto is within End Zone and 70% RES or 25 mph occurs.	Open throttle to stop. Hold until past End Point at 70% RES or 40 km/hr (25 mph).	Open throttle fully. Hold until past End Point at 100% RES.	Open throttle fully. Hold until past End Point at 100% RES.
Measurement	Minimum 4 runs per side. Report higher of two arithmetic means of each side.	Minimum 4 runs per side. Report higher of two arithmetic means of each side.	Minimum 4 runs per side. Average two highest headings each side.	Minimum 2 runs per side. Average readings for each side.

5.2.2.2 Local and State Noise Legislation

The existent light-duty vehicle noise legislation is at the local and state levels. At the local level, legislation generally takes the form of urban vehicle speed limits. Although set primarily for reasons of public safety, these limits serve the secondary purpose of noise control. At the state level, legislation is typically specified by state vehicle codes (Ref. 5-14). At a minimum, these codes require that a vehicle be equipped with a type-approved muffler. Several states, as shown in Table 5-2, have specified maximum noise emission levels, usually based upon constant speed driveby at 50 ft (Ref. 5-15). A few states have also implemented new product emission standards and have applied the standards to new automobiles. The State of Oregon has twice delayed a controversial 1982 Model Year 75 dB(A) noise limit, based upon the SAE test procedure. Both GM and the Ford Motor Company have indicated that they plan to withhold noncomplying models rather than attempt to meet the Oregon Department of Environmental Quality regulation (Ref. 5-16).

TABLE 5-2. SELECTED STATE LIGHT-DUTY VEHICLE NOISE LIMITS
(Ref. 5-15).

State	Noise Limits, dB(A) ⁽¹⁾		New Product Emission Standard
	Below 35 mph	Above 35 mph	
California	76	82	Yes
Colorado	74	80	Yes
Connecticut	76	82	No
Hawaii ⁽²⁾	69-73	75-83	No
Indiana	76	82	No
Pennsylvania	82	86	Yes
Minnesota	82	86	Yes
New York	88	None	No
<p>(1) Constant speed, at 50 ft, 1974 figures.</p> <p>(2) Noise limit varies with posted speed limit.</p>			

There are three major sources which contribute to the overall noise emission of diesel engines. These are (1) combustion noise, (2) mechanical noise, and (3) structural response noise. The relative importance of each source is dependent on the size and configuration of the engine. For example, combustion noise is the predominant source in large (7-10 liter) heavy-duty DI engines, while in the light-duty (2-4 liter) engines both combustion noise and mechanical noise are of similar magnitude (Ref. 5-17). In general, turbocharging reduces overall diesel combustion noise, albeit at the expense of increased mechanical noise. These two sources usually involve abrupt and discontinuous forces that are rich in harmonics, and excite fundamental vibration modes in the engine structures. The structural responses amplify and modify certain of the excitation frequencies and, in the end, act as the major means of transmitting the frequencies to the air.

Combustion noise is generated in the chamber during burning of the fuel charge. Microscopically, it is caused by random fluctuations in an unsteady chamber pressure field, due to turbulence and the rapid release of heat (Ref. 5-18). Figure 5-5 depicts cylinder pressure diagrams for several engine types. Comparing the naturally aspirated DI engine to the turbocharged DI under full load conditions, the latter has a smoother pressure diagram, although the peak pressure is higher. Reduction of the ignition delay both smooths the pressure development and lowers the peak pressure of the IDI engine (Ref. 5-7).

The SI engine has a smooth pressure diagram and a low peak pressure. Macroscopically, the noise can be attenuated through control of the peak chamber pressure and the rate of pressure rise. These factors depend upon chamber compression ratio, turbulence, inlet temperature, injection delay, fuel injection rate and pattern, spray velocity, droplet size, cetane number, and fuel composition. However, noise reduction via direct alteration of many of these parameters is limited inasmuch as the gain in noise reduction is usually modest, and there are usually offsetting penalties in the form of increased specific fuel consumption and smoke. Combustion noise, although present at all audio frequencies to some degree, is of most interest between 80 and 3000 Hz. In addition, on some engines cylinder pressure variations appear around 6000-8000 Hz and are visible

FIGURE 5-5. PRESSURE DIAGRAMS OF VARIOUS COMBUSTION SYSTEMS (Ref. 5-7).

in the cylinder pressure spectrum as well as the overall engine noise spectrum (Ref. 5-6). Combustion noise is particularly pronounced for a long injection delay, such as occurs when idling or starting on a cold morning, making "diesel knock" an attribute of this engine (Ref. 5-6).

Mechanical noise is caused by the impacts of engine working parts due to abrupt discontinuous forces acting on these parts. For example, in a cam-operated mechanism, the total torque on the camshaft undergoes variations as the cam lobe follower moves from the rising side to the falling side of the lobe. In the size range of light-duty diesel engines, mechanical noise is approximately equal in importance to combustion noise. The main sources of mechanical noise are due to piston-cylinder wall impacts, timing gear rattle, and fuel injection equipment forces.

Structural response noise is produced by combustion and mechanical sources which are further modified, amplified, and selectively augmented by the physical responses of the various engine structures to the noise and vibration spectra. In general, the structural responses tend to be either bending

and torsional modes at low frequencies for load-bearing components, or vibration resonances at higher frequencies for non-load-bearing components. It is primarily via the structural responses that noise is transmitted from the engine surfaces to the surrounding air.

5.3.1 Piston-Cylinder Wall Impacts

As the piston moves in the cylinder, it impacts upon and rebounds from the cylinder wall, causing the phenomenon of "piston slap". In this case, the line of action of the gas pressure forces acting on the piston differs from the line of action of the mechanical forces transmitted from the crankshaft via the crankarm connecting rod assembly. This results in a net force toward one side of the cylinder or the other. Because of the physical clearances between piston and cylinder wall, which are necessary to provide for thermal expansion and safety of operation, the piston impacts on the wall and rebounds to strike the opposite wall several times during each stroke. The magnitude of piston slap is affected by piston-cylinder wall clearances, connecting rod length, crankarm length, piston mass and shape, crankcase lubrication, engine speed, and chamber pressure. The frequencies of most interest are those between 1500 and 3000 Hz.

5.3.2 Timing Gear Rattle

On many engines, the camshaft, which operates the rocker arms and valves, is driven by the crankshaft via a set of gears. In operation, the crankshaft has small fluctuations in rotational velocity due to the imposed torques of the compression and expansion strokes occurring in the cylinders. The camshaft too is subjected to fluctuating torques as the rocker arms pass from rising lobe face to falling lobe face. These fluctuations of the two shafts result in timing gear tooth rattle as the backlash in the meshed gears is taken up. The rattle is rich in harmonics, covering much of the engine noise spectrum.

5.3.3 Fuel Injection Equipment

Diesel engine fuel injection equipment can constitute a variety of noise sources, depending on design. Engine-driven cam-operated pumps rattle in a manner similar to the timing gears. Normally, the injection needle is held firmly in its seat until opened by high hydraulic pressure. As the opening pressure declines, the needle slams back into its seat in the injection nozzle holder,

which generates pulses in the hydraulic fluid and reverberation in the nozzle holder. The impact noise is rich in harmonics, and can be a distinctive noise source in the high frequency range at low engine speeds.

5.3.4 Firing Rate

The detonation of the air-fuel mixture in the chamber causes localized deflections of the cylinder head directly above the firing cylinder. The resulting wave propagates throughout the cylinder head, inducing vibration in the cover. The exciting frequency is, of course, directly related to the number of cylinders and the engine speed. For a typical 4-stroke, 4-cylinder, high-speed, light-duty diesel engine operating at rated speed, the exciting frequency determined by the firing rate is 100 to 150 Hz. This is normally a clearly visible and pronounced component of the noise spectrum, as shown in Figure 5-4.

5.3.5 Piston-Connecting Rod Resonance

Another induced source of engine noise is due to the reciprocating motion of the pistons and the cylinder pressures. The lower end of the piston connecting rod assembly is firmly attached to the crankshaft and the piston is laterally constrained by the cylinder walls, but has no axial restraint except the connecting rod. As a result of the reciprocating motion, the piston connecting rod assembly acts much like a spring (the connecting rod), with a mass on the end (the piston), all being excited by a driving force.

This type of system has a resonant frequency which depends upon such factors as the piston mass, engine speed, and connecting rod mass, length, and stiffness (Ref. 5-19). The resonant frequency tends to lie in the 2000 to 3000 Hz region, and is a major source for vibration-induced noises throughout the engine structure (Ref. 5-17).

5.3.6 Crankshaft-Main Bearings

In response to the excitation forces of the cylinder and piston connecting rod assembly, the crankshaft and its main bearings vibrate at induced resonances. The crankshaft vibrates as a beam simply supported by its main bearings at 1000 Hz and the flywheel and timing gear amplify and transmit the vibrations to other engine regions (Ref. 5-17). Similar shaft vibrations at 200 Hz have been noted in the camshaft at low engine speeds. The main bearings also act to further transmit the exciting forces.

5.3.7 Block and Crankcase Modes

The block and crankcase, which are subjected to all of the preceding exciting forces and resonances, respond by transmitting the forces and by adding their own vibrational resonances. The primary resonances are due to free-free horizontal bending modes and torsional modes. The frequencies of resonance depend on the engine structure, the excitations, and the engine supports. The bending resonance frequency generally lies in the 400 to 800 Hz region, with the higher frequency found in smaller engines. Typically, the bearings resonate at 1000 Hz, and the crankcase panels and bearing supports have resonant modes in the 2000 to 3000 Hz region (Ref. 5-17).

5.3.8 Oil Pan

The sump, or oil pan, is a significant source of diesel engine noise in all sizes of vehicles. The vibrational excitations, especially those of the lower crankcase, connecting rod, crankshaft, and main bearings, induce a resonance mode near 1000 to 3000 Hz (Ref. 5-20). Typically, the oil pan acts as an effective noise radiator, with up to 30 percent of the radiated engine noise originating there (Ref. 5-10).

5.3.9 Cover Modes

Light structural covers on the outside surface of diesel engines act as efficient noise radiators: Analogously to the oil pan, the various covers resonate at frequencies determined by the combustion, mechanical, and structural forces, and their own composition. Rocker cover, manifolds, injection pump housing, timing gear cover, and other structures contribute about 30 to 40 percent of total engine noise. The vibration modes have resonances which typically lie in the 800 to 3000 Hz region (Ref. 5-21). Figure 5-6 illustrates the contributions of various structural panels.

5.3.10 Hydraulic Slap

Hydraulic slap occurs when a film of fluid is squeezed between two metal parts. Examples of this phenomenon are the pressure pulses in the fuel, water, and lubrication circuits due to pumping actions, and in the lubrication film between moving parts in the crankcase. In this case, the fluid films transmit the noise generated by the impacts to other engine locations.

FIGURE 5-6. NOISE SPECTRUM OF ENGINE STRUCTURAL COMPONENTS
(Ref. 5-17).

5.4 NOISE REDUCTION TECHNIQUES

Engine noise may be reduced in several ways, including structural modification, direct force reduction, noise suppression, noise modification, isolation, and shielding. Each technique applies to one or more of the various noise sources. In addition, there are a few techniques which result in a reduction of overall engine noise. However, generally engine noise cannot be significantly reduced by treating a single noise source, unless that one source is significantly noisier than all others. For example, in an engine having four equal noise sources contributing to an overall noise level of 96 dB(SPL), the elimination of a single source reduces the overall noise level by only 1.2 dB(SPL). Elimination of two sources reduces the overall level by 3 dB(SPL), while elimination of three sources results in a 6 dB(SPL) reduction.

5.4.1 Combustion Noise Reduction

Combustion noise is one of the most important engine noise sources, and the most difficult one to effectively treat. Because combustion noise is

directly related to combustion, it can only be reduced by modifying the combustion process itself. However, this approach is frequently not practical because of offsetting penalties. For example, an increase in engine compression ratio might reduce diesel knock during the cold-start phase, but only at the expense of an increase in specific fuel consumption. In general, a reduction in combustion noise is accompanied by a decrease in oxides of nitrogen emissions (NO_x) and an increase in specific fuel consumption and smoke. In the following discussion, the effects of combustion noise reduction techniques on NO_x , and fuel consumption are analyzed. The options considered are summarized in Table 5-3.

TABLE 5-3. COMBUSTION NOISE REDUCTION TECHNIQUES AND IMPACTS.

Controlling Factor	Treatment	Engine Rating Point	Overall Noise Reduction dB(A)	Impact of Treatment		
				BSFC	NO_x	Smoke
Rate of Pressure Rise	Matched Turbocharging	Peak Torque	3-4	Moderate Increase	Minor Increase	Significant Decrease
		Full Load Rated Speed	10-12	Minor Decrease	Moderate Decrease	Significant Decrease
Injection Rate	Increase Injection Rate and Reduce Ignition Delay	Full Load Rated Speed	3	Negligible Effect	Significant Decrease	Minor Decrease
Ignition Delay	Fumigation	Peak Torque	5	Negligible Effect	Negligible Effect	Moderate Decrease
		Full Load Rated Speed	Negligible Effect	Significant Increase	Negligible Effect	Moderate Decrease
Fuel Composition	Increase Fuel Cetane Number	Peak Torque	4	Negligible Effect	Minor Increase	Unknown
		Full Load Rated Speed	3	Negligible Effect	Moderate Increase	Unknown
Rate of Pressure Rise and Ignition Delay	Exhaust Gas Recirculation	Idle	4-5	Minor Increase	Moderate Decrease	Negligible Effect
Chamber Turbulence	Low Turbulence Chamber	2/3 Load 2500 rpm	5-6	Significant Increase	Minor Decrease	Minor Increase

Turbocharging does not reduce combustion noise, but rather modifies it. In this case, pressure rise rate is reduced at the expense of a higher peak pressure and increased mechanical noise. Indeed, under light load conditions, the total combustion noise of a turbocharged engine may actually exceed that of

a naturally aspirated engine (Ref. 5-9). The net effect is a reduction of combustion noise in the higher frequency range and an increase in noise in the lower frequency range (Ref. 5-22). As a result, the overall engine noise spectrum shows a noise reduction in the sensitive 800 to 3000 Hz range and a noise increase in the less critical lower frequency regime. The magnitude of the reduction depends upon engine speed and load. Reductions of as much as 12 to 15 dB(A) are possible at full load and rated speed, while only 4 to 6 dB(A) are possible at low speeds. In addition, the turbocharged engine provides simultaneous improvements in fuel consumption, NO_x , and smoke emissions (Ref. 5-23).

By increasing the rate of injection and simultaneously reducing the ignition delay, modest improvements in combustion noise are possible. However, the increased injection rate also results in a small increase in mechanical noise, thus offsetting part of the gain. In addition to the observed noise reductions of approximately 3 dB(A), net decreases in NO_x and smoke are possible, with negligible effects on specific fuel consumption (Ref. 5-23). Ignition delay can be also reduced by fumigation, that is by spraying fuel directly into the intake manifold. While 20 percent fumigation offers modest advantages at peak torque conditions, there are negating disadvantages at full load and rated speed. For example, a 5 dB(A) reduction in noise at peak torque is coupled with innocuous effects on fuel consumption and emissions. However, under heavy acceleration conditions, the noise reduction potential of this technique vanishes and a severe fuel penalty appears (Ref. 5-23).

Combustion noise is dependent upon both cetane number (CN) and fuel composition. An increase in CN, in conjunction with reduced ignition delay, provides a nearly linear reduction in noise. For example, in one test, an increase in CN from 53 to 60 has resulted in a 4 dB(A) reduction in noise, with minor effects on other engine parameters (Ref. 5-23). However, the penalty associated with the use of higher CN is the requirement of more severe refinery processes, resulting in a reduction in total refinery fuel yields. Also, for a given CN, fuel composition has a bearing on combustion noise. For example, commercial diesel fuel, augmented by 33 percent unleaded gasoline to yield a CN of 46, produces a lower noise level than a naphthenic fuel of the same CN (Ref. 5-24).

Diesel knock is especially evident when idling a cold engine, because of a higher pressure rise rate relative to a hot engine. Rapid cold-

start noise reduction is possible by using a large fraction of exhaust gas recirculation (EGR). Test data from a Volkswagen Rabbit diesel engine indicate a noise reduction of 4 dB(A) within 10 seconds after a cold start at -20°C using 40 percent EGR (Ref. 5-6). Apparently, the effect of the EGR is to slow the burn rate by introducing a large fraction of inert gas into the chamber. This is accompanied by a reduction in NO_x emissions and fuel economy (Ref. 5-6).

Since combustion noise is produced in part by random pressure fluctuations, a reduction in chamber turbulence generally leads to a reduction in the pressure rise rate and lower combustion noise. This is frequently accompanied by an increase in fuel consumption (Ref. 5-24).

5.4.2 Mechanical Noise Reduction

Abatement of mechanical noise is a most difficult task, and is constrained by many factors, including lubrication requirements, engine wear, thermal expansion, clearances, and component inertia. A number of different techniques, listed in Table 5-4, have been investigated in the past. These techniques are aimed at reducing the ability of the transient forces to generate and transmit noise in mechanical parts, rather than eliminating or reducing these forces themselves.

Noise reduction techniques are frequently intended to reduce piston slap noise by lowering the magnitude of piston-cylinder wall impact forces. One technique uses wrist pins which are offset from the piston center. By allowing piston impact to occur when the net driving forces on the piston are low, this approach results in noise reductions of 1 to 2 dB(A) (Ref. 5-24). However, the use of pin offset may require chamber redesign, and excessive offset, especially to the major thrust side, can lead to increased ring wear and reduced piston lubrication (Ref. 5-22). Alternately, the force of the impact can be absorbed by using a more resilient piston. For example, strips of various polymer materials may be inserted on both thrust sides of the piston, or a complete resilient skirt of polymer may be installed. Depending on the material and its configurations, a 4 to 5 dB(A) reduction may be achieved (Ref. 5-16). However, the use of polymers in the piston environment raises the question of long-term durability, although wear properties of some polymers are claimed to be acceptable (Ref. 5-25).

TABLE 5-4. MECHANICAL NOISE SOURCES AND REDUCTION TECHNIQUES.

Noise Source	Treatment	Typical Noise Reduction, dB(A)	Impact of Treatment
Pistons	Offset Wrist Pins	2	Possible Ring Wear, Reduced Piston Lubrication. Chamber Redesign May Be Necessary.
	Polymer Piston Inserts	4-5	Possible Reduction in Long-Term Piston Thermal Stability and Mechanical Integrity
	Reduced Clearances	2-3	Pistons With Controlled Thermal Expansion Necessary.
	Modified Piston Lubrication	2-3	Potential Reduction in Oil Consumption, Unless Upper Scraper Ring Fails.
	Articulated Pistons	1-2	Better Chamber Sealing
Timing Gears	New Gear Designs	2	Increased Gear Wear
	Chain/Belt Drive	8	Potential Weight Reduction
	Reduced Backlash	2	Increased Gear Wear
Fuel Injection Equipment	Modified Mounting	2-3	Negligible Impact
	Change Needle/Holder Masses	2-3	Negligible Impact

Another approach involves the reduction of the piston-cylinder wall clearance to reduce piston impact force. In this case, the differential thermal expansion rates of both the cylinder and the piston must be controlled more rigidly. Also, additional piston strength is required, since the piston deformation during operation must be reduced and lightweight pistons must be used with care. Noise reductions for such thermally controlled pistons average 2 to 3 dB(A) (Ref. 5-22). Because of the higher maximum operating temperatures of turbo-charged engines, use of reduced clearances in these engines is even more difficult (Ref. 5-22).

Modification of the piston lubrication system is another approach for providing improved lubrication film properties to cushion the impact. This

may be accomplished by injecting an oil cushion into the ring belt or by adding two scraper rings to the piston skirt. In addition, dual scraper rings offer the potential for reducing engine oil consumption. However, in case of a failure of the upper scraper ring, oil consumption will increase instead (Ref. 5-22).

The use of a multi-piece piston permits reduction of the impact forces. In general, the articulated piston consists of a separate crown and skirt, both joined to the connecting rod by the same piston pin. The separate crown is less affected by the lateral forces, and its rings are better able to provide chamber sealing. In addition, the differential motion of crown and skirt allows separate optimization of their clearances (Ref. 5-26).

The noise reduction treatments of timing gear rattle are designed to mitigate the noise-generating capacity of the transient torque changes in the shaft. Several treatments relate to gear redesign. One approach involves reduction of the free play in the gears to diminish the backlash between gear teeth. This approach requires reduction in the tolerances during gear manufacture and installation, because a buildup of stress might cause increased gear wear or breakage. The use of resilient gears has been suggested, which would absorb a portion of the impact energy. However, no significant noise reductions have been achieved with this approach. Because the impact force is proportional to the inertia of the gears, the force could also be reduced by using lower inertia gears. These three techniques are projected to permit a small overall noise reduction of about 2 dB(A).

The most effective technique for reducing timing gear noise is to eliminate the meshed gears and replace them by a chain or toothed-belt drive. An overall 8 dB(A) reduction is possible with this approach, in addition to a small net weight reduction (Ref. 5-17).

A number of other mechanical noise reduction approaches have been identified, including backlash reduction to minimize injection pump rattle, special mounting of the fuel injection pump on the engine, and reduction of the injection nozzle needle-holder impact forces. By mounting the base of the pump rigidly to the engine rather than mounting it on a flange bolted to an engine cover, a 2 to 3 dB(A) reduction has been achieved (Ref. 5-27). Reduction of the needle-holder impact forces, by reducing needle mass and increasing holder mass, has resulted in noise reductions of 2 to 3 dB(A) (Ref. 5-28).

5.4.3 Structural Response Noise Reduction

Structural response noise treatments may be grouped into three major categories: stiffening, isolation, and shielding. Stiffening a structure generally involves adding integral ribbed crossmembers and corrugations, or selectively thickening certain areas. Generally, the intent of stiffening is to shift the structural resonances to higher frequencies where their radiation has less impact on the overall noise. Of course, the added material usually results in increased engine weight. Also, some work has been done in the area of alternate component materials. Overall noise reductions of 1 to 4 dB(A) have been achieved with extensive stiffening.

Isolation requires physical separation of the radiating component from the engine structure by means of absorbent intervening structures. For example, the oil pan may be cut close to its point of attachment to the block and remounted with a resilient silicon elastomer. Isolation is restricted to those components that do not bear heavy loads. Noise reductions of 2 to 4 dB(A) are typical for isolation treatment approaches.

Shielding involves the use of thin lightweight covers on specific engine components. In this case, a resilient, absorbent layer, often fiberglass, synthetic rubber, or silicon elastomer, is generally placed between these components and the cover. Noise reductions of 5 to 10 dB(A) are typical for shields, depending on type and location. Figure 5-7 indicates the magnitudes of noise reduction that have been achieved in structural components.

In addition to these three major reduction techniques, other special treatments are applicable to specific components. However, these special treatments are generally of limited value because of counteracting factors. For example, hydraulic slap in the crankshaft bearings can be lowered by reducing clearances, but this requires close production tolerances and parts manufactured from controlled thermal expansion materials. Alternately, a higher viscosity oil could be used, but at the expense of increased knock during cold-start (Ref. 5-6). Similarly, methods other than shielding for reduction of structural vibrations in load bearing components involve major redesign of engine components that have already been optimized for durability and efficiency.

FIGURE 5-7. STRUCTURAL RESPONSE NOISE REDUCTION TECHNIQUES AND LEVELS OF REDUCTION (Ref. 5-29).

5.4.4 General Techniques

Two noise reduction procedures involve treatment of the engine as a whole rather than treatment of specific components. These are (1) engine redesign for lower noise emissions, and (2) shielding of the entire engine. Engine redesign entails increasing the number of cylinders and reducing the bore and stroke of each individual cylinder. Figure 5-8 shows the relationships between engine speed, cylinder bore, and noise for three engine types (Ref. 5-22). According to Figure 5-8, a 2.4 liter IDI diesel engine with a bore-to-stroke ratio of 0.98 and operating at a rated speed of 4200 rpm emits 99.2 dB(A) in a 4-cylinder configuration, and 97.2 dB(A) with 5 cylinders. If the speed of the 5-cylinder engine is reduced to a 4000 rpm rated speed, the level declines to 96.3 dB(a). The engine compartment of a typical

FIGURE 5-8. ENGINE NOISE PREDICTION CHARTS (Ref. 5-22).

compact automobile provides 4.4 dB(A) attenuation of engine noise, primarily above 400 Hz (Ref. 5-30). By reducing the size of the front and bottom openings, 5 to 6 dB(A) additional noise reduction is possible (Ref. 5-31) and a 2 to 3 dB(A) attenuation is obtained by lining the compartment with sound absorbent material (Ref. 5-30). Alternately, a separate enclosure may be placed around the entire engine. Figure 5-9 indicates the magnitude of reduction possible with engine encapsulation (Ref. 5-32). However, encapsulation has several disadvantages. For example, a larger cooling system or a secondary fan would be required to restore air circulation around the engine and vehicle weight may be increased. Also, engine maintenance is impeded by the shell. However, advanced encapsulation techniques have been devised to offset these deficiencies. The weight penalty and reduced cooling of the engine can be partially offset by making the acoustic enclosure an integral part of the engine. The engine and enclosure may be made structurally self-supporting with modified engine mounts that reduce vibration transmission to the chassis. The timing gears and fuel injection equipment drives can be moved to the flywheel end of the engine, allowing a solid capsule wall at the front of the engine, while still permitting routine maintenance (Ref. 5-32).

FIGURE 5-9. ENGINE NOISE SPECTRUM FOR A PROTOTYPE ENGINE ENCLOSURE (Ref. 5-32).

5.5

NOISE LEGISLATION AND FUTURE R&D NEEDS

The EPA has shown concern over projected negative impacts on traffic noise as a result of larger fleet fractions of light 4-cylinder spark ignition and diesel engine powered vehicles. This concern, if confirmed by noise emissions testing, will likely be promulgated as a noise emissions standard. Because of dual emphasis on both the instantaneous noise level of individual vehicles and the total daily noise contribution of specific vehicle classes, the noise standard could apply selectively to light diesel vehicles, 4-cylinder engine vehicles, or both; rather than to the entire light-duty vehicle fleet. However, prior to setting a noise emission standard, data on the impact of implementation would be required. The significant fuel economy advantage of the diesel over its SI counterpart, and the moderate difference in operational noise levels compared with heavy-duty diesel trucks, makes an outright noise-based ban on light-duty diesel engines unlikely. However, the economical level of noise reduction has not been extensively explored. Ricardo Consulting Engineers forecast a common world legislative level of 75 dB(A), based upon the ISO R362 Procedure (Ref. 5-33). By comparison, the ISO R362 noise levels of several existing passenger automobiles average 77.5 dB(A) for SI vehicles, and 79.9 dB(A) for diesel vehicles (Ref. 5-12). A noise

reduction of 3 to 5 dB(A) is certainly possible technically, although many of the noise reduction techniques would require extensive redesign of major engine components, thus introducing economic factors.

Since extensive work has been performed on specific noise reduction methods, future work should be addressed to the integration of the various treatments and to the determination of their effects on engine longevity. Specific guidance is afforded by the Quiet Truck Program begun by DOT and currently managed by EPA (Ref. 5-34). The on-going program has demonstrated the practical reduction of overall vehicle noise in heavy-duty trucks by 10 dB(A) (Ref. 5-34). It has also resulted in the development of a DOT-sponsored noise control handbook to assist owners and operators in diagnosing and reducing heavy-duty vehicle noise, using commercially available retrofit components. The EPA is also pursuing a companion program for noise reduction in various systems utilizing internal combustion engines. In addition, a number of individual researchers are currently, or have recently been, engaged in limited overall noise reduction projects. However, a specific light-duty vehicle noise reduction program of the Quiet Truck Program scope and depth is not currently being addressed. Development of a Quiet Engine Demonstration to address the economic and longevity aspects of light-duty vehicle noise reduction is a fundamental future need. Development of a light-duty engine noise control handbook, similar to the DOT-sponsored handbook for heavy trucks, is highly desirable.

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SECTION 6

DIRECT INJECTION LIGHT-DUTY DIESEL ENGINE TECHNOLOGY

6.1

ENGINE CHARACTERISTICS

As a direct result of the rapidly increasing cost of automotive fuels during the past several years and in light of the promulgation of increasingly stringent Corporate Average Fuel Economy (CAFE) standards for Model Year 1978 through 1985, a growing number of automobile manufacturers and other organizations have become interested in the direct injection (DI) diesel engine as a power plant for automobile and light-duty truck applications (Refs. 6-1 through 6-12). Based on many years of development work on heavy-duty diesel engines, it has been shown that DI diesels have a fuel consumption advantage of up to 15 percent relative to equivalent indirect injection (IDI) diesel engines. Although the DI combustion system is not new to the light-duty engine sector, as evidenced by the existence of a number of small industrial DI production diesel engines, the DI concept has not yet been applied to automobiles because of a number of inherent problem areas (Refs. 6-1 and 6-2). These include:

- (1) Limited Speed Range: Relative to IDI diesel and spark ignition (SI) engines, DI diesels of current design have a limited speed range and a relatively low maximum speed capability. As a result, power output per unit displacement is lower than for other internal combustion engines, and driveability characteristics are not compatible with automobile manufacturers' requirements.
- (2) High Gaseous Exhaust Emissions: Current DI diesel engines have significantly higher HC and NO_x emissions than equivalent IDI diesels. For example, computer simulations performed by AVL of Austria over the Federal Urban Driving Cycle indicate HC and NO_x emissions as much as eight times and three times higher, respectively, than for IDI engine equipped vehicles of the same size and performance capability.
- (3) Excessive Odor: Generally, the concentrations of odorous and irritating exhaust compounds are higher for DI diesels than for IDI configurations, and have been one more reason against the use of the DI diesel in light-duty automobile applications.

- (4) High Noise Levels: DI diesel engines of current design have significantly higher noise emissions than IDI engines. The shape of the combustion chamber pressure versus crank angle (CA) schedule is the principal parameter affecting the level of combustion generated engine noise. In IDI engines, the pressure rise rate in the main chamber is generally rather mild, because the combustion process is initially confined to the prechamber. Conversely, in the single chamber DI diesel the combustion pressure in the main chamber rises much more rapidly, resulting in an increase in combustion noise.
- (5) High Engine Weight: As a result of the higher peak combustion pressures developed in DI diesel engines, load carrying structural engine components are heavier than in IDI engines, adding to the overall weight of the engine. In addition, the lower speed capability of the DI engine increases engine size for a given rated power level.

6.2

LIGHT-DUTY DIRECT INJECTION ENGINE DESIGN

AVL of Graz, Austria, has pioneered the development of small, high-speed DI diesel engines for potential application in automobiles since 1974, partly with in-house funding, and partly in cooperation with other organizations. Since the inception of this program, AVL has expended considerable effort in the area of combustion process modification as a means of solving the noise and weight problems. This work has culminated in the design and testing of a number of new small and lightweight prototype engine configurations that have the potential for application in automobiles and light-duty trucks.

The principal features incorporated by AVL in its DI engine design are aimed at accelerating the rate of combustion, particularly in the high-speed regime, while minimizing smoke emission levels in the exhaust. Specific design modifications are the use of (1) helical intake ports, (2) bowl-in-piston type combustion chambers combined with a turbulence rim, (3) multi-hole fuel injection nozzles, (4) fuel injection timing retard, (5) increased engine compression ratio, and (6) zero-sac injection nozzles.

The use of helical intake ports is intended to improve the air-fuel mixing process, while the addition of a turbulence rim and the use of a multi-hole nozzle is intended to increase the rate of combustion and to improve air utilization. As a result, engine output power is increased significantly in

the high-speed regime, accompanied by a reduction in smoke emissions over the whole speed range. Injection retard is applied as a means of NO_x control, at the expense of a small increase in fuel consumption. HC reduction is achieved by increasing engine compression ratio, combined with the use of zero-sac valve seal orifice (VSO) type injection nozzles. In addition to reducing HC, these modifications have resulted in marked reductions in peak chamber pressure and the emissions of odor, irritants, white smoke, and noise, and in significant improvements in the cold-start characteristics of the engine. These factors are further examined in the following subsections.

6.2.1 Combustion Chamber Modifications

The effects of combustion chamber modifications on the minimum permissible fuel-air equivalence ratio, consistent with a Bosch smoke meter reading of 4, and on brake mean effective pressure (bmep) are shown in Figure 6-1 (Ref. 6-1). In these tests, which were performed on a 2.2 liter DI diesel engine, fuel injection timing was varied as a function of engine speed to maintain NO concentrations of 550 parts per million. This level corresponds to NO_x emissions of 1.5 g/mi in a compact size car operated over the Federal Urban Driving Cycle. Combustion chamber A is of conventional design, while configurations B, C, and D are new designs incorporating a turbulence rim. In addition, chamber D uses an optimized fuel injection system. Since the test engine was a modification of an existing IDI diesel engine, and not an entirely new design, it was not possible to incorporate the optimal intake port configuration. This deficiency is considered by AVL to be responsible for the relatively low bmep levels achieved at high engine speeds. According to AVL, this problem could be alleviated by means of optimized helical intake ports, which would assure volumetric efficiencies of 90 percent and 85 percent at peak torque and rated power, respectively. With these improvements, the bmep of the DI engine is expected to be identical to that of equivalent IDI configurations.

As shown in Figure 6-1 the smoke limited fuel-air equivalence ratio of combustion chamber D, which incorporates a compression ratio of 22.9:1, is reduced significantly over the whole speed range, relative to baseline A and the other two chamber modifications. These improvements are accompanied by corresponding increases in bmep.

FIGURE 6-1. EFFECT OF COMBUSTION CHAMBER MODIFICATIONS ON AIR-FUEL EQUIVALENCE RATIO AND BRAKE MEAN EFFECTIVE PRESSURE (Ref. 6-1).

Smoke emissions, bme_p, and brake specific fuel consumption (bsfc) of a 1.5 liter swirl chamber IDI diesel and a 1.6 liter DI diesel are shown in Figure 6-2 as a function of engine speed at full load (Ref. 6-1). The IDI engine is a Volkswagen Rabbit, while the DI engine was designed by AVL. Both engines are calibrated to meet a NO_x standard of 1.5 g/mi. As indicated, smoke and bme_p are quite comparable for the two engines, while bsfc of the DI engine shows a 14 percent advantage over the whole speed range.

Turbocharged swirl chamber and DI engine performance parameters at full load are presented in Figure 6-3 (Ref. 6-1). The IDI engine is a 5-cylinder 3 liter Mercedes-Benz engine, while the DI engine represents a 4-cylinder AVL design, having a displacement of 2.1 liter. The observed trends in smoke, bme_p, and bsfc are similar to those shown in Figure 6-2 for the naturally aspirated engine.

FIGURE 6-2. FULL LOAD SMOKE, BMEP, AND BSFC OF NATURALLY ASPIRATED DI AND IDI DIESEL ENGINES - 1.5 g/mi NO_x STANDARD (Ref. 6-1).

6.2.2 Engine Noise

Under full load operating conditions and at a distance of 1 meter, DI engines have approximately 1 to 2 dB(A) higher noise emissions than their IDI counterparts. Conversely, at idle, the noise emissions of DI engines

FIGURE 6-3. FULL LOAD SMOKE EMISSIONS, BMEP, AND BSFC OF TURBOCHARGED DI AND IDI DIESEL ENGINES - 2.0 G/MI NO_x STANDARD (Ref. 6-1).

are approximately 0 to 2 dB(A) lower. Vehicle noise tests have confirmed these trends. For example, in the ISO driveby test, the DI engine equipped vehicle was about 1.5 dB(A) noisier than the IDI, while no difference in idle noise was noted for the two vehicles.

The low combustion noise of the AVL engine relative to conventional DI engines is directly attributed to the improved combustion pressure and heat release schedules shown in Figure 6-4 (Ref. 6-1). As indicated, combustion starts in a smooth manner, with pressure rise rates remaining below 4 bar per degree CA. This characteristic is the combined result of a significant reduction in the ignition delay time achieved with the increased compression ratio, and the fact that the first spike in the heat release curve is much lower than in conventional DI engines. With turbocharging, the initial heat release spike is almost completely eliminated, and the pressure trace of the engine resembles that of an IDI configuration.

6.2.3 HC Emissions

The effect of engine compression ratio variations on the HC emissions of a 2.2 liter Mercedes-Benz engine, converted by AVL to DI operation,

FIGURE 6-4. COMBUSTION CHAMBER PRESSURE AND HEAT RELEASE RATES FOR AVL DI DIESEL ENGINE (Ref. 6-1).

and installed in a 3500 lb inertia weight vehicle is illustrated in Figure 6-5 (Ref. 6-1). In general, HC declines with increasing compression ratio, and is strongly affected by the engine calibration selected to achieve a certain NO_x level. As indicated, a compression ratio of at least 22:1 is required to meet the 0.41 g/mi HC emissions standard for 1980 model year automobiles.

Another parameter affecting HC emissions is the injector sac volume. Tests conducted by AVL on a 2.1 liter prototype DI engine operated at 2500 rpm indicate HC emissions between 300 and 400 parts per million C_1 for its mini-sac configuration, and between 50 and 100 parts per million C_1 for the zero-sac VSO nozzle design. AVL considers the use of VSO nozzles mandatory for the achievement of the 0.41 g/mi HC standard in production vehicles.

6.2.4 Engine Starting

Advanced DI diesel engines of the type currently under development by AVL show more favorable cold-start and warmup characteristics than IDI engines. This is the direct result of the lower heat losses associated with the use of a single combustion chamber per cylinder in the DI engine.

Figure 6-5. HC EMISSIONS VERSUS ENGINE COMPRESSION RATIO - 2.2 LITER DI DIESEL ENGINE IN 3500 LB INERTIA WEIGHT AUTOMOBILE (Ref. 6-1).

No starting aids are required for temperatures above 32°F, and the engine generally starts instantly under these conditions. For temperatures between about +5°F and -5°F, cranking for up to 30 sec may be required to achieve engine start. Starting aids, such as an intake manifold air heater and/or advanced fuel injection timing are required for temperatures between about -5°F and -30°F.

6.2.5 Gaseous Emissions and Fuel Economy

Regulated gaseous emissions and fuel economy data are presented in Figure 6-6 for DI and IDI diesel equipped automobiles operated over the Federal Urban Driving Cycle without the use of exhaust gas recirculation (EGR) (Ref. 6-1). As shown, the emissions for the two engine types are very similar, while the fuel economy of the DI vehicles is about 15 percent higher than for the IDI cars. The higher fuel economy shown for the turbocharged (TC) 3000 lb vehicle relative to the naturally aspirated (NA) configuration is directly related to the use of a lower numerical rear axle ratio in the turbocharged car. This choice permits the engine to operate in the more fuel efficient low-speed - high-load regime.

The data clearly show that achievement of a NO_x standard of 1.5 g/mi will be difficult without EGR for either engine, except perhaps in vehicles with inertia weights of 2250 lb or less.

The effect of EGR on gaseous emissions, smoke, and bsfc was determined experimentally by AVL over wide ranges of bmep and EGR flow rates. In general, NO_x and HC emissions decline significantly with increasing EGR, at the expense of a marked increase in smoke. For example, at 2000 rpm and a bmep of 4 bar, the use of 30 percent EGR resulted in NO_x and HC reductions of 70 percent and 40 percent, respectively. These improvements were accompanied by a 200 percent increase in smoke and a 10 percent increase in CO.

Emissions and fuel economy data determined experimentally by AVL, using modulated EGR, are presented in Figure 6-7 (Ref. 6-1). In all vehicles NO_x was reduced to less than 1 g/mi, accompanied by a moderate increase in CO and a small improvement in the fuel economy of the DI vehicles. The observed fuel economy improvements are attributed to the more advanced fuel injection

FIGURE 6-6. EXHAUST EMISSIONS AND FUEL ECONOMY OF DI AND IDI DIESEL AUTOMOBILES - NO EGR (Ref. 6-1).

FIGURE 6-7. EXHAUST EMISSIONS AND FUEL ECONOMY OF DI AND IDI DIESEL AUTOMOBILES - WITH EGR (Ref. 6-1).

timing that may be used in conjunction with EGR. The fuel economy improvements of the DI vehicles relative to the IDI vehicles are 20 percent for the heavier vehicles, and 22 percent for the lightest vehicle class considered in the figure. AVL noted a number of problems associated with the use of EGR. These include deposit buildup in the intake system, lube oil contamination, increased wear of vital engine parts, and increased particulate emissions.

6.2.6 Particulate Emissions

Particulate emissions of naturally aspirated and turbocharged DI and IDI diesel engine equipped automobiles are presented in Figure 6-8 (Ref. 6-1). As indicated, without the use of EGR the 0.2 g/mi particulate level might be achievable in small vehicles at low mileage, although the margin of safety might

FIGURE 6-8. PARTICULATE EMISSIONS FOR DI AND IDI DIESEL AUTOMOBILES WITH AND WITHOUT EGR - 2250 LB INERTIA WEIGHT (Ref. 6-1).

not be sufficient to account for hardware-to-hardware and test-to-test variations, and for mileage accumulation. The use of EGR to achieve NO_x levels below 1 g/mi is accompanied by a two-fold increase in particulates. It is interesting to note, however, that the DI data, which are based on both AVL measurements and calculations, show a trend towards lower particulate emissions, compared to the IDI vehicle data. This trend is consistent with the previously discussed lower DI smoke levels at part load.

6.3 FUEL INJECTION SYSTEM REQUIREMENTS

The achievement of rapid, low-pressure combustion in DI diesel engines, which is required for low emissions of gaseous species, particulates, odor, and noise, is predicated upon the availability of improved fuel injection systems. As previously noted, low HC emissions require the use of VSO nozzles in conjunction with nozzle and needle guide diameters of 7 mm and 4.5 mm, respectively. Nozzles of this type have the demonstrated capability of providing faster closing, and the small displacement of the needle assures a higher rate of injection at the beginning of the injection process. Desirable fuel injection system parameters for DI engines are as follows:

Injection Timing: Constant timing is generally preferred over the whole load range. However, in the very light load regime, a timing advance of less than 4 degrees CA might be desirable.

Start and Warmup: To reduce white smoke, a timing advance of about 5 degrees CA is desirable during starting and warmup at very low ambient temperatures.

Injection Duration: The optimal fuel injection period at full load varies from about 10 degrees CA at 1000 rpm to about 30 degrees CA at 5000 rpm.

Optimal Injection Pressure: The optimal fuel injection pressure varies from about 200 bar at 1000 rpm to about 700 bar at 5000 rpm. These high-pressure levels are required to assure sufficiently low HC emissions at engine speeds below 3000 rpm, which is the range corresponding to the Federal Urban Driving Cycle. In general, the lower the desired emission levels, the smaller the required spray hole area and the higher the injection pressure.

Unit Injector: The presence of secondary injection is an undesirable feature of some existing fuel injection systems, because

of the associated increase in HC emissions. These problems were eliminated by AVL by means of a unit injector which is being used in place of the conventional injection system. The unit injector has a number of significant advantages, including (1) the capability of providing a more precise fuel injection rate versus CA schedule, which results in lower smoke emissions, (2) absence of cavitation in the fuel lines, (3) lower noise emissions, (4) improved cold-start characteristics, because good fuel atomization is achieved of the small quantities of fuel required during an engine start, (5) lower power requirements, (6) more uniform fuel delivery rates to different cylinders, and (7) smaller number of different parts. The disadvantages associated with the use of unit injectors are (1) the need for a linkage system to the governor, (2) a more complex timing schedule, (3) the requirement of fuel supply and return lines, and (4) some difficulties generally associated with the torque curve matching.

Based on AVL's experience, the advantages of the unit injector far outweigh its drawbacks, and this injector is recommended by AVL for DI diesel engines. The use of unit injection in conjunction with the other improvements identified in this section of the report, provides the opportunity for overcoming the deficiencies of current DI engines, including their low specific output power, limited speed range, high exhaust emission rates, and high engine weight.

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SECTION 7

HEALTH EFFECTS OF DIESEL EXHAUST EMISSIONS

7.1 INTRODUCTION

This section provides a brief examination of diesel exhaust emissions related health effects issues. Subsection 7.2 treats the composition and health effects of light-duty diesel exhaust emissions. The principal health effects research methodologies currently in use are outlined in Subsection 7.3, while Subsection 7.4 identifies health effects research needs. In addition to hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x), diesel engines emit a number of currently unregulated species, including particulates, sulfates, and odor. Of particular concern are the particulates, which consist of porous carbonaceous agglomerations containing adsorbed aliphatic and aromatic compounds and posing potential health threats. Benzo(a)pyrene (BaP), is frequently discussed, but associated with it are many other polynuclear aromatics (PNA) or polynuclear aromatic hydrocarbons (PAH).

7.2 COMPOSITION AND HEALTH EFFECTS OF DIESEL EXHAUST

Considering the typical composition of current diesel exhaust, the widespread use of diesel engines poses a potential threat to human health. Diesel exhaust contains known mutagens, known carcinogens, and known respiratory irritants. The extent to which this potential threat will actually be realized is currently not understood and is the subject of current experimental work. The final integrated assessment of the health threat will include projected risks (Ref. 7-1). Despite the presence of compounds known to have adverse effects on human health, there is as yet no history of such adverse effects among humans chronically exposed to diesel exhaust.

As an illustration of the current dichotomy of results in health studies, BaP, which is a known human carcinogen, is exemplary. This compound is emitted by diesel engines in substantially larger amounts than by equivalent catalyst equipped spark ignition engines, and has been implicated with cancers resulting from exposure to coal tars, soot, and cigarette smoke. Both BaP and diesel exhaust show adverse effects in some laboratory tests.

The presence of adsorbed BaP and other chemicals upon the diesel particulate is of human consequence because the size of the particulates is small enough to permit them to reach the deep recesses of the lungs. Figure 7-1 depicts the size distribution of particulate material and the fraction of each size category deposited in various respiratory locations. As much as 30 to 40 percent of the inhaled particulates may be deposited in the lungs. The clearance time in the lungs is much longer than for other depositional areas, ranging from days to years. This enhances the probability that adsorbed carcinogens will be absorbed into the body. The small size also ensures a long atmospheric settling time, increasing the likelihood of inhalation (Ref. 7-3).

FIGURE 7-1. DIESEL PARTICULATE DEPOSITION IN HUMAN RESPIRATORY SYSTEM (Ref. 7-2).

Further complicating the analysis of diesel exhaust effects are the interactions which will occur when the exhaust disperses into the atmosphere. Atmospheric interaction of exhaust components with other atmospheric pollutants, influenced by the presence of sunlight, causes the destruction of some substance

and the synthesis of others not originally present in the exhaust. At this time, the atmospheric processes are not understood well enough to predict the ultimate fate of the various pollutant species, except in a general sense.

Although the diesel engine contributions to ambient pollutant levels are generally 1 percent or less of the total burden of each pollutant species, such overall figures must be viewed cautiously (Ref. 7-4). The mobile emissions represent concentrated sources distributed where the human population is densest. For example, in 1971, all motor vehicles combined contributed 680,000 tons of particulates, approximately 0.5 percent of the total suspended particulate load (Ref. 7-5). Yet 42 percent of the particulate burden in urbanized Los Angeles County, and virtually all BaP, was attributed to motor vehicles (Ref. 7-6). Table 7-1 summarizes the permissible exposure levels and projected ambient urban concentrations of several diesel related pollutants, and the known health effects of each. The diesel contribution to each is expected to be small. Nitrosamines and ozone have not been detected in diesel exhaust, but may be formed by chemical reaction with other atmospheric components. Reviews of the current National Ambient Air Quality Standard (NAAQS) regulatory levels by EPA are due in 1980 (Ref. 7-7). NAAQS particulate levels are measured as Total Suspended Particulates (TSP), principally airborne solid materials between 0.1 and 100 μ m diameter (Ref. 7-8). This category includes diesel carbonaceous particulates, SO_x particulates, and particulates derived from abraded tire and roadway surfaces. Estimated Permissible Exposures (EPE), calculated by Research Triangle Institute, are included in Table 7-1 for currently unregulated pollutants (Ref. 7-4).

7.3 HEALTH EFFECTS RESEARCH METHODOLOGY

The various health effects research methods may be divided into three general classifications. In-vitro tests utilize cellular-level organisms maintained in nourishing media. In-vivo tests utilize living higher-level animals, and human effects studies utilize living humans. Each of these methods offer certain advantages and disadvantages relative to the others. A comprehensive listing of short-term test methods and organisms is provided in Reference 7-12.

7.3.1 In-Vitro Testing

The general process of in-vitro testing uses a cellular-level organism, which is maintained in a nourishing medium and subjected to regulated

TABLE 7-1. DIESEL EMISSIONS AND POSSIBLE HEALTH EFFECTS.

Pollutant	Permissible Exposure Levels	Estimated Ambient Exposure Levels	Human Health Implications
Hydrocarbons (HC)	160 $\mu\text{g}/\text{m}^3$ (0.24 ppm) 3 hr MNTE (NAAQS)	Varies with atmospheric conditions	Throat irritant (25 ppm). Comp. of ozone production (2)
NO_x	100 $\mu\text{g}/\text{m}^3$ (0.05 ppm) annual arith. mean (NAAQS)	82 $\mu\text{g}/\text{m}^3$ (0.041 ppm) annual arith. mean (1)	Increased airway resistance. Acute respiratory bronchitis. Poss. nitrosamine precursor (2)
SO_x	80 $\mu\text{g}/\text{m}^3$ (0.03 ppm) annual mean, 365 $\mu\text{g}/\text{m}^3$ (0.14 ppm) 24 hr MNTE (NAAQS)	6 $\mu\text{g}/\text{m}^3$ (2) 24 hr = 36 $\mu\text{g}/\text{m}^3$ (1)	Eye and respiratory irritant (2)
Total Suspended Particulates	75 $\mu\text{g}/\text{m}^3$ annual geometric mean, 260 $\mu\text{g}/\text{m}^3$ 24 hr MNTE (NAAQS)	40 $\mu\text{g}/\text{m}^3$ 24 hr (2)	Death and respiratory illness in susceptible population. 100 $\mu\text{g}/\text{m}^3$ ann. geometric mean (2)
Photochemical Oxidants (Ozone)	240 $\mu\text{g}/\text{m}^3$ (0.12 ppm) 1 hr MNTE (NAAQS)	Varies with atmospheric conditions	Eye and respiratory irritant (0.1-0.15 ppm)(3)
Carbon Monoxide (CO)	10 ⁴ $\mu\text{g}/\text{m}^3$ (9 ppm) 8 hr MNTE. 4.10 ⁴ $\mu\text{g}/\text{m}^3$ (35 ppm) 1 hr MNTE (NAAQS)	4 ppm, 1 hr (2)	Visual impairment (16 ppm). Psychomotor impairment (27 ppm)
Polycyclic Aromatic Hydrocarbons (BaP)	4.10 ⁻⁴ $\mu\text{g}/\text{m}^3$, 24 hr (RTI)	4.10 ⁻⁴ $\mu\text{g}/\text{m}^3$ (2)	Known human carcinogen (4)
Nitrosamines	2.1 $\mu\text{g}/\text{m}^3$ (dimethyl nitrosamine), 74 hr (RTI)	0.2 $\mu\text{g}/\text{m}^3$, 24 hr (2)	Carcinogen. Liver damage (2)
Phenols	Not Established	20 $\mu\text{g}/\text{m}^3$ (0.001 ppm) (2)	Irritant (2)
Aldehydes Formaldehyde Acrolein	0.6 ppm (acrolein) 7.14 ppm (formaldehyde) 24 hr (RTI)	0.5 ppm (2)	Eye and respiratory irritant

MNTE: Maximum, not to be exceeded more than once per year.

NAAQS: Regulatory exposure level established by National Ambient Air Quality Standard (Ref. 7-8).

RTI: Suggested exposure level established by Research Triangle Institute (Ref. 7-4).

Sources: (1) Reference 7-9.
(2) Reference 7-4.
(3) Reference 7-11.
(4) Reference 7-10.

dosages of the test substance. Following an incubation period, the organism is examined for indications of change in growth and viability. The organism may be of bacterial, mammalian, or human origin, depending on test method. The advantages of in-vitro testing are its short duration and low cost, permitting large numbers of test substances to be tested rapidly and economically. The primary disadvantage of these tests is the difficulty of extrapolating test results to higher animals or to humans. For this reason, in-vitro tests are used primarily for preliminary screening rather than for final determination of hazard levels.

As an illustration of the issues involved in interpreting in-vitro test results, the Ames test serves as an excellent example. Among the in-vitro assay tests, the Ames Salmonella/Mammalian Microsome Mutagenicity test is of major importance, due to its widespread use. Various special strains of Salmonella typhimurium bacteria are exposed to the test substance, generally consisting of whole particulates or particulate extracts in a solvent. These strains were chosen for the presence of a deoxyribonucleic acid (DNA) mutation that prevents them from synthesizing histidine, an amino acid essential for their growth. The Ames test detects mutagenicity due to exposure to a test substance by noting the reverse mutation of Salmonella typhimurium DNA back to that of a histidine-producing bacterium. The reverse-mutated bacteria are able to grow and are detected visually (Ref. 7-13). While some substances are not direct mutagens or carcinogens themselves, metabolic activity with a living body converts such promutagens to their active, or mutagenic forms. To test for such promutagens, the Ames test includes samples which contain an extract of rat liver designed to metabolize a promutagen to its active form. BaP, for example, is a promutagen (Ref. 7-14). The various bacterial strains respond with reverse mutations of different modes, thereby enabling the test to indicate the manner in which the mutagen has altered the bacterial DNA.

Weighed against this are several caveats. First, the demonstration of mutagenic or carcinogenic activity in a bacterial cell is no guaranty that such activity can be demonstrated in other species (a "false positive" response). Human cells possess sophisticated DNA repair mechanisms, which restore slightly damaged DNA, and these mechanisms differ between species. Second,

the test measures a particular mutation at a particular DNA site, and the test will not yield positive results if an induced mutation does not lead to restoration of histidine production (a "false negative" response). Third, demonstration of DNA mutation, even in human cells, does not ensure that it will lead to a carcinoma. Many chemically induced carcinomas appear to require both an initiation, via DNA damage, and a promotion, via additional chemicals, in order to produce carcinogenesis. BaP, for example, is a tumor initiator, while croton oil is a tumor promotor (Ref. 7-2). Hence, the Ames test should be regarded as an effective means for screening large numbers of substances for those which require further scrutiny, rather than as a definitive method for determining carcinogenicity.

Ames tests of whole particulates have yielded moderate levels of potential mutagenicity. Tests of particulate extracts have shown a high degree of variability, with sensitivity to both the method of particulate collection and to the solvent used to elute the adsorbed particulate components, as shown in Figure 7-2. Some solvents have been determined to be not representative of lung fluids (Ref. 7-4). Dichloromethane (DCM), which is used extensively as a solvent, shows a much higher rate of mutation than the more "body-compatible" solvents such as Fetal Calf Serum when used in the Ames test. Some researchers have concluded that this "solvent effect" results from the DCM solvent creating a more potent mutagen. Recently, however, it has been noted that serum-type solvents may bind with potential mutagens, rendering them unavailable to some types of bacterial cells (Ref. 7-15). Therefore, this solvent effect may be due to depressed response with serum solvents rather than enhanced response with DCM. Higher mutagenicity has been noted from samples collected on a filter vis-a-vis those collected by an electrostatic precipitator (Ref. 7-16). One explanation for this effect is that the filter sample is more exposed to the exhaust stream and that interaction with other exhaust components, particularly NO_x , occurs. Nitration of PAH's can increase their mutagenicity (Ref. 7-14). Nitration reactions may also occur in the urban atmosphere.

Other common in-vitro tests, utilize *Escherichia coli* bacteria (Ref. 7-10), mouse lymphoma cells, hamster cells, or human Xeroderma Pigmentosum (XP) cells. While all show some degree of response to challenge with diesel exhaust particulate samples, they too should be considered as preliminary screening tests.

FIGURE 7-2. RELATIVE AMES TEST MUTAGENICITY OF DIESEL PARTICULATE EXTRACTS FOR SEVERAL EXTRACTION SOLVENTS (Ref. 7-2).

7.3.2 In-Vivo Studies

In-vivo studies use live animals for effects testing. In these tests, whole diesel exhaust may be inhaled by the test animals, or particulates may be instilled directly into bronchial passages. Also, soluble extracts of particulates may be painted on their skins, or injected beneath it. While in-vivo studies do provide better data for establishing human dose-response relationships than in-vitro tests, they are still not completely analogous to human exposure. Substances which are toxic or oncogenic in one species may not be so in other species.

Some animal inhalation studies have shown only moderately detrimental effects. Other studies have demonstrated increases in respiratory resistance, decreases in lung clearance rates, anthracotic lesions in the lungs, acute pneumonia, and emphysema. Depending on exposure, the effects are partially reversible within three to four days following the end of exposure. However, major long-term inhalation studies have not yet been completed, most exposures lasting only a few weeks. Inhalation studies using labelled BaP have demonstrated a reduced lung

clearance rate at high particulate loads, increasing the lung retention time for 50 percent of the BaP from three days to seven days (Ref. 7-14). They also provided evidence that the uptake of BaP is less when adsorbed on a particulate than in pure forms (Ref. 7-17). When BaP is instilled in concert with SO_x particulates, lung clearance is also slowed, suggesting BaP uptake to be strongly controlled by the total particulate burden in the lungs. Animals showed enhanced susceptibility to respiratory disease when challenged with a pathogen within two hours of inhaling diesel exhaust. When the pathogen was presented 22 hours after exhaust exposure, there was no susceptibility enhancement (Ref. 7-18).

Skin painting studies have shown a high degree of induced tumors in laboratory mice. Epoxide isomers of BaP demonstrate varying degrees of carcinogenicity, reinforcing the significance of the interaction of atmospheric pollutants with adsorbed BaP. The PAH 6-methylchrysene, known to exist in diesel exhaust, is a stronger skin tumor initiator than BaP (Ref. 7-18). Benzene extracts of exhaust particulates have also shown capacity to induce tumors. As in the cellular assays, such extracts have been challenged as nonrepresentative of ambient human exposure mechanisms.

7.3.3 Human Effects Studies

Human effects studies have been limited to acute exposure tests at moderate pollutant levels and to epidemiological surveys of chronic, usually occupational, exposures. Further insight is also afforded by historical episodes of acute urban air pollution. Absence of a demonstrated cause-effect relationship in epidemiological studies should not be considered adequate evidence to exonerate a substance completely. Rather, that exposure level should only be considered as a potential upper limit. Further, substances which exacerbate common respiratory ailments or cancers will often not be noticed unless there is a large excess rate of risk (Ref. 7-19).

Acute human exposure tests have found little effect from moderate exposures of up to four hours. In such cases, the subject's airway resistance and residual lung volume typically have changed only slightly. Among asymptomatic asthmatics, slightly higher sensitivity has been noted, but due to the small sample size, the result could have been due to the subject's personal thresholds rather than to synergistic effects of the aerosol with the subject's asthmatic conditions (Ref. 7-20).

Chronic exposures to diesel exhaust have not produced clear health trends in workers. Most past studies of diesel-exposed workers have been found to be of limited usefulness due to confounding factors not considered. These include (1) changes in working conditions, (2) cohort differences in age, employment, and smoking habits, (3) the "healthy worker effect", and (4) incomplete exposure data. As an example, a study of Egyptian bus garage workers found higher rates of respiratory and gastric disease; however, a large percentage of the sample were also smokers (Ref. 7-21). Since in-vivo studies have demonstrated the sensitivity of lung clearance to particulate load levels, the heavy particulate load of a smoker will exacerbate any effect of diesel particulates. Indeed, one study of lung cancer mortality in urban versus rural areas indicates that the highest correlation of lung cancer is with smoking (Ref. 7-18), rather than location.

Those studies which have shown visible health effects have generally relied not upon exposure to diesel exhaust but upon exposure to non-diesel generated pollutants similar to those present in diesel exhaust. However, some caution in interpreting such results is necessary, because the generating processes may not be equivalent to those of diesel engines and, in the case of ambient air samples, the ultimate source of the pollutant may not be known. For example, open-grate fires in London sustained thick fogs that were green-tinged from unburned tars. Inhalation of it may not have resulted in excess lung cancer (Ref. 7-22), but it was responsible for deaths due to respiratory disease (Ref. 7-23). Earlier, chimney sweeps exposed to flue soot developed scrotal cancer (Ref. 7-10). Extrapolation to diesel exhaust is not straightforward because the entire combustion process, fuel composition, and fuel-air ratio are different.

Several studies of coke workers, coal-gas workers, and roofers exposed to higher than average levels of PAH, particularly BaP, have found correlation between increased levels of PAH and excess cancer mortalities. Similarly, several studies of urban and rural dwellers have found the same trends in the general population. Ambient particulate levels do not correlate well with urban versus rural levels of respiratory disease, but acute episodes of high urban particulates have produced severe respiratory illnesses and deaths in susceptible subpopulations (Ref. 7-18).

There is no consensus regarding the risk to human health attendant with the large-scale introduction of diesel vehicles, and such a consensus should not be expected for several years. Diesel vehicles have been relatively few in number, and thus the human exposure data have been correspondingly sparse. Although currently available data have not demonstrated, to the satisfaction of most researchers, that exposure to actual diesel exhaust, in the ambient concentrations projected for urban areas, has caused or will cause human illness, it is generally agreed that diesel exhaust has the potential to be harmful to human health. It is the degree to which the emissions will actually be detrimental that must be established.

Much of the current research work is emphasizing diesel particulates and the resultant respiratory cancer risk. Sufficient attention should also be given to the interaction of other exhaust components, particulates, and atmospheric pollutants. In addition, while respiratory cancer is a likely response, respiratory and gastro-intestinal disease exacerbation, birth defects, and non-respiratory cancers are also likely avenues of expression. Also, the controversy surrounding the solvent effect should be resolved with additional tests. Because the design and operation of a diesel engine influence the composition and mutagenicity of its pollutants, a large data base will be necessary in order to evaluate the different engine designs. At present, such data are relatively sparse.

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SECTION 8

CURRENT STATUS OF DIESEL ENGINE RESEARCH AND DEVELOPMENT PROGRAMS

This section briefly describes the light-duty diesel engine technology development and health effects programs currently conducted by government agencies, the automobile industry, and a number of other organizations.

8.1 GOVERNMENT AGENCIES

A number of government agencies are actively engaged in a variety of inhouse and contracted programs in the areas of diesel engine technology and health effects. These agencies include the Department of Energy (DOE), the Environmental Protection Agency (EPA), the Department of Transportation, (DOT), the National Institute of Occupational Safety and Health (NIOSH), the Department of Defense (DOD), and the Bureau of Mines. Generally, the thrust of these programs is aimed at the development of emission control systems and techniques for use in light-duty diesel engines, and the human health risks associated with the projected increase of diesel powered automobiles in the near and mid term.

8.1.1 Department of Energy

The DOE is currently conducting a number of diesel engine related research and development programs, either inhouse, or under contract to industry, or in cooperation with other government agencies. These programs involve diesel engine and emissions control technology assessments, emissions characterization and health effects projects.

8.1.1.1 Particulate Research Program

The principal objective of DOE's particulate research program is to develop the basis for an independent DOE assessment of the environmental acceptability of light-duty diesel vehicles (Ref. 8-1). The primary means of achieving this objective will be health effects testing, while ancillary projects will be performed to investigate engine and emission control systems effects. These projects are designed to provide DOE with experimental and theoretical data defining the dependence of particulate formation on variations

in engine design, combustion process, emission control system, and engine operation. The results of both the health effects research and the ancillary engine and control systems projects will be integrated to form the basis for a human risk assessment study.

The scope of the health effects testing program encompasses the physical and chemical characterization of the exhaust particulates and their adsorbed species, their transport and modification after emission, and their deposition and ultimate fate after inhalation or ingestion. Particulate samples are being collected by the Bartlesville Energy Technology Center (BETC) over a range of engine operating conditions. Additional samples are being provided by the DOT. Physical, chemical, and biological characterization is being performed by the Inhalation Toxicology Research Institute of the Lovelace Biomedical and Environmental Research Institute (LITRI), with coordinated research occurring at the Massachusetts Institute of Technology (MIT). Transport and modification processes are under study at the University of California at Riverside (UCR), Argonne National Laboratory (ANL) and Lawrence Livermore Laboratory (LLL). LITRI is also examining the deposition and fate of particulates in animals and the effects of occupational exposures, and will assess the overall human health risk.

Much of the program is just getting under way. To date, BETC has collected samples from 14 late-model diesel automobiles (Ref. 8-2), and LITRI has examined the deposition, retention, and biological activity of a tagged surrogate aerosol in nasal inhalation experiments with dogs. In these tests approximately 33 percent of the total inhaled dosage was deposited in respiratory passages, with 27 percent of the total dosage deposited in the lungs (Ref. 8-3). Methylene chloride extracts of lung lavage fluids showed the largest biological activity in Ames testing. In contrast, several biological solvent extracts showed minimal biological activity.

Based on in-vitro tests, using fractionated particulate extracts with Salmonella bacteria, 60 to 70 percent of the mutagenic activity was found to be in the alkyl substituted aromatics and polycyclic aromatic hydrocarbons (Ref. 8-2). In-vitro tests performed by MIT with particulate extracts indicate that the highest biological activity is associated with elution by a pentane-toluene solvent (Ref. 8-4).

Transport and transformation studies conducted at UCR indicate increased mutagenic activity in nitrated benzo(a)pyrene (BaP). Apparently, the transformation can occur at ambient urban air pollution levels, although ambient nitrated BaP has not yet been detected (Ref. 8-5).

Future work will further examine these issues. Also, chronic whole diesel exhaust exposures of laboratory rats and mice will be performed over the two to three year lifespan of these animals. In addition, a General Motors (GM) 5.7 liter diesel engine will be operated on the dynamometer, under simulated urban driving operating conditions. In these tests, engine exhaust will be routed through a conventional exhaust system, then diluted to the experimental concentrations and delivered to the exposure chambers. In addition to particulates, regulated and unregulated emissions species will be measured periodically.

8.1.1.2 Emission Control Technology Assessment

The Lewis Research Center (LeRC) of the National Aeronautics and Space Administration (NASA) is currently involved in the conduct of a DOE-sponsored diesel engine control technology program. The objectives of this program are (1) to provide a technical basis for an independent assessment by DOE of the environmental acceptability of the light-duty diesel engine, (2) to provide DOE with particulate filter samples for examination and analysis, and (3) to contribute engine emissions and performance data as affected by the use of different emission control systems and techniques (Ref. 8-6).

Baseline performance and emissions mapping of the AVL Model 521 diesel engine has been completed by NASA-LeRC. Also complete are studies of the effects of variable inlet air temperature and variable fuel injection timing. Test data show that an increase in inlet air temperature increases oxides of nitrogen (NO_x) emissions and fuel consumption, while timing retard increases NO_x but decreases particulate emissions.

Current efforts include the installation of a high-pressure fuel injection system, and the conduct of a study of the effects of variations in injection timing and injection rate on engine performance, fuel economy, and emissions. Also planned is further study of ceramic coatings as thermal barriers.

Some prior work performed by Oklahoma State University has indicated good durability of zirconia (ZrO_2)-coated pistons, with variable effects shown in power and fuel consumption.

Future work will investigate advanced thermal barrier components, with particular emphasis on improved insulating ability, lighter weights, and low-cost designs. Both non-porous ceramic and metallic encapsulization of piston tops, valves, fire deck, and exhaust ports will be studied as means to reduce the effect of porous coatings on fuel absorption and ignition delay. Also, the feasibility of hypergolic combustion will be investigated. In such a system the fuel will be preheated before injection to temperatures of about $800^{\circ}F$ at supercritical pressure. Under these conditions the fuel charge will spontaneously ignite in the chamber. Theoretically, a system of this type has very low particulate emissions, equal or lower NO_x , equal or higher efficiency, and higher power output. It also possesses a multifuel capability and diesel knock is largely eliminated.

8.1.2 Environmental Protection Agency

The objective of the ongoing EPA Diesel Emissions Research Program is to assess the human health risk associated with an increased use of light-duty diesel vehicles. The overall program is divided into two parts. The first, and major, effort is concerned with health effects. Particulates will be collected and analyzed for physical and chemical composition and biological activity. Atmospheric transport mechanisms will be examined to determine the effects of exposure rates and atmospheric modifications. Occupational exposures to diesel exhaust will be reviewed for significant health effects. The second effort is concerned with diesel engine emission control technology. This effort is intended to provide basic information on engine emission control systems and their technological and economical feasibility for meeting required emissions levels. These results will be weighed along with those of the health effects program to permit final EPA regulatory decisions regarding the diesel engine (Ref. 8-7).

8.1.2.1 Health Effects Program

EPA's multipart health effects program is being conducted by a number of laboratories, both inhouse and contract agencies. The collection

of particulate samples from several light- and heavy-duty diesel engines under different operating modes is being performed by the Environmental Sciences Research Laboratory, Research Triangle Park (RTP), North Carolina, and by the Office of Mobile Source Air Pollution Control, Ann Arbor, Michigan. RTP also is conducting the chemical analysis of the sample. Ambient urban air samples, both with and without particulates, are being collected for analysis and testing by RTP. This effort will be combined with long-term air quality monitoring and computer predictions of human exposure levels to permit an estimation of the mutagenic potential of urban air.

Biological activity will be researched by a battery of in-vitro and in-vivo tests. In-vitro tests, which have been partially completed, will explore gene mutation, deoxyribonucleic acid (DNA) damage, chromosomal alterations, and oncological changes in various organisms from bacterial and yeast levels up to those of mammalian and human cells. In-vivo tests are under way to explore both carcinogenic-mutagenic effects as well as noncarcinogenic effects, including neurological, reproductive, and respiratory changes. This work is being performed by the EPA Health Effects Research Laboratory, Cincinnati (HERLC), the Illinois Institute of Technology Research Institute (IITRI), and the Oak Ridge National Laboratory (ORNL).

One step in the overall program involves subjecting diesel exhaust to a battery of in-vitro and in-vivo tests, along with particulates from other sources such as gasoline engines, coke ovens, roofing tar, and cigarette smoke. The matrix of results will then be reviewed to establish the relative potency of each substance. Eventually these potencies will be used to establish the relative health risk of each substance. Some preliminary results of the matrix are available, indicating large engine-to-engine and test-to-test variations in response (Ref. 8-8). Other in-vitro tests will focus on the evaluation of complex mixtures and air samples (Ref. 8-9). Animal exposure tests will be performed separately and in conjunction with NIOSH (Ref. 8-10).

8.1.2.2 Engine Emission Control Technology

EPA's Industrial Environmental Research Laboratory at Research Triangle Park (IERL-RTP) is developing and evaluating several methods for the reduction of particulate and organic emissions from diesel engines. Particulate

research is focusing on removal of the particles in the exhaust stream, using several techniques. In one system the particles are collected on a shallow filter, where they are continuously burned off by catalytic oxidation at the filter surface. Another system relies upon a more conventional deep-bed filter to trap the particles. However, this system requires periodic filter replacement to prevent particulate emission and engine efficiency deterioration. Electrostatic filtration also is being investigated, but a reliable particulate disposal method has not yet been developed. Similarly, an electrostatic collector that is kept clean by a circulating fluid requires periodic fluid replacement to remove the accumulated particulates. In addition, cyclonic agglomerators are under study, but they also require periodic removal of the accumulated particulate matter at 5000 mile intervals (Ref. 8-7). The effectiveness of these potential particulate control devices in removing organics is being investigated by IERL-RTP. Oxidation catalysts are also being evaluated by IERL to determine their effectiveness in the destruction of gaseous organics. Emissions characterization of heavy-duty production diesel engines is being carried out at Southwest Research Institute (SWRI).

8.1.3 Department of Transportation

The Transportation Systems Center (TSC) of DOT is conducting several diesel-related programs, both in-house and in conjunction with other contractors and government agencies. The objectives of these programs are to investigate the fuel efficiency of light-duty diesel engines, to assess engine and vehicle systems aspects, to characterize exhaust emissions, and to investigate exhaust emission control systems and techniques (Ref. 8-11).

8.1.3.1 Volkswagen

Volkswagen has completed its DOT-sponsored diesel engine evaluation program. The overall objective of that program was the development of a light-duty diesel vehicle data base which would permit the assessment of the overall effects of diesel vehicles in the U.S. automotive fleet. Fuel economy, regulated and unregulated emissions, noise characteristics, performance, and driveability were explored, and engine design tradeoffs were investigated.

8.1.3.2 Fiat

The Fiat project is part of a continuing effort to develop an emissions and performance data base for 4- and 6-cylinder light-duty diesel engines. To date, tests have been completed on the indirect injection 4-cylinder 8400 series Fiat engine in a 3000 lb IW vehicle. Vehicle/engine optimization work has explored the benefits and design tradeoffs of turbocharging, EGR, and injection timing control. Vehicle test data showed hydrocarbon (HC), carbon monoxide (CO), NO_x, and particulate emissions at or below 0.41 g/mi, 3.4 g/mi, 1.5 g/mi, and 0.5 g/mi, respectively. In these tests, combined cycle vehicle fuel economy with a naturally aspirated engine was 37.9 mpg, compared to 39.8 mpg for the vehicle equipped with turbocharged engine and modified rear axle ratio. Catalytic treatment of exhaust gases also has been investigated by Fiat. Future efforts will involve similar investigations on a direct injection version of the 8400 series engine, and possibly the 6-cylinder 8600 series engine (Ref. 8-12).

8.1.3.3 Chrysler

Chrysler is continuing work on a DOT-sponsored light-duty diesel engine development program. Dieselized, indirect injection versions of the Chrysler 225 CID slant six and 318 CID V-8 have been used as prototype power plants for potential light truck applications. Similar to the Fiat program, engine/vehicle optimization studies were performed by Chrysler to explore the benefits and tradeoffs associated with the use of EGR and injection timing modifications. These data will be used as the basis for the development of an optimal control strategy which will yield good performance and fuel economy at regulatory emission levels. In addition, several particulate samples for bio-assay testing by EPA have been generated. Electronic engine controls have been explored offering simultaneous improvements in fuel economy and emissions (Ref. 8-12).

8.1.3.4 Ricardo Consulting Engineers

Ricardo's efforts are primarily aimed at the achievement of low exhaust emissions. Baseline tests with a 4000 lb inertia weight Aspen automobile, equipped with a dieselized version of Chrysler's slant six engine, yielded

HC, CO, NO_x, and particulate emissions of 0.71, 1.89, 1.46, and 0.5 g/mi. Based on parameteric studies, Ricardo has concluded that the NO_x versus particulate emissions tradeoff is the limiting relationship in the optimization process. Tests performed by Ricardo on the Chrysler slant six engine equipped with an electronic control system and a prototype Stanadyne electronic fuel injection pump indicate particulate emissions of 0.2 g/mi, accompanied by 1 g/mi NO_x emissions, low HC, and a significant increase in fuel economy (Ref. 8-13). The observed improvements are attributed to the increased range and sophistication of the electronic control system relative to mechanical systems. The electronic control system will be tested in a light-duty truck installation at a later date.

Ricardo is in the process of beginning a new series of tests using a single-cylinder engine. The tests will examine the fuel economy and emissions effects of a variety of design parameters, including compression ratio, nozzle design, fuel injection timing, spray pattern and rate, EGR, metallic cylinder liners, and catalytic exhaust treatment. Likely future work also will study the benefits of re-optimizing the engine design to increase low speed torque via smaller prechamber volumes (Ref. 8-12). Eventually, Ricardo will re-assess these modifications in multi-cylinder diesel engines.

8.1.4 National Institute of Occupational Safety and Health

For the past several years, the NIOSH has been involved with investigations of health effects issues related to the increasing use of diesel engines in mines. In the near future, NIOSH will initiate a two year animal inhalation program. In this program, rats and monkeys will be chronically exposed to either coal dust, diesel exhaust, or both simultaneously at an overall level of 2 mg/m³ total respirable particles. The rats will be examined for evidence of carcinogenicity, mutagenicity, and other pathological changes. The monkeys will be examined for pulmonary and immunological changes (Ref. 8-14). NIOSH is currently conducting several occupational exposure studies involving mine workers exposed to elevated levels of diesel emissions (Ref. 8-15). Much of the direction of this work involves acute rather than chronic exposures. NIOSH is also attempting to update previous work by contacting participants of epidemiological studies performed several years ago (Ref. 8-16).

The U.S. Army Tank-Automotive Research and Development Command (TARADCOM) has been involved in diesel engine development for many years. Currently, a number of programs are being conducted, primarily through contracts to industry (Refs. 8-17 through 8-19). The major activities involve (1) the adiabatic diesel, (2) advanced turbochargers, (3) high-pressure fuel injection systems and (4) the turbocharged low compression diesel. The principal objective of these programs is the demonstration of higher engine efficiency, combined with a reduction in smoke emissions. Of these projects, the adiabatic engine and the advanced turbochargers are of particular interest to the automotive sector.

In the adiabatic engine, ceramic coatings and components are used as a means of reducing heat losses into the engine block. The insulated components include the piston crown, cylinder head, valve heads, cylinder liner, and exhaust ports. Since adiabatic engines operate without a cooling system, the combustion temperature is increased, providing a significant engine efficiency improvement potential. Maximum benefits will be achieved by incorporating turbocompounding and/or a Rankine bottoming cycle. The brake specific fuel consumption of such combined systems is projected to be in the 0.25 to 0.28 lb/bhp-hr range, compared to about 0.35 lb/bhp-hr for large conventional diesels. To date, the durability of ceramic piston caps and ceramic coatings has been demonstrated for more than 400 hours. In addition, a 350 hour engine durability test has been completed, and testing of this engine in a vehicle will commence in the near future.

Research in the area of advanced turbocharger concepts is continuing. The objective of this project is the definition of viable configurations that have the capability of improving engine efficiency, transient response, and operating range. The development of a variable area turbocharger is nearing completion, and the unit will then be tested in a 12-cylinder military diesel engine.

The objective of the high-pressure fuel injection system project is the achievement of higher engine efficiency and lower exhaust emissions by means of more precise control of the combustion process. Initial bench testing

of one system has been completed, preparatory to adaptation of the system to a multi-cylinder military engine.

Feasibility assessment of the low compression diesel with turbo-charging is continuing to determine the efficiency potential of such engines, and to examine the issues related to the use of commercial production engines in military vehicle applications.

8.1.6 Bureau of Mines

The programs currently performed by the Bureau of Mines, either inhouse or through contracts to industry, are primarily concerned with the characterization of gaseous and particulate emissions of diesel engines currently used in underground mining applications, and the development of emission control techniques for potential use in these engines (Ref. 8-20).

Pollutant species characterization efforts are continuing, with particular emphasis on particulates, organic compounds, and noise. Engine operation with fuels having low aromatic fractions has resulted in significant reductions in the emission of polynuclear aromatics relative to conventional diesel fuel. Efforts are continuing in the area of diesel noise abatement. The principal diesel noise source was determined to be the transmission, closely followed by the engine itself. Engine enclosures or the use of acoustic materials appear to be the most cost effective approaches at this time.

In the area of exhaust emission control, the emphasis is on catalytic exhaust aftertreatment, water scrubbers, and filter traps. With new catalysts, the emission reductions are quite significant, amounting to about 90 percent for CO, and 50 to 95 percent for BaP. As expected, catalyst effectiveness increased in these tests with increasing exhaust gas temperature. Initial indications are that particulate deposition on the catalyst surface is not a serious problem area. The use of scrubbers and filter trap systems in the engine exhaust has been partially successful. A water scrubber has achieved 99 percent effectiveness in coal dust removal, but its efficiency in removing the smaller particulates is expected to be lower. To date, trapping efficiencies up to 65 percent have been demonstrated with new filters, and even higher efficiencies are expected as filter pore size is reduced.

8.1.7 Summary

A tabular summary of engine programs currently conducted or sponsored by government agencies is provided in Table 8-1.

8.2 AUTOMOBILE INDUSTRY

Many domestic and foreign automobile manufacturers are actively involved in the development of light-duty diesel engines and the exhaust emission control technology applicable to these engines. The manufacturers considered in this section are BMW, British Leyland, Chrysler, Daimler-Benz, Fiat, Ford, General Motors, Peugeot and Volkswagen.

8.2.1 Bavarian Motor Works (BMW)

BMW is currently involved in the development of a 2.4 liter, 6-cylinder, turbocharged, swirl chamber diesel engine for use in 1983 Model Year automobiles (Ref. 8-21). The engine has a compression ratio of 23:1, a swirl chamber volume of about 50 percent of the total clearance volume, and a rated power output of 115 hp at 5000 rpm. At this time, efforts are concentrated in the areas of combustion chamber and fuel injection system optimization, considering parameters such as chamber geometry, fuel spray angle, nozzle sac volume, glow plug location, and fuel injection system tolerances.

Initial vehicle tests at inertia weight settings of 3000 to 3500 lb indicate HC, CO, and NO_x emissions of 0.25, 1.2, and 1.6 g/mi, respectively, and a combined cycle fuel economy of 30 to 32 mpg.

Emissions control work is primarily concerned with the development of HC and NO_x abatement techniques. The use of low sac nozzles, in conjunction with a reverse flow damping valve developed by Bosch, has resulted in significant reductions in HC emissions. Also, reduction of critical fuel injection system tolerances to limit flow leakage has been beneficial in this regard. Two different EGR systems have been evaluated on the engine dynamometer in conjunction with timing retard. One system is similar to that used by BMW in its spark ignition engines, while the other is patterned after the Bosch system. In tests of these systems, the use of EGR was always accompanied by an increase in HC emissions. Problems encountered with EGR include deposit buildup, result-

TABLE 8-1. DIESEL ENGINE RESEARCH PROGRAMS - GOVERNMENT AGENCIES.

RESEARCH CATEGORY	GOVERNMENT AGENCY	CONTRACTOR	STATUS	COMMENTS
<u>ENGINE TECHNOLOGY</u>				
Indirect Injection Diesel	DOT	Chrysler Fiat Ricardo	Vehicle Testing Near Completion In Progress	The Objectives of the Chrysler and Fiat Programs are the Determination of the Fuel Economy and Emissions Potential of Light Duty Diesels Through Optimization of Engine Design and Emission Control Devices and Techniques. Ricardo Investigates the Potential of Both State-of-the-Art and Advanced Engine Design and Control Technology.
Direct Injection Diesel	DOT	-----	Future Program	To Provide a Fuel Economy, Performance, and Emissions Data Base For Light Duty Diesel Engines, and to Assess the Effects of State-of-the-Art Emission Control Technology on Engine Operation, Fuel Economy, and Emissions.
Adiabatic Diesel	U. S. Army	Cummins	In Progress	Adiabatic Engine Operation Eliminates the Need For a Cooling System, Resulting in Higher Engine Efficiency. A 250HR Feasibility Demonstration Will Be Completed Early in 1980. The Development of Ceramic Piston Caps and Ceramic Coatings For the Piston, Cylinder Liner, Cylinder Head, and Valve Heads Will Be Continued During FY 1980. Development Efforts On a Low Friction Adiabatic Engine With Turbocharging Have Been Initiated. This Engine Will Be Unlubricated and the Goal is to Reduce Mechanical Friction by 50 Percent, Fuel Consumption By 10 Percent.
Low Compression Diesel	U. S. Army	Cummins	Ongoing	The Objective of This Program is to Demonstrate the Feasibility of Converting Commercial Engines to Military Applications and, in Conjunction With Turbocharging, Achieve High Efficiency in a Compact Design.
Turbocharging	DOT	Chrysler Fiat Ricardo Teledyne and Thermo Mechanical Systems (TMS)	In Progress In Progress	The DOT-Sponsored Work Involves Incorporation of State-of-the-Art Turbochargers in Chrysler and Fiat Diesel Engines. Engine and Vehicle Tests are Nearing Completion. Single Cylinder Tests Will Be Initiated by Ricardo in the Near Future. Fiat Vehicle Data Indicate Significant Reductions in Particulate Emissions With Turbocharging. A High Efficiency Variable Area Turbocharger Developed By Teledyne and TMS is Being Tested and a Phase II Design is Scheduled for Testing in FY 1980. TMS is Developing an Advanced Turbocharger Having High Efficiency, Wide Range, and High Pressure Ratio.
Turbocompounding	DOE	Cummins	Vehicle Tests in Progress	Turbocompounding Increases Engine Power Output, Reduces Fuel Consumption, and in Conjunction With Injection Retard Has the Potential of Providing NO _x Control. One Cummins Engine Incorporating the Turbocompound Feature Has Been Tested in a Truck Over 2000 Miles. Another Engine Will Be Tested in a Truck Operated Over 50,000 Long Distance Miles.
Combustion Chamber Optimization	DOT	Chrysler Fiat Ricardo Inhouse (BETC)	In Progress Completed In Progress Future Program	Chrysler is Exploring the Effects of Valve Timing and Compression Ratio Variations on Emissions and Fuel Economy. Ricardo Examines Prechamber to Main Chamber Volume Ratio Variations As a Means of Optimizing Fuel Economy and Emissions Under Light Load Operating Conditions, and Will Investigate Means of Reducing Wall Quenching. BETC Will Examine the Effects of Engine Modifications on Fuel Economy and Emissions.
Injection System Optimization	DOT	Chrysler Fiat Ricardo	In Progress Near Completion Soon to be Initiated	Chrysler is Optimizing Injection Timing as a Function of Load, With Particular Emphasis on the Light Load Regime. Fiat Has Completed Its Injection Timing Optimization Work. Ricardo Will Collect Fuel Consumption and Emissions Data on a Single Cylinder Engine, as Affected by Injection Timing, Rate, and Spray Angle Variations.
Advanced Fuel Injection System	U. S. Army	Physics International	In Progress	The Initial Design of a High Pressure Fuel Injection System Has Been Completed and Bench Tests Have Been Started. The System is Designed to Provide Very High Injection Rates For Optimum Fuel Economy and Emissions Operation.

TABLE 8-1. DIESEL ENGINE RESEARCH PROGRAMS -- GOVERNMENT AGENCIES (Continued)

RESEARCH CATEGORY	GOVERNMENT AGENCY	CONTRACTOR	STATUS	COMMENTS
<u>EMISSION CONTROL</u>				
Exhaust Gas Recirculation	DOT EPA DOE	Chrysler Fiat Ricardo SWRI Inhouse (BETC)	In Progress In Progress Planned for FY 1980	Chrysler, Fiat, and Ricardo Have Performed Vehicle Tests with EGR to Determine the Effect On Gaseous and Particulate Emissions. While NO _x Declines With EGR, Particulate Levels Increase Significantly. Ricardo Will Investigate EGR Characteristics in a Single Cylinder Engine Test Program. SWRI Will Perform Emissions Baseline Tests of EGR Equipped Heavy Duty Diesels. Light Duty Diesel Testing Has Been Completed by SWRI As Part of a Comprehensive Control Technology Assessment Program. BETC Will Determine the Effects of EGR on Exhaust Emissions of Production Vehicles.
Catalytic Converter	DOT DOE EPA Bureau of Mines	Chrysler Fiat Ricardo Inhouse (BETC) Inhouse at Michigan T. U. and at SWRI Engelhard	In Progress Planned for FY 1980 In Progress In Progress	The DOT-Sponsored Work Includes Engine Vehicle Tests With Exhaust Catalysts. HC and CO Reductions Have Been Demonstrated, Permitting a NO _x /HC Tradeoff to be Made in Conjunction With Other Engine Modifications. Ricardo Will Perform Technology Development Work With Catalysts Placed Inside the Combustion Chamber. BETC, EPA, and Michigan Technological University Will Perform Assessments of the Pollutant Control Effectiveness of Catalysts. SWRI Will Establish an Emissions Data Base for Diesel Automobiles, and Will Examine the Effectiveness of Catalysts as a Technique for Control of Organics. Engelhard is Conducting Engine Tests of Various Catalysts.
Particulate Traps and Scrubbers	DOE Bureau of Mines EPA	Inhouse (BETC) Inhouse and with Engelhard Inhouse	Future Program In Progress In Progress	BETC Will Evaluate the Effectiveness of Traps as a Means of Reducing Particulate Emissions From Diesel Engines. The Bureau of Mines is Determining the Effectiveness of Particulate Filters and Scrubbers. 65 Percent Initial Particulate Removal Effectiveness Has Been Achieved in These Tests, But Device Deterioration is an Unresolved Problem Area. The EPA is Investigating the Particulate Removal Characteristics of Different Traps.
Fuel Composition	DOE Bureau of Mines EPA DOT	Inhouse and at Cummins Inhouse SWRI Ricardo	In Progress In Progress In Progress Completed	BETC is Establishing the Emissions Characteristics of Four Production Diesel Vehicles as Affected by Fuels Modifications, and Cummins Will Be Evaluating the Multifuel Capability of Its Adiabatic Engine, With Particular Emphasis on Gaseous and Particulate Emissions. A Comprehensive Assessment of Fuels Effects on Diesel Engine Performance and Emissions is Planned for FY 1980. The Bureau of Mines Has Found that Low Aromaticity Results in Lower BaP Emissions. A Vehicle Test Program is Underway at SWRI to Isolate Those Fuels Parameters That Have a Beneficial Effect on Particulate Emissions. Ricardo Has Determined the Effect of Cetane Number on Emissions and Found Little Change in the Particulate Level.
Noise Emission Control	Bureau of Mines EPA	Inhouse Inhouse and at SWRI, Purdue, and Ricardo	In Progress In Progress	The Bureau of Mines is Actively Involved in Noise Reduction of Underground Machinery. Potential Noise Abatement Techniques are Engine Enclosures and the Use of Acoustic Materials. EPA is Developing Noise Test Procedures for LDV's. Studies of Light, Medium, and Heavy Truck Engine and Tire Noise Reduction are Planned. Purdue Will Explore Noise Reduction Through Engine Encapsulation. Ricardo Will Demonstrate Noise Reduction Techniques in Vehicles Powered by Internal Combustion Engines.
<u>EMISSIONS AND MEASUREMENT TECHNOLOGY</u>				
Regulated Emissions	EPA DOT	Inhouse and at SWRI Chrysler Fiat Ricardo SWRI Inhouse (BETC)	In Progress In Progress In Progress In Progress	EPA Continues Emissions Certification Testing and Continues to Perform Emissions and Fuel Economy Testing of Prototype Vehicles. SWRI is in the Process of Establishing Baseline Emissions Maps for a Number of Heavy Duty Diesels and Will Establish an Emissions Data Base for Advanced Diesel Engine Vehicle Configurations. Chrysler and Fiat are Establishing Baseline HC, CO, and NO _x Emissions as Affected by Various Control Techniques. BETC is Characterizing the Emissions of Four Diesel Passenger Cars to Isolate Modal Effects.

TABLE 8-1. DIESEL ENGINE RESEARCH PROGRAMS -- GOVERNMENT AGENCIES (Continued)

RESEARCH CATEGORY	GOVERNMENT AGENCY	CONTRACTOR	STATUS	COMMENTS
EMISSIONS AND MEASUREMENT TECHNOLOGY (Cont'd)				
Unregulated Emissions	EPA DOE Bureau of Mines DOT	Inhouse and at SWRI Inhouse (BETC) Inhouse Chrysler Fiat Ricardo	In Progress In Progress Future Program In Progress	The EPA Will Perform Exhaust and Crankcase Emissions Measurements of Currently Unregulated Pollutants, Including Ammonia, Formaldehyde and Sulfates. SWRI Will Determine the Emissions of Particulates and Other Unregulated Species for a Number of Heavy Duty Diesels. In Addition SWRI Will Collect Samples for EPA's Bio-Assay Test Program. BETC is in the Process of Characterizing Total Particulate and Organic Mass Distributions for Four Production Diesels Over the Urban Driving Cycle and at Steady State. The Bureau of Mines Has Plans to Measure Exhaust PNA's and Particulates of a DI Diesel. Chrysler, Fiat, and Ricardo are Involved in the Characterization of Particulate Emissions From IDI Diesels, and in the Measurement of Total Particulates and Organics from IDI Engines Incorporating Emission Control Equipment.
Measurement Technology Development	EPA DOE Bureau of Mines	Inhouse and at Michigan T. U. Inhouse (BETC) Inhouse and at A. D. Little	Near Completion In Progress In Progress	Rulemaking for Particulate Measurement Of Light Duty Engines is Being Finalized by EPA and Investigations of Methodologies for Partitioning Organics are in Progress. BETC is Involved in the Development of Particulate Measurement Techniques. The Bureau of Mines Has Developed a Sulfate Test Procedure, and A. D. Little Has Completed an Assessment Study of Diesel Exhaust Measurement Methods.
HEALTH EFFECTS				
In-Vitro Testing	EPA DOE	Inhouse and at Battelle Columbus LITRI, MIT and Inhouse (BETC)	In Progress In Progress	At EPA, Bacterial and Mammalian Cell Bioassays Will Be Used to Compare the Mutagenic Activity of HDD and LDD Truck Exhaust as Well as Emissions From Other Sources. LITRI Will Research the Effect of Extraction Solvent on PAH Desorption Rates, and the Biological Characterization of Exhaust Components. DETC, in Cooperation With LITRI, Will Perform Ames Tests.
In-Vivo Testing	EPA DOE	Oak Ridge IITRI Inhouse LITRI	Continuing In Progress	Oak Ridge Is Performing Mutagenesis Studies Involving Whole Exhaust Exposures of Mice and Drosophila. Skin Painting Studies Will Focus on Extracts of Diesel and Other Exhausts. IITRI Will Use Chronic Intratracheal Instillation of These Test Substances. EPA Will Use Chronic Inhalation and Intraperitoneal Injection to Assess Transport and Oncogenesis Effects. LITRI Will Pursue In-Vivo Studies of Chronic Whole Exhaust Exposures and Extraction Solvent Effects on PAH Desorption. Respirator Deposition Will Be Studied, Using Surrogate Aerosols of Known Composition.
Epidemiological Studies	EPA DOE NIOSH	Inhouse Inhouse Inhouse	In Abeyance Future Program In Progress	EPA Continues Its Search of Suitable Study Populations. DOE Will Embark on a Study of Occupational Exposures to Diesel and Gasoline Engine Exhausts. NIOSH is Continuing Its Epidemiological Studies of Mine Workers Exposed to Diesel Exhaust.
Integrated Assessment Studies	EPA DOE	Inhouse LITRI	Future Program Future Program	EPA Will Establish Relative Potencies of Various Diesel and Non-diesel Compounds as an Aid to Estimating Dose-Response Relationships. LITRI Will Define an Integrated Assessment of the Human Risk Issue.

ing in a change in air-fuel ratio and exhaust emissions, and lube oil contamination.

Particulate trap oxidizers are not considered by BMW to be feasible in the near term. BMW has no ongoing efforts in this area, except to monitor industry activities. Although it is recognized that fuels composition can have a significant effect on particulate emissions, BMW is currently not involved in in-house research in this area. Also, no catalyst research is performed at this time by BMW, and any future involvement in health effects research will probably be carried out through contracts to German biological institutes.

8.2.2 British Leyland

British Leyland has been producing light-duty swirl chamber diesel engines for many years. The engines currently in production have displacements of 1.5, 1.8, and 2.5 liters, and are used in taxicabs, vans, and four-wheel drive vehicles (Ref. 8-22).

With regard to emissions control, British Leyland feels that EGR will probably be required to meet future NO_x standards in the United States. However, British Leyland expects the use of EGR to result in an increase in particulate emissions. Catalytic particulate control system development work is performed in cooperation with catalyst manufacturers. These systems are designed to promote incineration of the trapped particulate matter before their discharge into the atmosphere. In spite of some initial success with systems of this type, British Leyland is not very optimistic regarding the near-term prospects of particulate control. Carbon buildup on the catalyst surface, and sulfur poisoning, are considered to pose additional problems for catalysts.

Turbocharging is being considered by British Leyland as a technique to increase the inherently low specific power output capability of the diesel. Test data indicate power boosts of 25 to 30 percent, accompanied by some reduction in exhaust emissions. However, unless the rear axle ratio is reduced, there is no fuel economy benefit associated with turbocharging.

Because of its 10 to 12 percent higher fuel economy, the direct injection diesel is regarded by British Leyland as a strong candidate for use in light-duty vehicle applications in the future. Reduction in exhaust emissions

are thought to be achievable by means of modifications to the combustion process, which might be realized through the use of reduced cylinder cooling, improved port designs, and high-pressure fuel injection systems.

8.2.3 Chrysler

Chrysler is continuing the development of its dieselized 225 CID slant six swirl chamber engine, with technical assistance provided by Ricardo Consulting Engineers of England (Ref. 8-23). Dieselization of a 4-cylinder and a V-8 spark ignition engine is under consideration. A number of Dodge Aspen sedans and Dodge pickup vehicles, equipped with naturally aspirated and turbocharged versions of the slant six diesel engine, are being tested on the dynamometer and on the road. The performance of the naturally aspirated diesel engine is comparable to the spark ignition engine, while the torque characteristics and rated power of the turbocharged engine are similar to a V-8 spark ignition engine.

In the area of exhaust emissions control, Chrysler is developing a modulated EGR system, and is experimenting with catalysts and trap oxidizers for particulate abatement. Tests are in progress to determine the effectiveness of these systems in controlling total particulates, organics, and aldehydes. Particulate samples are being collected for use in health effects tests.

The development of a light-duty direct injection diesel engine is proceeding. This engine is expected to improve fuel economy by 15 to 20 percent relative to equivalent indirect injection diesels. The emphasis in this program is placed on the development of an advanced electronically controlled fuel injection system. The purpose of this system is to provide better control of pertinent fuel injection and combustion parameters as a means for reducing peak chamber pressure, combustion generated noise, and pollutant formation. Also, the concept of dual injection is being investigated, using pilot injection of small amounts of fuel prior to the main injection process. Chrysler expects to achieve further reduction in particulate emissions with this technique.

8.2.4 Daimler-Benz

Because of its more favorable combustion noise and vibration characteristics, Daimler-Benz has always favored the prechamber design over the swirl

chamber for light-duty diesel engine applications (Ref. 2-24). More recently, Daimler-Benz has re-examined the swirl chamber concept and has concluded that the swirl chamber has a number of inherent advantages over the prechamber, and vice-versa. For example, the swirl chamber provides a 2 to 4 percent advantage in fuel economy and has somewhat lower NO_x emissions, while the prechamber has a distinct advantage in HC, odor, and possibly polynuclear aromatics emissions. Current Daimler-Benz vehicles have no difficulty meeting the 0.41 g/mi HC emissions standard. However, at that HC level, a NO_x standard of 1.0 g/mi cannot be met without the use of EGR.

Daimler-Benz has examined many different engine modifications, and has found that chamber geometry, fuel injection system operation, and fuel composition, are the most significant parameters affecting the various pollutant formation processes during combustion.

Turbocharging is considered by Daimler-Benz only as a means for increasing engine power per unit displacement, and not for reducing emissions over the Federal Driving cycle. However, under high-load conditions, the use of turbocharging may actually result in a reduction in particulate emissions, because of the associated increase in engine air-fuel ratio at a fixed load setting. In addition to a power increase, the use of a turbocharger in conjunction with a smaller numerical rear axle ratio, can result in a 5 to 10 percent improvement in fuel economy relative to naturally aspirated engines of the same displacement.

Daimler-Benz has investigated the use of EGR as a NO_x control technique for quite some time. In fact, all 3.0 liter Mercedes-Benz diesel vehicles marketed in California are equipped with EGR. However, to prevent large increases in particulate emissions, EGR rates must be closely controlled in accordance with engine load, engine speed, and ambient temperatures, and pressures. The principal problems associated with the use of EGR in diesel engines are related to lube oil contamination, engine wear, and coking of the intake ports and valves. Daimler-Benz feels that the EGR flow must be filtered before admission into the engine to remove soot particles. Since the soot emitted from prechamber engines is very dry, the application of a cyclone separator might be feasible.

With regard to exhaust aftertreatment as a means of emission control, Daimler-Benz has investigated a variety of devices. Thermal reactors have been tried unsuccessfully, and particulate filters are not considered to be practical for automotive engines. To date, some success has been achieved with particulate trap oxidizers, and the development of such systems is continuing at Daimler-Benz.

Tests performed by Daimler-Benz with different fuels indicate that particulate emissions levels are directly related to aromatics content of the fuel. For example, the use of U.S. diesel fuel at the lower end of the specification band, instead of European fuel, has resulted in a 200 to 300 percent increase in HC and a 100 percent increase in particulates. For these reasons, Daimler-Benz advocates tighter fuel specifications for the United States. Experiments with water-diesel fuel emulsions have shown significant reductions in particulates, but emulsion stability, emulsifier cost, and increased HC emissions are unresolved problem areas.

In the health effects area, Daimler-Benz is supporting the conduct of both Ames tests and long-term inhalation tests. Rats are used in the inhalation test program in which they are exposed to either diesel exhaust or exhaust from spark ignition engines. Daimler-Benz feels that short-term tests using concentrated soot do not correctly predict a valid dosage-response relationship. Mice which received periodic injections of pure BaP developed cancer within nine months, while injections of diesel soot with the same BaP level were much less harmful. In addition to these programs, most of which are performed for Daimler-Benz by specialty laboratories, particle size effects studies are underway to determine particle and organic compound retention in the lungs of animals.

8.2.5 Fiat

Approximately two years ago, Fiat initiated the production of naturally aspirated and turbocharged light-duty swirl chamber diesel engines (Ref. 2-25). Current efforts are aimed at improving the exhaust emission and fuel economy characteristics of these engines by means of design modifications to the combustion chamber and fuel injection system, and optimization of shift schedules. Turbocharging is used primarily to upgrade the performance of the engine, and to further improve vehicle fuel economy via engine-driveline

matching. In addition, turbocharging has resulted in significant reductions in particulates, smoke, noise, HC, CO, and NO_x. The observed reduction in particulate emissions, which is contradictory to Daimler-Benz and General Motors data, is attributed by Fiat to the use of leaner mixtures in the turbo-charged engine.

Fiat is currently involved in the development of a light-duty direct injection diesel engine. This engine uses the block from the swirl chamber engine and a newly designed head. The fuel economy of this engine is projected to be about 15 to 20 percent higher than that of equivalent indirect injection engines. However, the HC emissions of the direct injection engine are about three times as high, and NO_x and noise levels are also higher. The principal objectives of ongoing activities are to reduce exhaust emissions without adversely affecting fuel economy, driveability, and noise.

The use of EGR is being investigated by Fiat as a potential NO_x control technique for both indirect and direct injection diesel engines. While the NO_x reduction potential of EGR has been demonstrated in experimental engines, engine durability is an unresolved problem area. Water injection was investigated several years ago, and was found to be effective in controlling NO_x in diesel engines. However, because of corrosion and other potential problems, this technique is no longer considered to be feasible by Fiat for use in automotive diesels. Other emission control systems and devices are being examined, including catalysts for HC control, and traps and trap-oxidizers for particulate control.

Fuel and lube oil composition have been shown to have significant effects on the particulate formation process in the combustion chamber. In general, low cetane fuels result in higher HC, NO_x, and particulate emission levels, primarily because of a deterioration in the combustion process. For example, diesel engine tests performed with 43 cetane U.S. fuel resulted in a 50 percent increase in HC and a 20 percent increase in NO_x, relative to operation of the engine with 51 cetane Italian fuel. Fiat feels that fuel aromaticity and volatility might be an even more important parameter than cetane number. Like Daimler-Benz, Fiat suggests that a special fuel be provided by the refining industry for use in diesel automobiles. This fuel should have low aromaticity, high volatility, and a low sulfur content.

In the advanced diesel engine area, Fiat is investigating the benefits of adiabatic diesels. Various ceramic components have been manufactured and bench tested. However, a ceramic swirl chamber failed after 5 minutes of engine testing. The Rankine bottoming cycle is being examined as an alternative to the adiabatic engine for potential use in heavy-duty engine applications.

8.2.6 Ford

Ford is involved in a number of research programs to determine the benefits and limitations of light-duty diesel engines with regard to exhaust emissions and fuel economy (Ref. 8-26). Parameters under investigation include combustion chamber geometry, exhaust aftertreatment devices, and fuel composition.

Diesel engine durability and emission control degradation associated with the use of EGR is determined experimentally. Two diesel vehicles, one equipped with EGR, are tested over 50,000 miles of AMA driving. The performance of the EGR system is monitored through periodic measurement of exhaust emissions.

Activities in the area of exhaust aftertreatment are concerned with the investigation of various particulate trap and trap oxidizer systems, with particular emphasis on particulate collection and abatement efficiency, pressure drop, and trap durability. In a parallel program, particulate emissions collected from a number of diesel vehicles are characterized for chemical composition and biological activity.

Another experimental program is concerned with the development and testing of an emission control system to meet the 1 g/mi NO_x emission level in naturally aspirated and turbocharged diesel engines with displacements ranging from 2.1 to 4.3 liter. The vehicles under consideration have inertia weights in the 2000 to 4250 lb range.

The prospect of meeting HC, CO, and NO_x emissions of 0.41, 3.4, and 0.4 g/mi, respectively, in a diesel engine is being investigated by Ford, considering extensive modifications to the combustion chamber and fuel injection system, as well as the addition of aftertreatment devices.

General Motors (GM) continues its light-duty diesel engine research programs which were initiated several years ago. The overall objective of GM's research is the development of engines which have low emissions and low fuel consumption in conjunction with commercially acceptable performance and durability. Specific program areas include (1) particulate measurement and removal, (2) engine modifications, (3) fuel modifications, and (4) health effects.

GM has developed an opto-acoustical particulate measurement system which permits accurate, near-instantaneous, real-time measurement of particulates (Ref. 8-27). This system permits measurement of particulates emissions under changing load and speed without the drawbacks of optical smoke meters and filter collection. The system uses a modulated infrared laser to cause the particulates to alternately heat and cool the surrounding air in a sample chamber. The fluctuating air temperature is detected acoustically as the chamber pressure fluctuates with temperature.

Particulate removal has concentrated on the reduction of tailpipe particulate emissions via exhaust gas treatment. Centrifugation, water scrubbing, electrostatic precipitation, oil bath collection and trapping concepts have been examined (Ref. 8-28). The primary drawback of most removal concepts is the need for periodic disposal of the accumulated particulates. Manual cleaning and automatic incineration are two regeneration methods under review. GM feels that particulate trap oxidizer systems offer the most viable solution at current emission levels. Current work in this area is focusing on the selection of trap materials, selection of the regeneration method, and integration of the trap oxidizer system and its controls in test vehicles.

In the area of engine modifications, GM is investigating the effects of combustion chamber geometry, EGR, turbocharging, intake valve timing, and fuel injection system modifications, including timing, rate, and spray direction (Ref. 8-29). Combustion chamber design has focused on chamber swirl and catalytic chamber surfaces. However, neither approach appears to be feasible for total emission reduction, as reductions in one emission species were generally offset by increases in others. EGR has been applied for the purpose of NO_x reduction, but engine durability degradation appears to be a serious problem

area. In one vehicle, the carbon content in the lube oil increased from 1.2 percent to 1.8 percent over a 50,000 mile interval without EGR, but subsequently increased to 2.5 percent over a 6000 mile interval with EGR. Another vehicle operated with EGR throughout the test reached 7 percent carbon and suffered a rocker arm failure at 27,000 miles. Turbocharged engines are under scrutiny both for improving fuel economy at equal performance levels and for possible emissions reduction. GM feels that turbocharging increases NO_x in most cases, although there is a modest reduction in HC. Valve timing tests with a 5.7 liter engine have demonstrated improved volumetric efficiency at low RPM for a 20 degree earlier intake valve closing (Ref. 8-30). In these tests, noise and HC decreased with no adverse effects on smoke and NO_x .

Improved fuel injection timing control is expected by GM to offer reduced engine emissions. Preliminary tests of electronically controlled injection pumps have been performed, but additional efforts are required in this area. GM is also exploring emissions reduction through modified injector nozzle design. Tests of a poppet-type injector indicate lower HC emissions relative to the pintle-type injector. Fuel spray orientation has been shown to affect emissions. Spray orientations directed against the chamber swirl are best with respect to HC and particulate emissions, but result in high NO_x emissions and noise.

Fuel modification research at GM has stressed the effect of fuel and lubricants on particulate formation. Tests with a carbon-14 tagged lubricant show that the oil contributes from 2 to 25 percent of the total particulate mass, with the greatest contribution occurring at high speed and light load. Virtually all of the oil's contribution is in the soluble portion of the particulate (Ref. 8-28). Similar experiments with tagged fuel components indicate that all fuel components participate in the particulate formation process, and that aromatics have the highest tendency to contribute. Particulate reductions up to 27 percent have been achieved with special fuel blends. However, GM feels that the need for refinery and distribution system changes would require a fairly long lead time. Although some reduction in particulate emissions was achieved with fuel additives under part-load conditions, the effectiveness of the additive declined significantly in the high-load regime. Tests with water-fuel emulsions indicate particulate reductions up to about 7 percent.

GM is engaged in a major long-term four-part program designed to provide data on the potential health threats associated with increased diesel engine use (Ref. 8-31). The program will explore (1) particulate formation and characterization, (2) development of realistic test procedures and instrumentation, (3) particulate collection methods, and (4) assessment of potential health effects.

8.2.8 Peugeot-Citroen

Peugeot has been marketing swirl chamber diesel powered cars for many years. It has recently completed the development of a turbocharged 2.3 liter 4-cylinder diesel engine for use in its 604 model, scheduled for introduction in the U.S. in 1981 (Ref. 8-32). This engine is based on the current production 2.3 liter diesel engine, but incorporates many modifications to accomodate the higher stress levels and thermal loads resulting from turbocharging. In this engine turbocharging is used solely to increase power output and not to control emissions. However, Peugeot feels that turbocharging will be required in EGR equipped diesel engines to meet future HC, NO_x, and particulate emission regulations.

Currently, Peugeot employs EGR in all its diesel vehicles sold in California. Advanced EGR systems are under development in conjunction with Bosch. A hydraulically controlled system has achieved NO_x and particulate emissions of 1 g/mi and 0.5 g/mi, respectively, in a 604 model vehicle. Peugeot feels that electronic controls will be required in the long term to properly match engine operating conditions, injection system control parameters, and EGR rates.

Exhaust aftertreatment devices are also under investigation, both inhouse and with contractors. Trap-oxidizer development work is under way in conjunction with Ricardo Consulting Engineers, while catalytic converters are being developed in cooperation with Engelhard. Although difficulties have been encountered in regenerating the trap-oxidizer, work is continuing in this area. Catalytic aftertreatment has resulted in a 20 to 30 percent reduction in HC over the Urban Cycle. However, a large increase in the conversion rate of sulfur to sulfates was noted, with catalyst poisoning a distinct problem area.

In addition, Peugeot is active in noise reduction work, and in the development of DI diesel engines for light-duty applications. The addition of

a turbocharger resulted in a 2.5 dB(A) noise reduction in the 2.3 liter engine. Other factors to be examined as part of Peugeot's overall noise reduction program include the use of lower fuel injection rates at idle, combined with structural modifications on the engine. These improvements are projected to reduce engine noise by an additional 2 dB(A).

Ongoing health effects studies include the measurement of pollutants and the conduct of short- and long-term in-vitro bioassays.

8.2.9 Volkswagen

Major efforts at Volkswagen (VW) are concerned with NO_x and particulate emission control (Ref. 8-33). In addition to EGR and turbocharging, VW is investigating combustion chamber and fuel injection system modifications. VW feels that the use of these techniques might be sufficient for meeting future regulations in its Rabbit and Dasher vehicles. However, the heavier Audi vehicles are expected to require the use of aftertreatment devices.

Ricardo Consulting Engineers are involved in the development of trap-oxidizer systems for VW, while Johnson-Matthey is working on the development of catalysts under a contract from VW. To date, both catalytic and noncatalytic filter mesh configurations have been investigated. A number of the more promising trap-oxidizer configurations were subjected to durability testing, revealing the need for further design refinements. In the tests with catalysts, VW noted an increase in the conversion rate of sulfur to sulfates. Sulfate poisoning of the catalyst is being investigated also.

The development of a light-duty DI engine is being pursued by VW. Although this engine type promises improved fuel economy, the achievement of sufficiently low pollutant and noise levels poses a potential problem area.

8.2.10 Summary

A tabular summary of diesel engine programs currently conducted or sponsored by the automobile industry is provided in Table 8-2.

8.3 OTHER ORGANIZATIONS

A number of organizations other than the automobile manufacturers and government agencies are engaged in the conduct of diesel related research

**TABLE 8-2. DIESEL ENGINE RESEARCH PROGRAMS --
AUTOMOBILE INDUSTRY**

CATEGORY	COMPANY	STATUS	COMMENTS
ENGINE TECHNOLOGY DEVELOPMENT			
Indirect Injection Diesel	British Leyland Daimler-Benz Fiat General Motors Isuzu Nissan Peugeot Toyota Volkswagen	In Production	General Motors and a Number of European and Japanese Automobile Manufacturers are Marketing Diesel Automobiles or Light Duty Trucks. BMW, With Assistance From AVL, is Developing a Turbocharged Diesel Engine for Production in 1983, and Toyo Kogyo Will Start Production of Two New Engines in the Near Future. Chrysler is Dieselizing Its 225 CID Gasoline Engine and Ford is Involved in Diesel Study and Development Efforts. Except for Daimler-Benz all Manufacturers Use Swirl Chambers. Current Daimler-Benz Engines are of the Prechamber Type, But Swirl Chamber Configurations are Being Evaluated. Daimler-Benz Feels That Prechamber Engines Have Lower HC, CO, and NO _x Emissions Potentials, at the Expense of a Small Loss in Fuel Economy. All Manufacturers Are Involved in Engine Improvement and Emission Control Technology Programs.
	BMW Chrysler Ford Toyo Kogyo	Under Development	
Direct Injection Diesel	BMW British Leyland Chrysler Cummins Daimler-Benz Fiat Peugeot	Under Study or Development	These Manufacturers are Involved in the Design and Development of Prototype DI Engines for Potential Application in Passenger Cars or Light Duty Trucks. Projected Fuel Economy Improvements Relative to IDI Diesels Vary from About 10 to 15 Percent for Naturally Aspirated Engines, and From 15 to 25 Percent for Turbocharged Engines. Noise, NO _x and HC Emissions are Considered by Some Manufacturers to Be Principal Problem Areas.
Adiabatic Engine	Fiat	Studies in Progress	Preliminary Design Investigations Have Been Initiated. Fiat Expects to Achieve Lower Particulate and HC Emissions and Better Startability Relative to Conventional Diesels.
Turbocharging	Daimler-Benz Peugeot Volkswagen	In Production In Production Near Production Near Production	These Manufacturers are Considering the Use of Turbocharging as a Means of Improving Engine Vehicle Performance, and/or Reducing Fuel Consumption and Gaseous and Particulate Emissions. Some Manufacturers are in the Process of Conducting Vehicle Testing. Fuel Economy Improvements of 5-15 Percent Relative to Naturally Aspirated Engines are Projected When Turbocharging is Combined With Gearing Changes.
	Fiat BMW British Leyland Cummins Toyota Chrysler Ford	In Development Under Study	
Engine Component Modifications	BMW British Leyland Chrysler Cummins Daimler-Benz Fiat Ford General Motors Isuzu Nissan Peugeot Toyo Kogyo Toyota Volkswagen	In Progress	All Manufacturers Have Active Programs in the Areas of Combustion Chamber and Fuel Injection System Modifications as a Means of Optimizing Engine Torque, Fuel Economy, Exhaust Emissions and Noise in Conjunction With the Use of Other Emission Control Devices and Techniques. Parameters Under Examination Include Chamber Shape and Volume Ratio, Compression Ratio, Prechamber/Main Chamber Passage, Glow Plug Location, Materials Selection, Valve Timing, Fuel Injection Timing, Injection Pressure and Rate, Injection Nozzle Design, Sac Volume, Fuel Spray Formation, Spray Pattern, and Air/Fuel Mixing. High Pressure Injection Systems Permit the Use of High Injection Rates, Resulting in Improvements in Fuel Economy and Emissions.
Electronically Controlled Fuel Injection	Chrysler	In Progress	Several New Systems are Being Developed to Provide Better Control of Injection and Combustion Parameters in DI Diesels. These Designs Feature High Speed Valving Devices and Other Means for Precise Fuel Flow Control.
EMISSION CONTROL			
Exhaust Gas Recirculation	Robert Bosch BMW British Leyland Chrysler Cummins Daimler-Benz Fiat Ford General Motors Isuzu Nissan Peugeot Toyo Kogyo Toyota Volkswagen	In Progress	EGR is Considered to Be a Promising NO _x Control Technique. 40-60 Percent NO _x Reduction Has Been Achieved, Generally at the Expense of Higher Particulate, Smoke, HC, CO, and Odor Emissions. In Experimental 4500LB IW Vehicles, General Motors Has Achieved NO _x Levels Below 1 Gram/Mile. Potential Problem Areas are Deposit Buildup, Engine Wear and Lube Oil Contamination. Improved Modulated EGR Systems are Being Developed by a Number of Manufacturers. Daimler-Benz and Peugeot Have Tested the Bosch Hydraulic-Pneumatic EGR System. Peugeot is Continuing With the Bosch System, While Daimler-Benz is Developing an Electronically Controlled System. Toyota is Evaluating Both Mechanically and Electronically Controlled Systems. Daimler-Benz's 1980 California Diesel Vehicles Will Incorporate EGR to Meet the 1.5 Gram/Mile NO _x Standard.

**TABLE 8-2. DIESEL ENGINE RESEARCH PROGRAMS --
AUTOMOBILE INDUSTRY (Continued)**

CATEGORY	COMPANY	STATUS	COMMENTS
EMISSION CONTROL (Cont'd)			
Catalytic Converter	British Leyland Daimler-Benz Fiat Ford Chrysler General Motors Peugeot Volkswagen	Under Consideration	Divided Chamber Light Duty Diesels Have Inherently Low HC and CO Emissions. However, the Use of EGR for NO _x Control Results in Higher HC and May Require the Use of a Catalyst to Meet the 0.41 Gram/Mile HC Standard. Problem Areas are Catalyst Degradation and an Increase in Sulfate Particulate Emissions. With Catalysts, Test Data Indicate Significant Reductions of the Organic Particulate Fraction.
Water Injection and Emulsions	Cummins Daimler-Benz Fiat Peugeot Toyota	Inactive Under Evaluation Inactive Under Consideration	Effective NO _x Control Technique. Daimler-Benz is Evaluating Water Injection and Induction Systems of Different Designs. In Conjunction with EGR and Turbocharging, They Have Achieved 0.4 Gram/Mile NO _x Plus Improved Fuel Economy in an Experimental Vehicle. Problem Areas are Corrosion, System Complexity, Cost, and Freezing of the Water. Toyota Has Experimented With Water/Fuel Emulsions and Has Demonstrated the Beneficial Effects Caused by "Micro Explosions". Emulsion Stability and Cost are Problem Areas.
Particulate Traps and Trap Oxidizers	Chrysler Daimler-Benz Fiat General Motors Peugeot Volkswagen	In Progress Under Investigation R & D Initiated Testing In Progress Under Investigation	Daimler-Benz Has Achieved Some Success With Experimental Trap Oxidizers. GM Has Demonstrated That Traps With In-Situ Regeneration By Incineration Are the Most Practical Means of Particulate Removal. Tests Have Indicated Problems With Back-Pressure, Loss of Trapping Efficiency, Durability and Safety. Peugeot Has Contracted Work to Ricardo While Volkswagen Has an Inhouse Program and Has Ricardo Under Contract. Problem Areas are Durability and Uncontrolled Lightoff of Carbonaceous Material.
Fuels and Lubricants Composition and Additives	Daimler-Benz Fiat General Motors Peugeot Volkswagen	Under Investigation	Daimler-Benz Data Indicate That Modification in Fuel Composition Can Have Beneficial Effects on HC and Particulate Emissions Levels. Fiat Has Shown Reductions in HC, Particulates and Organics Through Fuel Modifications and Use of Additives. Low Aromatic Fuels Give Low PNA's and Soot, While High Volatility Improves Engine Startability and Particulate Emissions. GM Has Used Carbon-14 Tracers to Determine the Effects of Fuel and Lubricant Compositions on Emissions, and Has Evaluated the Emissions Effects of Additives. Peugeot Has Found That the Low Cetane Rating of U.S. Diesel Fuels Relative to European Fuels Has an Adverse Effect on Emissions.
Noise Emission and Control	British Leyland Cummins Daimler-Benz Fiat General Motors Peugeot Volkswagen	In Progress	All Manufacturers are Engaged to Some Degree in Noise Characterization and Control Programs as Part of Their Normal R & D Activities. Daimler-Benz Has Constructed an Experimental Vehicle Featuring an Encapsulated Engine. General Motors has Experimented With Transmission Noise Reduction, and Has Proposed an Alternative Part-Throttle Test Procedure to EPA. Peugeot is Experimenting With Noise Reduction Via Shielding, Damping, and Engine Support Modifications, and is Experimenting With Turbocharging as a Means of Noise Reduction Through Engine Operation at Lower RPM. VW Has Achieved Some Reduction of Cold Knock Via EGR.
EMISSIONS AND MEASUREMENT TECHNOLOGY			
Pollutant Species Characterization	BMW British Leyland Chrysler Daimler-Benz Fiat Ford General Motors Peugeot Volkswagen	Ongoing Efforts.	In Addition to Measuring Regulated Pollutants, Most Manufacturers are Involved in Determining Particulate Size Distributions and Particulate Organic Composition Through Inhouse Efforts or Contracted Work. BMW Has SWRI Under Contract to Characterize Particulates. Fiat Has Found That Turbocharging can Reduce the Organic Fraction. Manufacturers Will Be Using the Procedures Established by EPA for Certifying Diesels. Concern Over the Double-Counting of Hydrocarbons Has Been Expressed. The Effects of the Characterization of Organic Compounds Are Being Studied.
Measurement Technology Development	Daimler-Benz Peugeot Toyota	Studies in Progress	Daimler-Benz is Analyzing Different Sample Collection Methods, and is Developing a Chromatography-Based Method Identifying Odorous Constituents of Diesel Exhaust. Dilution Ratio Has Been Determined to Be a Very Important Parameter. Peugeot Has Experimented With Different Odor Measurement Techniques and Has Established a Need For More Reliable Instrumentation.
HEALTH EFFECTS			
In-Vitro Testing	BMW CCMC Chrysler Daimler-Benz General Motors Peugeot Volkswagen Volvo	In Progress	BMW and Volkswagen Have Contracted Work in This Area to German Biological Labs. Daimler-Benz Will Compare the Effects of Gasoline and Diesel Engine Exhausts on Bacterial and Mammalian Cells. GM Will Study the Effects of Diesel Exhaust Products Using Bacterial, Mammalian, and Human Cell Bioassays. CCMC Plans to Investigate the Effects of Extraction Solvent on Mutagenic Response. Peugeot Will Analyze Particulate Extracts With the Ames Test Procedure Through Contracts to Outside Labs. Volvo, in Cooperation With the Swedish Government, Will Investigate the Influence of Engine Operating Condition On In-Vitro Bioassays.
In-Vivo Testing	British Leyland CCMC Daimler-Benz Peugeot	In Progress	British Leyland is Performing Animal Inhalation Tests, and CCMC and Daimler-Benz are Conducting Chronic Inhalation Studies. GM Has Begun Exposure Tests in Its Chronic Inhalation Test Facility. Test Animals Will be Examined Periodically for Pathological, Oncological, and Respiratory Changes. Peugeot Plans to Study Exhaust Gases Via Chronic Inhalation or Skin Painting Experiments.

and development programs. These organizations include AVL, Exxon Research, Lucas CAV, Mobil Research, and Ricardo Consulting Engineers.

8.3.1 AVL

AVL, which is a privately owned research and consulting company located in Graz, Austria, has been involved in the design and development of heavy-duty DI diesel engines for many years. More recently, AVL has become involved in the development of a light-duty high-speed DI diesel engine for potential use in automobiles. The basic approach applied in the AVL design relies on the incorporation of a number of specific engine modifications to accelerate the combustion process, and to minimize HC emissions. These modifications include (1) helical intake port, (2) bowl-in-piston with turbulence rim, (3) multi-hole injection nozzles, (4) retarded fuel injection, (5) high compression ratio, (6) zero-sac nozzle tip, and (7) EGR. Based on initial engine and vehicle tests, the DI engine provides a 15 to 20 percent advantage in fuel economy relative to an equivalent IDI diesel engine, while maintaining gaseous and particulate emissions at IDI engine levels (Ref. 8-34).

Other diesel related research and development work in progress at AVL is concerned with catalysts, particulate trap oxidizer systems, turbo-charger improvements, combustion chamber and fuel injection system optimization, and EGR system effects.

8.3.2 Exxon Research

Exxon has completed a diesel emissions characterization program, which was concerned with the measurement of regulated emissions, smoke opacity, and polynuclear aromatics (PNAs) from heavy-duty engines, with particular emphasis on fuel composition variation. It appears that PNAs are oxidized in the exhaust stream, indicating that exhaust system configuration can influence the quantities of PNAs generated. With regard to exhaust opacity, test data indicate a definite correlation between opacity and fuel volatility, with more volatile fuels showing lower opacity levels.

Current efforts involve emissions characterization testing of light-duty diesel vehicles. The objective of this program is to investigate the effects of catalysts, trap-oxidizers, fuel injection timing, and fuel composition on diesel combustion and pollutant species formation. (Ref. 8-35).

8.3.3 Lucas CAV

In support of its diesel fuel injection system development and marketing activities, Lucas CAV is involved in the conduct of a number of research and development programs in the area of diesel combustion. Single cylinder engine work is performed to study basic combustion phenomena, using high-speed photography and advanced techniques, including laser-Doppler anemometry and Raman spectroscopy (Ref. 8-36).

Another program is concerned with air-fuel mixing and its effects on engine performance and pollutant formation. Reduction in injection duration has resulted in some improvement in fuel economy and smoke emissions, at the expense of higher combustion chamber pressures and temperatures, and higher NO_x and noise emissions. The simultaneous use of retarded timing has resulted in a marked reduction in the emissions, while maintaining high engine efficiency. Recent activities have been concentrated in the area of particulate emissions characterization and formation. The effects of EGR on pollutant emissions and engine durability are also being examined.

Investigations are being conducted to define the injection requirements of adiabatic diesel engines. Lucas CAV feels that a high swirl DI chamber configuration would be optimum for adiabatic engines.

8.3.4 Mobil Research

Mobil is currently conducting a number of projects involving the characterization of diesel exhaust emissions, as affected by engine type, engine and fuel injection system design and operation, and most importantly, fuel composition (Ref. 8-37). The principal objective of these activities is to assess the significance of fuel composition on the formation of particulate and gaseous emissions in the diesel combustion process, and to project the type of refinery modifications that would be required for the production of these fuels.

In the measurements area, different dilution tunnel designs are being examined to determine the effects of hardware variations on the composition and mass of particulate matter collected.

8.3.5

Ricardo Consulting Engineers

Ricardo is currently heavily involved in the area of diesel engine emission control research and development. Much of this work is being performed under contracts from the automobile industry. The development of a programmed EGR system has been completed. In conjunction with fuel injection retard, this system provides the capability of achieving 1 g/mi NO_x and 0.6 g/mi particulates in full size vehicles in the 4000 to 4500 lb inertia weight category.

The development of exhaust aftertreatment devices, such as particulate traps, trap-oxidizers, and catalysts has been pursued for sometime. To date, some of these systems have achieved satisfactory particulate reduction efficiencies, but there are unresolved durability problems. Although catalytic devices have shown substantial reductions in HC emissions in diesel engines, they are only usable in conjunction with low sulfur fuels, which are not readily available.

Other projects are concerned with the effects of variations in fuel composition on diesel particulate emissions. Low boiling point fuels were found to reduce particulates and smoke, but might increase HC emissions. However, the lower viscosity of these fuels might cause fuel injection pump problems.

Although water injection and emulsions are currently not being pursued by Ricardo, they have considerable experience in that area. Injection of 25 percent water with the fuel resulted in significant reductions in the smoke level of engines normally emitting high quantities of smoke, while little improvement was achieved in relatively clean engines. In these tests, fuel economy improvements of up to 15 percent were achieved relative to engine operation on diesel fuel only. In spite of these benefits, the use of water is not considered to be feasible for automotive diesels in the near term.

Optimization of the swirl chamber version of the Chrysler 225 CID slant six engine has been completed. Current efforts in this area are aimed at the design of a DI version which is projected to provide a 10 to 15 percent fuel economy advantage relative to the IDI. Although structural modifications to the block and other engine components are required, the resulting design is sufficiently similar to the IDI to permit production on existing tooling.

TABLE 8-3. DIESEL ENGINE RESEARCH PROGRAMS --
OTHER ORGANIZATIONS

RESEARCH CATEGORY	ORGANIZATION	STATUS	COMMENTS
<u>ENGINE TECHNOLOGY DEVELOPMENT</u>			
Direct Injection Engine	AVL Ricardo	In Progress In Progress	AVL is Pursuing the Development of DI Engines for Automobile Applications. DI has 15-20 Percent Fuel Economy Advantage and Comparable Emissions Relative to IDI.
Turbocharging	AVL Ricardo	Under Consideration Under Consideration	AVL and Ricardo are Investigating the Effects of Turbocharging on Fuel Consumption, Performance, and Exhaust Emissions. Moderate Reductions in Particulate Emissions Have Been Achieved.
Engine Modifications	AVL CAV Ltd. Ricardo	In Progress	Investigations are Underway to Characterize the Effects of Combustion Chamber and Intake Modifications on Efficiency, Performance, Exhaust Emissions, and Noise.
Fuel Injection System Modification	AVL Robert Bosch CAV Ltd. Ricardo	In Progress	Ongoing Projects are Concerned with Optimization of Injection Pressure, Rate, Spray Angle, and Nozzle Geometry, to Achieve Acceptable Compromise Between Emissions and Engine Efficiency.
<u>EMISSION CONTROL</u>			
Exhaust Gas Recirculation	AVL Robert Bosch CAV Ltd. Ricardo	In Progress In Progress Under Consideration Under Consideration	AVL is Experimenting With Modulated EGR as a NO _x Control Technique for DI Engines. Bosch is Optimizing an Integrated Hydro-Pneumatic EGR/Fuel Injection System. CAV and Ricardo are Examining the Effects of EGR on Fuel Economy, HC, Particulates, and Smoke.
Catalytic Converters	AVL Ricardo	In Progress In Progress	Catalyst Tests are Being Performed to Determine the HC, CO, Particulates, and Odor Reduction Potential of Catalysts. Low Sulfur Fuels May be Required to Limit Sulfate Particulate Formation.
Particulate Trap and Trap Oxidizer Systems	AVL Exxon Ricardo	Under Investigation Future Program Under Investigation	AVL and Ricardo are Testing Trap and Trap Oxidizer Systems. High Initial Particulate Trapping Efficiency Has Been Demonstrated. Durability is a Major Problem Area. Control of Light-Off Temperature is Difficult.
Water Injection	Ricardo	Inactive	Previous Efforts were Concerned With the Effects of Water Injection on Emissions. NO _x , Smoke, and Fuel Consumption Were Reduced, While HC Remained Unchanged for Water to Fuel Flow Ratios up to 0.85.
Fuel Modifications	AVL Exxon Mobil Ricardo	In Progress	Test Data Indicate a Reduction in Smoke Level with Low Boiling Point Fuel. European Diesel Fuel has Lower Aromatic Content and Higher Cetane Number, and Generally Results in Lower HC, NO _x , and Particulates. Exxon and Mobil are Investigating the Effects of Fuels Properties and Additives on the Performance and Emission Characteristics of Light Duty Diesels.
Noise	AVL CAV Ltd. Purdue U. Ricardo U. of Southampton	In Progress	These Organizations are Engaged in Engine Noise Characterization Work. AVL Has Done Extensive Work on Structural Noise Reduction and Engine Encapsulation. University of Southampton and CAV are Examining the Effects of Combustion Systems and Engine Component Design Variations on Noise Generation. CAV has Also Explored the Effects of Combustion Noise Control Measures on Fuel Consumption and Exhaust Emissions. Ricardo has Measured the Full-Throttle Noise Test Ratings of Passenger Vehicles, and is Investigating Noise Abatement Techniques.
Instrumentation and Measurement	AVL CAV Ltd. Michigan Technological University Mobil Ricardo	In Progress	These Organizations are Involved in the Development and Application of Particulate Measurement Devices and Techniques. CAV is Considering High Speed Photography, Raman Spectroscopy, and Laser Doppler Technology. Michigan Technological University is Developing Methods for Chemically Characterizing Particulate Organic Matter.
<u>HEALTH EFFECTS</u>			
In-Vitro Testing	Battelle Columbus MIT	In Progress In Progress	Battelle has been Investigating the Influence of Fuel and Engine Operating Conditions on In-Vitro Samples. Diesel Extracts have Shown Positive Test Responses. Based on Limited Samples, MIT has Demonstrated the Presence of a Powerful Direct Mutagen in Diesel Exhaust Components Extracted with a Pentane-Toluene Solvent.
In-Vivo Testing	Battelle Columbus	In Progress	Inhalation Studies are Continuing with Emphasis on Establishing In-Vitro/ In-Vivo Correlations for Particulate Matter From Diesel Engines.

8.3.6 Summary

A tabular summary of recent diesel engine programs conducted by organizations other than the automobile manufacturers and government agencies is provided in Table 8-3.

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SECTION 9

DIESEL RESEARCH AND DEVELOPMENT NEEDS

9.1

INTRODUCTION

Relative to spark ignition (SI) engines, light-duty indirect (IDI) and direct injection (DI) diesel engines have significant advantages in terms of fuel consumption, and hydrocarbon (HC) and carbon monoxide (CO) emissions. However, oxides of nitrogen (NO_x) emission levels and a number of currently uncontrolled pollutants, including particulates, organic compounds adsorbed on the particulates, odor, and sulfates, require significant reductions from current levels to meet existing and potential future regulations.

Many organizations, including the automotive industry, government agencies, and a number of other institutions, are currently involved in diesel engine technology and health effects research and development activities. Although there are indications that industry is actively pursuing diesel technology and health effects research, many of its programs are short-term oriented and are primarily directed towards meeting the increasingly stringent particulate standards promulgated by the EPA for Model Years 1982 and 1985. These standards limit total particulate mass emitted from the engine to 0.6 g/mi in 1982, and 0.2 g/mi in 1985, without directly controlling the potentially much more dangerous organic matter adsorbed on the carbonaceous particles. Since results from programs conducted by industry are not always available in a timely manner, more aggressive government participation in the diesel health effects and technology research and development areas is required to provide the basic information needed for the assessment of the near- and long-term emissions and fuel conservation potential of light-duty IDI and DI diesel engines developed for use in automobile applications.

The most important questions to be resolved are concerned with the toxicity, mutagenicity, and carcinogenicity of particulate and organic matter generated in the diesel combustion process. Other important parameters to be examined are related to fuel economy, odor, and noise. Although the Environ-

mental Protection Agency (EPA), the Department of Transportation (DOT), the Department of Energy (DOE), and the National Aeronautics and Space Administration (NASA) are actively involved in a number of diesel engine related research programs, additional government-supported efforts are desirable to supplement ongoing programs. Candidate areas include in-vitro and in-vivo tests, as well as a variety of projects examining the formation, composition, and abatement of particulate and organic matter in diesel engines.

Since conclusive results from ongoing health effects programs are not expected to be available for some time, well conceived and well conducted basic and applied technology research and development programs are needed, with particular emphasis on the control of particulates and organic compounds. Should the health effects programs prove conclusively that diesel particulates and organics are not harmful to human health, work in this area would be terminated, and the emphasis would then be placed on NO_x control and fuel economy improvement. Conversely, should the health effects research clearly show that diesel exhaust is indeed harmful to human health, research and development efforts in the area of particulate control would be further accelerated, considering such techniques as modification of the combustion process, variation in fuel composition and incorporation of aftertreatment devices.

Diesel engine research and development areas, in which additional government support is considered to be desirable, may be divided into four major categories: (1) Basic Diesel Combustion Research, (2) Applied Diesel Research and Development, (3) Health Effects Research, and (4) Measurement Technology Development. Specific program needs in these areas are identified in the following subsections. Although the automotive industry, government agencies, and individual researchers are currently conducting projects in these areas, lack of funding has inhibited progress in many cases in the past.

9.2 BASIC DIESEL COMBUSTION RESEARCH

Because of the complex nature of diesel combustion, there is still a lack of fundamental understanding of many of its aspects despite the many years of research in the field. However, recent advances in the fields of diagnostic instrumentation and computer technology give promise for the achievement of new insight into the combustion processes of diesel engines.

The program areas identified below are designed to eventually provide a better understanding of basic combustion and pollutant formation phenomena occurring in IDI and DI diesel engines, when operated on conventional and alternative fuels. Five of the nine program elements address the investigation of pollutant specie formation mechanisms, as affected by combustion and fuels related parameters. Exhaust gas recirculation is a principal candidate for NO_x control in diesel engines, and assessment of its impact on the combustion process, fuel droplet vaporization, and quench effects requires further study. Droplet combustion is the fundamental process in diesel engines, and a better understanding of the mechanisms involved in droplet formation, atomization, vaporization, and combustion is needed as an aid for the development of low emission, high efficiency IDI and DI diesel engines. The modeling efforts are designed to yield insight into the relative importance of the fundamental processes and attendant data gaps, to provide scaling information, and to allow optimization of development hardware. Equally important, modeling serves as a vehicle for transferring results from combustion research to practical applications.

HC Emissions

Investigate the formation of HC species in heterogeneous combustion processes for both conventional and alternative fuels. Parameters to be considered include flame quenching, ultra-lean air-fuel mixture zones, exhaust gas recirculation, and fuel spray distribution.

Investigate the transfer processes of unburned hydrocarbons from the quench layer into the bulk gases, and search for combustion chamber design modifications which would inhibit the discharge of the quench layer into the engine exhaust.

NO_x Emissions

Examine the formation mechanisms of NO_x and other potentially toxic nitrogen compounds, as affected by engine design parameters, fuel composition, and engine operation.

Particulate
Emissions

Investigate the processes governing the formation of particulates, polynuclear aromatics, and sulfates. Factors to be considered include air-fuel ratio, pyrolysis, air turbulence level, fuel injection system parameters, and fuel composition.

Exhaust
Odor

Investigate the formation mechanisms of odor-producing compounds, as affected by engine design, engine operation, and fuel composition, and identify promising odor control techniques.

Exhaust Gas
Recirculation

Examine the effects of EGR on flame speed, misfire limits, reaction kinetics, fuel droplets vaporization, combustion, and pollutant species formation.

<u>Emulsified Fuels</u>	Investigate the effects of water and other fluids in emulsions on the diesel combustion processes.
<u>Droplet And Spray Combustion</u>	Study the mechanisms governing the formation, vaporization, ignition, and combustion of unsteady fuel sprays, as affected by injection characteristics, bulk flow turbulence levels, air-fuel ratio, and fuel composition.
<u>Modeling</u>	Develop basic emission models for regulated and unregulated emission species, considering such factors as combustion chamber geometry, fuel spray characteristics, air swirl, fuel composition, and heat transfer.

9.3

APPLIED DIESEL RESEARCH AND DEVELOPMENT

The objective of the programs identified below is the development of technology required to achieve significant reduction in exhaust emissions from IDI and DI diesel engines, and to alleviate specific problems that otherwise might inhibit engine acceptance or degrade fuel efficiency.

<u>Gaseous Emissions</u>	<p>Characterize the gaseous emissions of modern light-duty diesel engines, with particular emphasis on toxic, mutagenic, and carcinogenic compounds.</p> <p>Determine the composition of the HC species from these engines, as affected by component design, operating conditions, and fuel composition.</p>
<u>Particulate Emissions</u>	Characterize the particulate emissions from light-duty IDI and DI diesel engines, and assess the effects of variations in engine design and operating parameters, and fuel composition on the formation mechanism.
<u>Fuel Injection System</u>	<p>Assess the emissions and fuel economy improvement potential achievable through optimization of the injection process.</p> <p>Explore the potential benefits of hypergolic combustion.</p>
<u>Emission Control Technology</u>	<p>Characterize the gaseous and particulate emissions and fuel economy benefits associated with the use of turbocharging in IDI and DI diesel engines.</p> <p>Examine the effects of EGR system variables on HC, NO_x, and particulate emissions.</p> <p>Characterize the HC, CO, and odor reduction benefits of catalytic converter systems, and develop low-light-off temperature catalysts for use in diesel engines.</p> <p>Develop trap-oxidizer technology and evaluate durability and effectiveness characteristics as a function of variations in combustion chamber and fuel injection system design and operation, EGR rates, and fuel composition.</p>

Develop viable EGR and alternative NO_x control techniques; determine the effects of these systems on other pollutants.

Characterize the effects of variation in fuel composition on gaseous and particulate emissions formation, fuel consumption, and refinery requirements.

High-Speed
DI Diesel

Characterize the particulate and gaseous emissions of light-duty high-speed DI diesel engines, as affected by variations in engine design and fuel composition.

Assess the emissions and fuel consumption improvement potential of light-duty DI diesel engines and determine critical engine design and operating parameters.

Starting and
Transients

Investigate the effects of cold-start and transient operation on currently regulated and unregulated emissions, and search for new techniques to improve the cold-start characteristics of diesel engines.

Advanced
Engines

Evaluate the fuel conservation and emissions potential of the adiabatic diesel engine in light-duty applications, with particular emphasis on NO_x and particulate emissions.

Investigate the potential benefits derived from the use of low compression ratio diesels, with particular emphasis on particulate formation.

9.4

HEALTH EFFECTS RESEARCH

The objectives of the following projects are to identify dangerous substances in diesel exhaust, and to determine conclusively whether the pollutant species and concentrations emitted from light-duty IDI and DI diesel engines pose a hazard to human health.

Particulate
Characterization

Characterize the particulates emitted from a select group of diesel engines of modern design, with particular emphasis on chemical composition, organic fractions, and fuels composition.

In-Vitro Versus
In-Vivo Tests

Examine the validity of the Ames test through comparison with in-vivo results.

Develop in-vitro test procedures which are more representative of in-vivo behavior.

Animal Tests

Determine the long-term effects of diesel exhaust on higher organisms and animals, with particular emphasis on carbonaceous material, organic compounds, dosage rate, and safe exposure limits.

Identify the toxic and carcinogenic compounds in the exhaust of diesel engines as affected by engine design and operation, fuel composition, and emission control technology.

Photochemistry Determine the photochemical reactivity of diesel exhaust
in the Atmosphere and study the formation of ozone and aerosols.

9.5 MEASUREMENT TECHNOLOGY DEVELOPMENT

The objective of the following project is to develop instrumentation for the measurement and characterization of particulate and organic matter emitted from diesel engines; and to explore new diagnostic instrumentation for in-situ measurement of combustion parameters.

Validation and Develop and verify dilution tunnel design criteria, considering
Standardization tunnel geometry, dilution ratio, sampling rate, filter types, and sampling temperature as principal parameters.

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