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Emissions Control Strategies for Heavy-Duty Diesel Engines

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Emissions Control Strategies for Heavy-Duty Diesel Engines

by

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ABSTRACT

This report presents basic information on Diesel engine technology, emissions, and emission controls, and describes a number of options for reducing emissions from both new vehicles and those which are already in use. Pollutant formation is determined by the Diesel combustion process. Factors which affect pollutant emission rates include the air-fuel ratio in the cylinder, charge temperature and composition, and the fuel injection characteristics and timing. Emission rates vary greatly between different operating conditions. As a result, the choice of a representative test cycle is critical to establishment of effective emissions regulations. For trucks and other highway vehicles, the emissions test cycle should include a wide range of operating conditions, especially transients, in order to represent real-life operating conditions adequately.

Many different levels of Diesel emissions control are possible, ranging from simple controls to reduce excessive smoke to the advanced technologies required to meet U.S. emissions standards in the mid-'90s. Technology cost and complexity tend to increase with increasing effectiveness of control, so that different emission control levels may be suited to different areas at different times. Simple and inexpensive emission controls can reduce Diesel NOx and particulate emissions from new vehicles by one-third to nearly one-half, at a cost of $100 to $200 per vehicle. More sophisticated engine controls can further reduce emissions, to about 40% of the uncontrolled level for NOx and 20% of the uncontrolled level for particulate matter. The cost of these controls is significant, however - ranging from about $800 to $2,000 per vehicle for heavy trucks. Still further control of particulate emissions can be achieved through the addition of aftertreatment devices such as catalytic converters or catalytic trap-oxidizers, at still higher cost.

Options for controlling emissions from existing vehicles do not follow such a neat hierarchy. Depending on the situation, maintenance, fuel modifications, transportation controls, and other measures could all play a role in an integrated emission control strategy. Inspection and maintenance programs may be useful in themselves, and may also be required to realize the full benefits of new-vehicle emission controls.

Although Diesels produce many different types of pollutants, one of the most significant (as well as visually obvious) pollutants is soot and other particulate matter. One effective measure for eliminating these emissions is to substitute an alternative, non-soot-producing fuel for Diesel fuel. Natural gas and methanol show particular promise in this regard. This may require substituting another type of engine as well. Such substitution can create other pollution problems, however, depending on the fuel and technology employed--the fact that emissions are not visible does not necessarily make them less objectionable.

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

FOREWORD

This report was originally drafted in Fall, 1988, as a lengthy chapter for use in a report on heavy-duty Diesel emissions control issued by the Organization for Economic Cooperation and Development (OECD). It was drafted by C.S. Weaver of Sierra Research, under contract to the U.S. EPA. Thomas Baines was the EPA Project Manager, and his comments and direction contributed significantly to the results. The OECD report is presently under review. At EPA's request, meanwhile, the report has been redrafted as a stand-alone document. This redrafting involved primarily editorial changes such as section numbering, etc. With a few exceptions, the technical information was not updated during the redrafting, and is therefore current as of Fall, 1988.

1. INTRODUCTION

This report presents basic information on Diesel engine technology, emissions, and emission controls, and describes a number of options for reducing emissions from both new vehicles and those which are already in use. Section 2 below presents background material on the factors that affect Diesel emissions, while Section 3 summarizes the key emissions-related technological features of heavy-duty Diesel engines. These sections provide necessary background for the remaining discussion. Options for reducing emissions from new vehicles are discussed in Section 4; those for existing vehicles in Section 5. Finally, Section 6 describes alternative fuel options for both new and existing heavy-duty Diesel engines.

Many different levels of Diesel emissions control are possible, ranging from simple controls to reduce excessive smoke to the advanced technologies required to meet U.S. emissions standards in the mid-'90s. Technology cost and complexity tend to increase with increasing effectiveness of control, so that different emission control levels may be suited to different areas at different times. The emission-control options for new vehicles discussed in Section 4 constitute a graduated sequence of control levels, beginning with the simplest and least stringent and working up to the most complex, expensive, and effective levels of technology.

Options for controlling emissions from existing vehicles do not follow such a neat hierarchy. Depending on the situation, maintenance, fuel modifications, transportation controls, and other measures could all play a role in an integrated emission control strategy. Inspection and maintenance programs may be useful in themselves, and may also be required to realize the full benefits of new-vehicle emission controls. Section 5 outlines the potential for reducing emissions through these measures, as well as the interrelationships between them, and between them and the various levels of new-vehicle emissions control.

Although Diesels produce many different types of pollutants, one of the most significant (as well as visually obvious) pollutants is soot and other particulate matter. One effective measure for eliminating these emissions is to substitute an alternative, non-soot-producing fuel for Diesel fuel. This may require substituting another type of engine as well. Such substitution can create other pollution problems, however, depending on the fuel and technology employed--the fact that emissions are not visible does not necessarily make them less objectionable. Section 6 discusses the major alternative fuels available, technologies to utilize them, and the pollution tradeoffs involved.

2. BACKGROUND: FACTORS AFFECTING EMISSIONS

In order to discuss the means available for reducing Diesel pollutant emissions, it is necessary first to understand their sources and the various engine and fuel-related factors that can affect their formation and emission. This section presents background information on the types of pollutants emitted by Diesel engines, their formation mechanisms, emissions testing and measurement procedures, and the effects of different engine and fuel variables on emissions levels.

2.1 Diesel Combustion and Pollutant Formation

Combustion

Diesel engine emissions are determined by the combustion process. This process is central to the operation of the Diesel engine. As opposed to Otto-cycle engines (which use a more-or-less homogeneous charge) all Diesel engines rely on heterogeneous combustion. During the compression stroke, a Diesel engine compresses only air. The process of compression heats the air to about 700 to 900° C, which is well above the self-ignition temperature of Diesel fuel. Near the top of the compression stroke, liquid fuel is injected into the combustion chamber under tremendous pressure, through a number of small orifices in the tip of the injection nozzle. The quantity of fuel injected with each stroke determines the engine power output.

The high-pressure injection atomizes the fuel. As the atomized fuel is injected into the chamber, the periphery of each jet mixes with the hot air already present. After a brief period known as the ignition delay, this fuel-air mixture ignites. In the premixed burning phase, the fuel/air mixture formed during the ignition delay period burns very rapidly, causing a rapid rise in cylinder pressure. The subsequent rate of burning is controlled by the rate of mixing between the remaining fuel and air, with combustion always occurring at the interface between the two. Most of the fuel injected is burned in this diffusion burning phase, except under very light loads.

A mixture of fuel and exactly as much air as is required to burn the fuel completely is called a "stoichiometric mixture". The air-fuel ratio λ is defined as the ratio of the actual amount of air present per unit of fuel to the stoichiometric amount. In Diesel engines, the fact that fuel and air must mix before burning means that a substantial amount of excess air is needed to ensure complete combustion of the fuel within the limited time allowed by the power stroke. Diesel engines, therefore, always operate with overall air-fuel ratios which are considerably lean of stoichiometric (λ greater than one).

The air-fuel ratio in the cylinder during a given combustion cycle is determined by the engine power requirements, which govern the amount of fuel injected. Diesels operate without throttling, so that the amount of air present in the cylinder is essentially independent of power output, except in turbocharged engines. The minimum air-fuel ratio for complete combustion is about equal to 1.5. This ratio is known as the smoke limit, since smoke increases dramatically at air-fuel ratios lower than this. The smoke limit establishes the maximum amount of fuel that can be burned per stroke, and thus the maximum power output of the engine.

Pollutant formation

The principal pollutants emitted by Diesel engines are oxides of nitrogen (NOx), sulfur oxides (SOx), particulate matter (PM), and unburned hydrocarbons (HC). Diesels are also responsible for a small amount of CO, as well as visible smoke, unpleasant odors, and noise. In addition, like all engines using hydrocarbon fuel, Diesels emit significant amounts of CO_2, which has been implicated in the so-called "greenhouse effect." With thermal efficiencies typically in excess of 40%, however, Diesels are the most fuel-efficient of all common types of combustion engines. As a result, they emit less CO_2 to the atmosphere than any other type of engine doing the same work.

The NOx, HC, and most of the particulate emissions from Diesels are formed during the combustion process, and can be controlled by appropriate modifications to that process, as can most of the unregulated pollutants. The sulfur oxides, in contrast, are derived directly from sulfur in the fuel, and the only feasible control technology is to reduce fuel sulfur content. Most SOx is emitted as gaseous SO_2, but a small fraction (typically 2-4 percent) occurs in the form of particulate sulfates.

Diesel particulate matter consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and sulfates. In older Diesels, soot was typically 40 to 80 percent of the total particulate mass. Developments in in-cylinder emissions control have reduced the soot contribution to particulate emissions from modern emission-controlled engines considerably, however. Most of the remaining particulate mass consists of heavy hydrocarbons adsorbed or condensed on the soot. This is referred to as the soluble organic fraction of the particulate matter, or SOF. The SOF is derived partly from the lubricating oil, partly from unburned fuel, and partly from compounds formed during combustion. The relative importance of each of these sources varies from engine to engine.

In-cylinder emission control techniques have been most effective in reducing the soot and fuel-derived SOF components of the particulate matter. As a result, the relative importance of the lube oil and sulfate components has increased. In the emission-controlled engines under development, the lubricating oil accounts for as much as 40 percent of the particulate matter, and the sulfates may account for another 25 percent. Lube oil emissions can be reduced by reducing oil consumption, but this may adversely affect engine durability. The only known way to reduce sulfate emissions is to reduce the sulfur content of Diesel fuel.

The gaseous hydrocarbons and the SOF component of the particulate matter emitted by Diesel engines include many known or suspected carcinogens and other toxic air contaminants. These include polynuclear aromatic compounds (PNA) and nitro-PNA, formaldehyde and other aldehydes, and other oxygenated hydrocarbons. The oxygenated hydrocarbons are also responsible for much of the characteristic Diesel odor.

Oxides of nitrogen--NOx from Diesels is primarily NO. This gas forms from nitrogen and free oxygen at high temperatures close to the flame front. The rate of NO formation in Diesels is a function of oxygen availability, and is exponentially dependent on the flame temperature. Figure 1 shows the experimentally-derived relationship between flame temperature and NOx emissions. In the diffusion burning phase, flame temperature depends only on the heating value of the fuel, the heat capacity of the reaction products and any inert gases present, and the starting temperature of the initial mixture. In the premixed burning stage, the local fuel-air ratio also affects the flame temperature, but this ratio varies from place to place in the cylinder and is very hard to control.

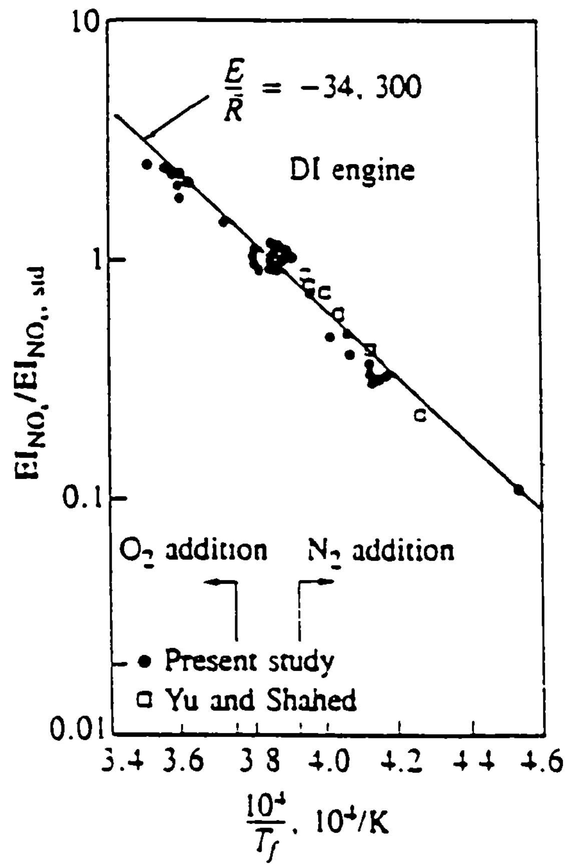
In Diesel engines, most of the NOx emitted is formed early in the combustion process, when the piston is still near top-dead-center (TDC). This is when the temperature and pressure of the charge are greatest. Recent work by several researchers (Wade et al., 1987; Cartellieri and Wachter, 1987) indicates that most NOx is actually formed during the premixed burning phase. It has been found that reducing the amount of fuel burned in this phase can significantly reduce NOx emissions.

NOx can also be reduced by actions which reduce the flame temperature during combustion. These actions include delaying combustion past TDC, cooling the air charge going into the cylinder, reducing the air-fuel mixing rate near TDC, and exhaust gas recirculation (EGR). Since combustion always occurs under near-stoichiometric conditions, reducing the flame temperature by "lean-burn" techniques, as in spark-ignition engines, is impractical.

Particulate matter--Diesel soot is formed only during the diffusion burning phase of combustion. Primary soot particles are small spheres of graphitic carbon, approximately 0.01 μm in diameter. These are formed by the rapid polymerization of acetylene at moderately high temperatures under oxygen-deficient conditions. The primary particles then agglomerate to form chains and clusters of linked particles, giving the soot its characteristic fluffy appearance. During the

Figure 1

Correlation of NOx Emissions Index with Reciprocal Flame Temperature (Source: Plee et al., 1983)



diffusion burning phase, the local gas composition at the flame front is close to stoichiometric, with an oxygen-rich region on one side and a fuel-rich region on the other. The moderately high temperatures and excess fuel required for soot formation are thus always present.

Most of the soot formed during combustion is subsequently burned during the later portions of the expansion stroke. Typically, less than 10% of the soot formed in the cylinder survives to be emitted into the atmosphere. Soot oxidation is much slower than soot formation, however, and the amount of soot oxidized is heavily dependent on the availability of high temperatures and adequate oxygen during the later stages of combustion. Conditions which reduce the availability of oxygen (such as poor mixing, or operation at low air-fuel ratios), or which reduce the time available for soot oxidation (such as retarding the combustion timing) tend to increase soot emissions.

The SOF component of Diesel particulate matter consists of heavy hydrocarbons condensed or adsorbed on the soot. A significant part of this material is unburned lubricating oil, which is vaporized from the cylinder walls by the hot gases during the power stroke. Some of the heavier hydrocarbons in the fuel may also come through unburned, and condense on the soot particles. Finally, heavier hydrocarbons may be synthesized during combustion, possibly by the same types of processes which produce soot. Pyrosynthesis of polynuclear aromatic hydrocarbons during Diesel combustion has been demonstrated by Williams et al. (1987).

Hydrocarbons--Diesel HC emissions (as well as the unburned-fuel portions of the particulate SOF) occur primarily at light loads in most engines. They are due to excessive fuel-air mixing, which results in some volumes of air-fuel mixture which are too lean to burn. Other HC sources include fuel deposited on the combustion chamber walls or in combustion chamber crevices by the injection process; fuel retained in the orifices of the injector which vaporizes late in the combustion cycle; and partly reacted mixture which is subjected to bulk quenching by too-rapid mixing with air. Aldehydes (as partially-reacted hydrocarbons) and the small amount of CO produced by Diesels are probably formed in the same processes as the HC emissions.

The presence of polynuclear aromatic hydrocarbons and their nitro-derivatives in Diesel exhaust is of special concern, since these compounds include many known mutagens and suspected carcinogens. A significant portion of these compounds (especially the smaller two and three-ring compounds) are apparently derived directly from the fuel. Typical Diesel fuel contains several percent PNA by volume. Most of the larger and more dangerous PNA's, on the other hand, appear to form during the combustion process, possibly via the same acetylene polymerization reaction that produces soot (Williams et al., 1987). Indeed, the soot particle itself can be viewed as essentially a very large PNA molecule.

Visible Smoke--Visible smoke is due primarily to the soot component of Diesel particulate matter. Under most operating conditions, the exhaust plume from a properly adjusted Diesel engine is normally invisible, with a total opacity (absorbtance and reflectance) of two percent or less. Visible smoke emissions from heavy-duty Diesels are generally due to operating at air-fuel ratios at or below the smoke limit, or to poor fuel-air mixing in the cylinder. These conditions can be prevented by proper design. The particulate reductions required to comply with the U.S. 1991 emissions standards are expected to essentially eliminate visible smoke emissions from properly functioning engines.

Noise--Diesel engine noise is due principally to the rapid combustion (and resulting rapid pressure rise) in the cylinder during the premixed burning phase. The greater the ignition delay, and the more fuel is premixed with the air, the greater this pressure rise and the resulting noise emissions will be. Noise emissions and NOx emissions thus tend to be related--reducing the amound of fuel burned in the premixed burning phase will tend to reduce both. Other noise sources include those common to all engines, such as mechanical vibration, fan noise, and so forth. These can be minimized by appropriate mechanical design.

Odor--The characteristic Diesel odor is believed to be due primarily to partially-oxygenated hydrocarbons (aldehydes and similar species) in the exhaust. These are believed to be due primarily to slow oxidation reactions in volumes of air-fuel mixture too lean to burn normally. Unburned aromatic hydrocarbons may also play a significant role. The most significant aldehyde species are benzaldehyde, acetaldehyde, and formaldehyde, but other aldehydes such as acrolein (a powerful irritant) are significant as well. Aldehyde and odor emissions are closely linked to total HC emissions--experience has shown that modifications which reduce total HC tend to reduce aldehydes and odor as well.

2.2 Influence of engine variables

The engine variables having the greatest effects on Diesel emission rates are the air-fuel ratio, rate of air-fuel mixing, fuel injection timing, compression ratio, and the temperature and composition of the charge in the cylinder. Most techniques for in-cylinder emission control involve manipulating one or more of these variables.

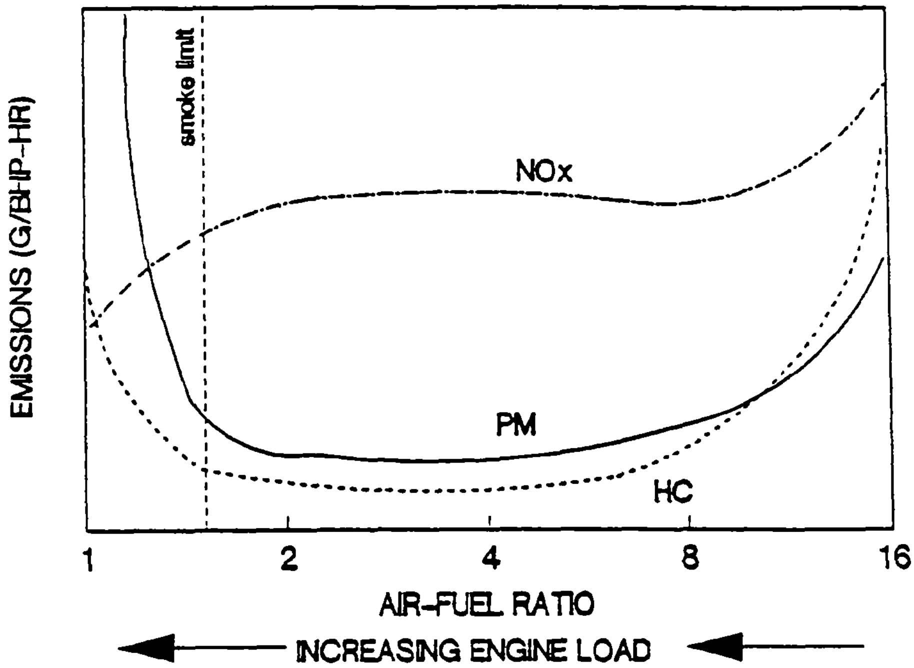
Air-fuel ratio

The ratio of air to fuel in the combustion chamber has an extremely important effect on emission rates for hydrocarbons and particulate matter. Figure 2 diagrams the typical relationship between air-fuel ratio λ and emissions in a Diesel engine. As discussed above, the power output of the engine is determined by the amount of fuel injected at the beginning of each power stroke. At very high air-fuel ratios (corresponding to very light load), the temperature in the cylinder after combustion is too low to burn out residual hydrocarbons, so emissions of gaseous HC and particulate SOF are high. At lower air-fuel ratios, less oxygen is available for soot oxidation, so soot emissions increase. As long as λ remains above about 1.6, this increase is relatively gradual. Soot and visible smoke emissions show a strong non-linear increase below the smoke limit at about $\lambda = 1.5$, however.

In naturally-aspirated engines (those without a turbocharger), the amount of air in the cylinder is independent of the power output. Maximum power output for these engines is normally "smoke-limited"--that is, limited by the amount of fuel that can be injected without exceeding the smoke limit. Maximum fuel settings on these engines represent a compromise between smoke emissions and power output. Where Diesel smoke is regulated (as in the U.S. and EEC), this compromise must result in smoke opacity below the regulated limit. Otherwise, opacity is limited by the manufacturer's judgement of commercially acceptable smoke emissions.

Figure 2

Typical Variation of Emissions with Air-Fuel Ratio and Load in a Direct-Injection Diesel Engine



In turbocharged engines, increasing the fuel injected per stroke increases the energy in the exhaust gas, causing the turbocharger to spin more rapidly and pump more air into the combustion chamber. For this reason, power output from turbocharged engines is not usually smoke-limited. Instead, it is limited by design limits on variables such as turbocharger speed and engine mechanical stresses.

Turbocharged engines do not normally experience low air-fuel ratios during steady-state operation. Low air-fuel ratios can occur during transient accelerations, since the inertia of the turbocharger rotor keeps it from responding instantly to an increase in fuel input. Thus, the air supply during the first few seconds of a full-power acceleration is less than the air supply in steady-state operation. To overcome this problem, turbocharged engines in highway vehicles commonly incorporate an acceleration smoke limiter. This device limits the fuel flow to the engine until the turbocharger has time to respond. The setting on this device must compromise between acceleration performance (drivability) and low smoke emissions. In the U.S., acceleration smoke emissions are limited by regulation; elsewhere, they are limited by the manufacturer's judgement of commercial acceptability.

Air-fuel mixing

The rate of mixing between the compressed charge in the cylinder and the injected fuel is among the most important factors in determining Diesel performance and emissions. During the ignition delay period, the mixing rate determines the amount of fuel that mixes with the air, and is thus available for combustion during the premixed burning phase. The higher the mixing rate, the greater the amount of fuel burning in premixed mode, and the higher the noise and NOx emissions will tend to be.

In the diffusion burning phase, the rate of combustion is limited by the rate at which air and fuel can mix. The more rapid and complete this mixing, the greater the amount of fuel that burns near piston top-dead-center, the higher the fuel efficiency, and the lower the soot emissions. Too-rapid mixing, however, can increase hydrocarbon emissions--especially at light loads--as small volumes of air-fuel mixture are diluted below the combustible level before they have a chance to burn. Unnecessarily intense mixing also dissipates energy through turbulence, increasing fuel consumption.

In engine design practice, it is necessary to strike a balance between the rapid and complete mixing required for low soot emissions and best fuel economy, and too-rapid mixing leading to high NOx and HC emissions. The primary factors affecting the mixing rate are the fuel injection pressure, the number and size of injection orifices, any swirling motion imparted to the air as it enters the cylinder during the intake stroke, and air motions generated by combustion chamber geometry during compression. Much of the progress in in-cylinder emissions control over the last decade has come through improved understanding of the interactions between these different variables and emissions, leading to improved designs.

Air-fuel mixing rates in present emission-controlled engines are the product of extensive optimization to assure rapid and complete mixing under nearly all operating conditions. Poor mixing may still occur during "lug-down"--high-torque operation at low engine speeds. Turbocharger boost, air swirl level, and fuel injection pressure are typically poorer in these "off-design" conditions. Maintenance problems such as injector tip deposits can also degrade air-fuel mixing, and result in greatly increased emissions.

Injection timing

The timing relationship between the beginning of fuel injection and the top of the compression stroke has an important effect on Diesel engine emissions and fuel economy. For best fuel economy, it is preferable that combustion begin at or somewhat before top-dead-center. Since there is a finite delay between the beginning of injection and the start of combustion, it is necessary to inject the fuel somewhat before this point (generally 5 to 15 degrees of crankshaft rotation before).

Since fuel is injected before the piston reaches top-dead-center, the charge temperature is still increasing as the charge is compressed. The earlier fuel is injected, the cooler the charge will be, and the longer the ignition delay. The longer ignition delay provides more time for air and fuel to mix, increasing the amount of fuel that burns in the premixed combustion phase. In addition, more fuel burning at or just before top dead center increases the maximum temperature and pressure attained in the cylinder. Both of these effects tend to increase NOx emissions.

On the other hand, earlier injection timing tends to reduce particulate and light-load HC emissions. Fuel burning in premixed combustion forms little soot, while the soot formed in diffusion combustion near TDC experiences a relatively long period of high temperatures and intense mixing, and is thus mostly oxidized. The end-of-injection timing also has a major effect upon soot emissions--fuel injected more than a few degrees after TDC burns more slowly, and at a lower temperature, so that less of the resulting soot has time to oxidize during the power stroke. For a fixed injection pressure, orifice size, and fuel quantity, the end-of-injection timing is determined by the timing of the beginning of injection.

The result of these effects is that injection timing must compromise between PM emissions and fuel economy on the one hand and noise, NOx emissions, and maximum cylinder pressure on the other. The terms of the compromise can be improved to a considerable extent by increasing injection pressure, which increases mixing and advances the end-of-injection timing. Another approach under development is split injection, in which a small amount of fuel is injected early in order to ignite the main fuel quantity which is injected near TDC.

Compared to uncontrolled engines, modern emission-controlled engines generally exhibit moderately retarded timing to reduce NOx, in conjunction with high injection pressures to limit the effects of retarded timing of PM emissions and fuel economy. The response of fuel economy and PM emissions to retarded timing is not linear--up to a point, the effects are relatively small, but beyond that point deterioration is rapid. Great precision in injection timing is necessary--a change of one degree crank angle can have a significant impact on emissions. The optimal injection timing is a complex function of engine design, engine speed and load, and the relative stringency of emissions standards for the different pollutants. To attain the required flexibility and precision of injection timing has posed a major challenge to fuel injection manufacturers.

Compression ratio

Diesel engines rely on compression heating to ignite the fuel, so the engine's compression ratio has an important effect on combustion. A higher compression ratio results in a higher temperature for the compressed charge, and thus in a shorter ignition delay and higher flame temperature. The effect of a shorter ignition delay is to reduce NOx emissions, while the higher flame temperature would be expected to increase them. In practice, these two effects nearly cancel, so that changes in compression ratio have little effect on NOx.

Emissions of gaseous HC and of the SOF fraction of the particulate matter are reduced at higher compression ratios, as the higher cylinder temperature increases the burn-out of hydrocarbons. Soot emissions may increase at higher compression ratios, however. Since the higher compression is achieved by reducing the volume of the combustion chamber, this results in a larger fraction of the air charge being sequestered in "crevice volumes" such as the top and sides of the piston, where it is not available for combustion early in the power stroke. Thus, the effective air-fuel ratio in the combustion chamber decreases, and soot emissions go up. This effect can be limited (and overall air utilization and power output improved) by reducing crevice volumes to the maximum extent possible.

Engine fuel economy, cold starting, and maximum cylinder pressures are also affected by the compression ratio. For an idealized Diesel cycle, the thermodynamic efficiency is an increasing function of compression ratio. In a real engine, however, the increased thermodynamic efficiency is offset after some point by increasing friction, so that a point of maximum efficiency is reached. With most heavy-duty Diesel engine designs, this optimal compression ratio is about 12 to 15. To ensure adequate starting ability under cold conditions, however, most Diesel engine designs require a somewhat higher compression ratio--in the range of 15 to 20 or more. Generally, higher-speed engines with smaller cylinders require higher compression ratios for adequate cold starting.

Charge temperature

Reducing the temperature of the air charge going into the cylinder has benefits for both PM and NOx emissions. Reducing the charge temperature directly reduces the flame temperature during combustion, and thus helps to reduce NOx emissions. In addition, the colder air is denser, so that (at the same pressure) a greater mass of air can be contained in the same fixed cylinder volume. This increases the air-fuel ratio in the cylinder and thus helps to reduce soot emissions. By increasing the air available while decreasing piston temperatures, charge-air cooling can also make possible a significant increase in power output. Excessively cold charge air can reduce the burnout of hydrocarbons, and thus increase light-load HC emissions, however. This can be counteracted by advancing injection timing, or by reducing charge air cooling at light loads.

Charge composition

NOx emissions are heavily dependent on flame temperature. By altering the composition of the air charge to increase its specific heat and the concentration of inert gases, it is possible to decrease the flame temperature significantly. The most common way of accomplishing this is through exhaust gas recirculation (EGR). At moderate loads, EGR has been shown to be capable of reducing NOx emissions by a factor of two or more, with little effect on particulate emissions. Although soot emissions are increased by the reduced oxygen concentration, particulate SOF and gaseous HC emissions are reduced, due to the higher in-cylinder temperature caused by the hot exhaust gas. EGR cannot be used at high loads, however, since the displacement of air by exhaust gas would result in an air-fuel ratio below the smoke limit--and thus very high soot and PM emissions.

Emissions Tradeoffs

It is apparent from the foregoing discussion that there is an inherent conflict between some of the most powerful Diesel NOx control techniques and particulate emissions. This is the basis for the much-discussed "tradeoff" relationship between Diesel NOx and particulate emissions. This "tradeoff" is not absolute--various NOx control techniques have varying effects on soot and HC emissions, and the importance of these effects varies as a function of engine speed and load. These tradeoffs do place limits on the extent to which any one of these pollutants can be reduced, however. To minimize emissions of all three pollutants simultaneously requires careful optimization of the fuel injection, fuel-air mixing, and combustion processes over the full range of engine operating conditions.

2.3 Emissions Testing and Measurement

The pollutant emissions measured for a given Diesel engine generally depend greatly on how the emissions are measured. Emission rates for Diesels vary as functions of speed, load, and other operating conditions, and transient emissions may be different from those measured in steady-state. Any meaningful discussion of achievable emissions standards and/or emissions levels in use must therefore consider the emissions testing and measurement methods used. Preferably, the engine operating conditions during the test should accurately reflect those in the real world.

This section describes the emissions measurement and testing procedures used in the U.S., Europe, and Japan, discusses the characteristics of an ideal test procedure, and evaluates the extent to which the currently used methods fulfill this ideal.

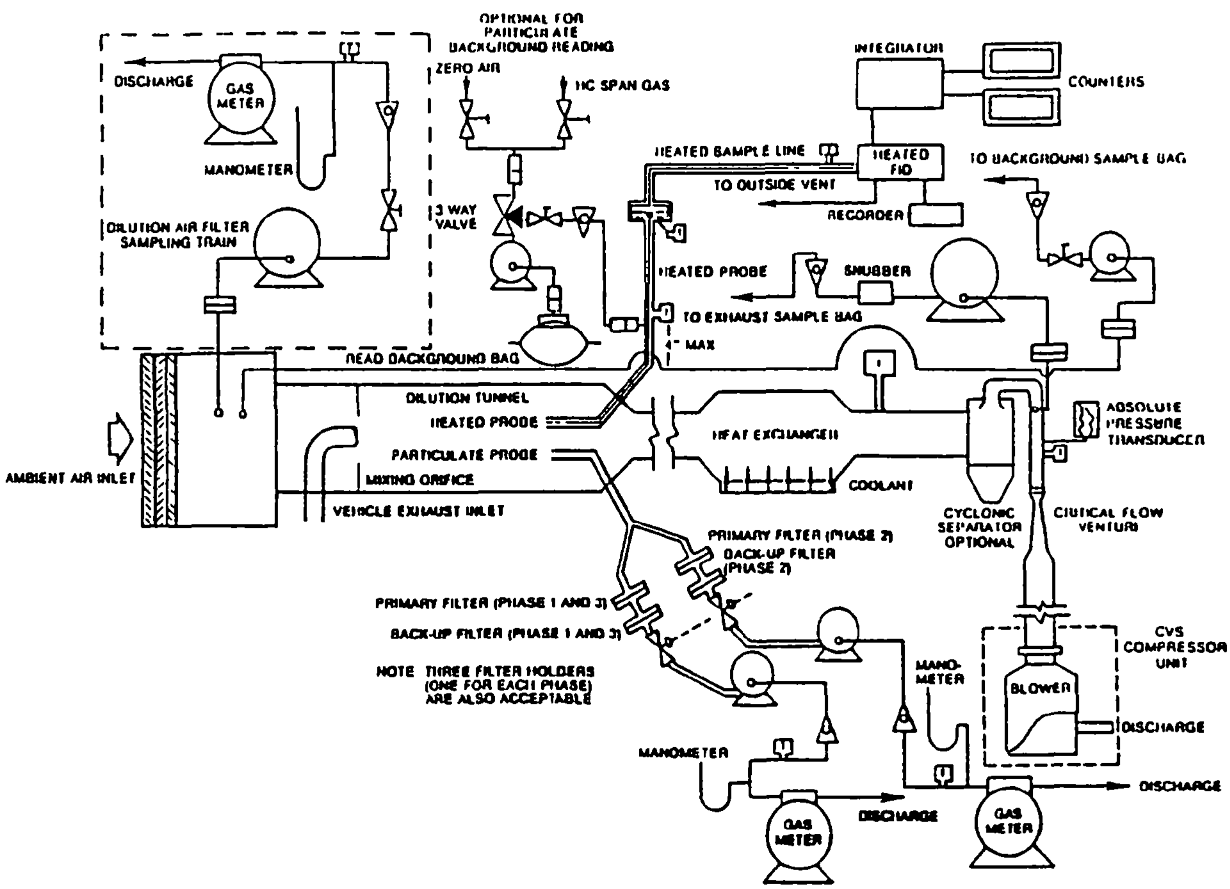
Emission Test Procedures

Measuring gaseous emissions from an engine in steady-state operation is a straightforward task--it is only necessary to measure the exhaust flowrate and the pollutant concentration in the exhaust. Although direct measurement of exhaust flowrates is difficult, this quantity is readily approximated through measurements of the fuel flowrate, along with either inlet air flowrate or carbon concentration in the exhaust.

The situation becomes considerably more complicated where measurements are needed during transient engine operating conditions. For these conditions, the approach specified by regulation in the U.S. (and used in nearly all research elsewhere) is known as <u>constant volume sampling</u> or CVS. With this technique, the exhaust from the engine or vehicle being measured is led to one end of a dilution tunnel, where it is mixed with atmospheric air. The air/exhaust mixture is pumped from the other end of the tunnel at a constant, known rate. Thus, the sum of the exhaust gas flowrate and the dilution air flowrate remains constant--no matter how the exhaust flowrate varies, the dilution air flowrate will automatically adjust to compensate. As a result, it can readily be shown that the pollutant <u>concentration</u> in the diluted exhaust stream is proportional to the pollutant <u>flowrate</u> in the raw exhaust. Average pollutant emissions over a given test cycle can then be determined easily by sampling from the diluted stream at a constant rate. Figure 3 is a diagram showing the principles involved.

Figure 3

Constant Volume Sampling System for Diesel Emissions Measurement
(Source: U.S. Code of Federal Regulation, 86-140.82)



Measurement of Diesel particulate emissions adds additional complications to the measurement procedure. Particulate emissions are measured by drawing dilute exhaust through a micropore filter at a constant rate, and then measuring the weight gained by the filter. However, Diesel particulate matter consists, in part, of condensed hydrocarbons. If the temperature at the filter were high enough, these could pass through the filter as hydrocarbon vapor, rather than being collected. For this reason, EPA regulations specify a maximum filter temperature of 50 °C. To ensure that this temperature is not exceeded even at full power, it may be necessary to use a very high dilution airflow, or to further dilute the gas stream to the particulate filter by means of a second dilution tunnel. This latter approach, which is more commonly used, is also shown in Figure 3.

The above discussion of the dilution tunnel technique emphasizes measurement issues. It should also be mentioned that another goal in sampling and analyzing air-diluted exhaust is to have the measurements relate to actual in-use human exposures to the various pollutants. Air-diluted exhaust is, therefore, a more realistic condition to analyze than raw exhaust because of the unique chemistry that occurs during the dilution process. This also was a reason for selecting the 50°C filter face temperature mentioned above.

Emissions Test Procedures

Mass emissions--In measuring vehicle emissions, it is desirable to relate the emissions measured to some measure of vehicle output. In the case of light-duty vehicles, the measure of output that has been adopted is vehicle-miles travelled (in the U.S.) or vehicle test cycles completed (in the European Economic Community). In the case of heavy-duty vehicles, a different unit of output is needed. Due to the variety of heavy-duty truck models, equipment options, and duty cycles, it would be impractical to specify heavy-duty emissions limits in terms of pollution per unit of distance travelled. Instead, heavy-duty emissions are measured for the engine alone, rather than a vehicle, and are expressed in terms of units of pollution per unit of work output (brake horsepower-hours in the case of the U.S. cycle, and kilowatt hours in the case of the European). As with light-duty vehicles, these emissions are measured while operating over a fixed test cycle, but in this case the test cycle is specified in terms of engine, rather than vehicle, parameters.

Three emissions test procedures for heavy-duty Diesel engines are in use around the world. The current procedure used in the U.S. is the Federal Heavy-Duty Transient Test Procedure. In this procedure, engine speed and load are continually varied according to a fixed schedule, in order to simulate a typical urban driving pattern. The particular speed-load schedule used is a composite developed from measurement and statistical analysis of actual speed-load histories for a large number of heavy-duty trucks driven in urban areas in the 1970's.

The Transient Test replaced an earlier 13-mode, steady-state emissions test procedure, a variation of which is still used as the basis for

European emissions regulations. The 13-mode test involves "mapping" the engine emissions by operating at 2, 25, 50, 75, and 100% of maximum torque at two speeds: rated speed for maximum power, and the maximum torque speed. Three periods of idle operation complete the 13 modes. Emissions (in g/hr) and power output (in HP or KW) from each mode are then combined according to a weighting scheme to arrive at a composite value for each. Dividing the composite emission rate by the composite horsepower gives composite emissions in grams per horsepower-hour or grams per kilowatt-hour.

In the original U.S. version of the 13-mode test, all of the non-idle modes were weighted equally in the calculation. The European version uses a different weighting scheme which gives much more emphasis to the maximum-torque operating modes. This is intended to reflect driving patterns in Europe, where operation near the maximum torque point (for best fuel economy) is said to be much more common than in the U.S.

Japanese emissions test procedures for gaseous pollutants from heavy-duty Diesel engines also involve a steady-state test, using a six-mode test cycle. Unlike the U.S. and European emissions standards, Japanese emissions standards are expressed in terms of pollutant concentration in the exhaust (thus giving an inherent advantage to turbocharged engines).

Smoke opacity testing--In addition to regulating mass emissions rates, both the U.S. and EEC also regulate Diesel smoke opacity. In the U.S., these regulations date back to 1972, and the numerical standards been the same since 1973. With the advent of increasingly stringent limits on PM emissions in 1988, 1991, and 1994, these standards are becoming increasingly irrelevant.

The smoke opacity test procedure used in the U.S. simulates an acceleration from stop, followed by a gear change and continued acceleration, followed by "lugging down" from full engine power to the maximum torque point. The degree of opacity of the exhaust plume is determined by a light-transmission opacimeter. The European test procedure is similar, but involves only the lug-down mode. These procedures measure only the occurrence of offensively high visible smoke levels--not particulate emissions. The correlation between the smoke measurements and average particulate mass emissions in new engines is poor.

Considerations in Choosing a Test Cycle

Diesel particulate and hydrocarbon emissions are fairly sensitive to the exact test cycle used, and especially to the presence of transient conditions. In tests of engines calibrated for U.S. emissions standards using the older 13-mode cycle, it was found that PM and HC emissions on the Transient Test were only moderately correlated with those measured in the 13-mode procedure (Barsic, 1984). Indices of correlation (R^2) values for transient vs 13-mode PM and HC emissions were only 0.55 and 0.59, respectively. Generally, PM and HC emissions on the transient test were found to be higher, but this was very engine-dependent. A large part of the excess emissions due to the transient test is believed to be due to turbocharger lag, as discussed in Section 2.2. NOx emissions showed better correlation--the index of correlation between 13-mode and transient test results was 0.80.

Modern emission-controlled engines have been designed to maintain effective control even during transient conditions. For these engines, some manufacturers and consultants have even found it practical to do their development testing using a steady-state test cycle, with results which generally track the transient values (some U.S. manufacturers have found that only transient testing gives them the reliable data required, however). The fact that good correlation can be demonstrated between transient and steady-state results in some engines does not imply, however, that it would now be practical to substitute a steady-state test for the transient test as the basis for regulation. The close control of transient emission levels which produced this correspondence was made necessary by the need to pass a transient test. Were the transient test element to be deleted, the transient emission controls would be unneeded, and would doubtless be eliminated.

This observation can be generalized as follows: regulations based on a specific emissions test procedure tend to control emissions only in the operating modes experienced during that test procedure. Since, in the real world (especially in urban areas), vehicles operate under a wide variety of speed-load conditions, including transients, it is important that the test procedure reflect these conditions. A procedure which measures emissions only at a limited number of specific operating conditions is vulnerable to circumvention by emission control strategies aimed specifically at those operating conditions.

With the advent of computer-controlled fuel injection systems, engine control strategies can become almost arbitrarily complex. In the case of the 13-mode, steady-state test, it would be easy to develop an engine control strategy which optimized for emissions only in a small area in the speed-load plane around each test point, with the strategy in the remainder of the speed-load plane being optimized for fuel economy and performance, instead. Nor is this simply a theoretical possibility--some manufacturers of light-duty vehicles in the U.S. have pursued a very similar strategy in calibrating their electronic engine control systems for the light-duty test procedure.

A recent set of tests in the EPA Motor Vehicle Emission Laboratory confirmed that such a defeat strategy is, in fact, very possible. A series of tests were performed on a Detroit Diesel Corporation 6V-92TAD engine with full electronic control. The first test was done with the electronic controller optimized for 1989 U.S. Federal standards. This means no NOx control and 0.60 g/BHP-hr particulate. The tests performed were the U.S. heavy-duty transient cycle and the old U.S. 13-mode test. The electronic controller was then reprogramed to a retarded timing condition only at the peak torque and rated speed points, which are the speeds at which all of the non-idle U.S. 13-mode testing is performed. Results of this testing are summarized in Table 1.

From the 13-mode results in Table 1, it would appear that the change in engine calibration dramatically reduced NOx emissions. The NOx emissions were reduced by almost half with only a slight increase in the particulate levels. (The HC and CO emissions increased, but since they are very low in an absolute sense they are not considered further.) In considering the transient test data, however, it is apparent that the reductions in NOx and particulate were minimal--only about three percent. Since the transient test results are considered representative of actual use, it can be concluded that minimal if any actual control of in-use emissions would have resulted under such a strategy.

Table 1
Effect of Engine Control Strategy
Transient vs. 13-Mode Emissions Test

	HC	CO	NOx	Part.
Transient Cycle				
Current Calibration	0.45	2.62	9.33	0.28
Modified Calibration	0.47	3.05	9.05	0.27
Difference	4%	16%	-3%	-4%
US 13 Mode				
Current Calibration	0.52	0.45	9.79	0.13
Modified Calibration	0.63	0.81	5.20	0.15
Difference	21%	80%	-47%	15%

Detroit Diesel 6V-92 TA
DDEC II electronic controls
Current Calibration - 1989 Federal U.S. Standards
Modified Calibration - same as "Current Calibration" except retarded timing at rated and peak torque speeds

As further evidence that emission reductions in the transient test are comparable to those in actual use, Table 2 compares transient test data with chassis dynamometer emissions measurements for a number of controlled and uncontrolled bus engines. Several pre-control bus engines were tested over the HD-FTP transient test in the EPA heavy duty emissions factors program. Also, a current (controlled) bus engine was tested at the EPA facility over the HD-FTP. The same types of engines were also tested on a chassis dynamometer by the City of New York Department of Environmental Protection. For our analysis, the chassis test is considered somewhat more representative of in-use emissions than the engine test. The results in Table 2 show that the same general levels of emissions reduction were seen as a result of going to emission controls when the tests were performed both with the HD-FTP Transient cycle test and the chassis test.

Table 2
Emission Reductions due to Emission Controls
Engine Transient vs. Chassis Tests

	HC	CO	NOx	Part.
Transient Test, g/BHP-hr				
Pre-Control	0.98	5.92	7.67	0.97
Control	0.67	1.52	7.50	0.24
Difference	-32%	-74%	-2%	-75%
Chassis test for buses, g/mile				
Pre-Control	9.19	32.90	42.28	4.40
Control	2.44	3.70	41.26	0.68
Difference	-73%	-89%	-2%	-85%

Another important consideration in test cycle selection is that engine calibrations to reduce emissions over the selected test cycle should result in a proportional reduction in emissions over typical in-use driving cycles. While there is presently little information available to show whether this is the case with the U.S. transient cycle, the engine/chassis data cited above are one indication that the transient cycle is resulting in effective control under other driving cycles as well.

As pointed out by Cornetti et al. (1988), most of the work produced during the U.S. test cycle is produced at near-rated speed and load. While EPA considers this to be typical of truck operations in U.S. cities, it is not typical of European driving patterns or--to an increasing extent--present long-distance driving patterns in the U.S. The development of high torque-rise engines, overdrive transmissions, road-speed governors, and the increasing concern for fuel economy are resulting in U.S. trucks spending much more operating time near peak torque speed. This is occurring to some extent even in urban areas. Since the transient test contains little operation at this speed, this will allow manufacturers to calibrate their engines for best performance and economy, rather than best emissions, in that area of the speed-load plane. To the extent that truckers actually run in that area, rather than near rated speed, actual in-use emissions may be increased. The extent of this potential increase will be unknown, however, until such time as tests are conducted.

Vehicle Testing

Experience with light-duty vehicles has shown that to obtain realistic estimates of actual emissions from vehicles in use it is necessary to test a representative sample of in-use vehicles. Extrapolation from the manufacturer's certification data is generally misleading. Since it would be impractical to remove the engines from any significant number of heavy-duty vehicles in order to measure their emissions, such tests would need to be made with the engine in the vehicle, using a chassis dynamometer. To simulate the effects of transient operating conditions, the dynamometer used must be capable of simulating the inertia of the moving vehicle, just like the chassis dynamometers used in present light-duty emissions testing. Since the inertia of a heavy-duty vehicle is much greater, however, the flywheels and the dynamometer itself must be correspondingly larger.

At present, only a very limited number of heavy-duty chassis dynamometers with transient emissions capability exist. Four such facilities have been built in the U.S., and one in Chile (another U.S. facility is under construction). Data from these facilities are presently much too limited to draw any firm conclusions about the relationship between in-use emissions and those projected from engine-dynamometer tests. The available data are not reassuring, however--they suggest that actual in-use emissions of HC and PM (including the effects of emissions deterioration) may be several times those projected from manufacturer's data. A fuller analysis of this issue for the case of California is given by Weaver and Klausmeier (1988).

2.4 Fuel Effects

The quality and composition of Diesel fuel can have important effects on pollutant emissions. The area of fuel effects on Diesel emissions has seen a great deal of study in the last few years, and a large amount of new information has become available. These data indicate that the fuel variables having the most important effects on emissions are the sulfur content and the fraction of aromatic hydrocarbons contained in the fuel. Other fuel properties may also affect emissions, but generally to a much lesser extent. Finally, the use of fuel additives may have a significant impact on emissions.

Sulfur Content

Diesel fuel for highway use normally contains between 0.1 and 0.5 percent by weight sulfur, although some (mostly less-developed) nations permit 1% or even higher sulfur concentrations. Sulfur in Diesel fuel contributes to environmental deterioration both directly and indirectly. Most of the sulfur in the fuel burns to SO_2, which is emitted to the atmosphere in the Diesel exhaust. Because of this, Diesels are significant contributors to ambient SO_2 levels in some areas. This makes them indirect contributors to ambient particulate levels and acid deposition as well. In the U.S., Diesel fuel accounted for about 620 thousand tons of SO_2 in 1984, or about 3% of all SO_2 emissions during the same period.

Most of the fuel sulfur which is not emitted as SO_2 is converted to various metal sulfates and to sulfuric acid during the combustion process or immediately afterward. Both of these materials are emitted in particulate form. The typical rate of conversion in a heavy-duty Diesel engine is about 2 to 3 percent of the fuel sulfur; and about 3 to 5 percent in a light-duty engine. The effect of the sulfate particles is increased by their hygroscopic nature--they tend to absorb significant quantities of water from the air. Sulfate and associated water particles typically account for 0.05 to 0.10 g/BHP-hr of particulates in heavy-duty engines.

Certain precious-metal catalysts can oxidize SO_2 to SO_3, which combines with water in the exhaust to form sulfuric acid. The rate of conversion with the catalyst is dependent on the temperature, space velocity, and oxygen content of the exhaust, and on the activity of the catalyst--generally, catalyst formulations which are most effective in oxidizing hydrocarbons and CO are also most effective at oxidizing SO_2. The presence of significant quantities of sulfur in Diesel fuel thus limits the potential for catalytic converters or catalytic trap-oxidizers for use in controlling PM and HC emissions.

Sulfur dioxide in the atmosphere oxidizes to form sulfate particles, in a reaction similar to that which occurs with the precious-metal catalyst. Viewed in another way, the presence of the catalyst merely speeds up a reaction which would occur anyway (although this can have a significant effect on human exposure to the reaction products). According to analysis by the California Air Resources Board staff (1984), roughly 1.20 lb of secondary particulate is formed per pound of SO_2 emitted in the South Coast Air Basin. For a Diesel engine burning fuel of 0.29 weight percent sulfur at 0.42 lb of fuel per horsepower-hr, this is equivalent to 0.85 grams per horsepower-hour. For comparison, the average rate of primary or directly-emitted particulate emissions from heavy-duty Diesel engines in use was about 0.8 grams/BHP-hr in a recent study (EMA, 1985).

Quite aside from its particulate-forming tendencies, sulfur dioxide is recognized as a hazardous pollutant in its own right. The health and welfare effects of SO_2 emissions from Diesel vehicles are probably much greater than those of an equivalent quantity emitted from a utility stack or industrial boiler, since Diesel exhaust is emitted close to the ground level in the vicinity of roads, buildings, and concentrations of people.

Aromatic Hydrocarbon Content

Aromatic hydrocarbons are hydrocarbon compounds containing one or more "benzene-like" ring structures. They are distinguished from paraffins and napthenes, the other major hydrocarbon constituents of Diesel fuel, which lack such structures. Compared to these other components, aromatic hydrocarbons are denser, have poorer self-ignition qualities, and produce more soot in burning. Ordinarily, "straight-run" Diesel fuel produced by simple distillation of crude oil is fairly low in aromatic hydrocarbons. Catalytic cracking of residual oil to increase gasoline and Diesel production results in increased aromatic content, however. A typical straight-run Diesel might contain 20 to 25% aromatics by volume, while a Diesel blended from catalytically cracked stocks could have 40-50% aromatics.

Aromatic hydrocarbons have poor self-ignition qualities, so that Diesel fuels containing a high fraction of aromatics tend to have low cetane numbers. Typical cetane values for straight run Diesel are in the range of 50-55; those for highly aromatic Diesel fuels are typically 40 to 45, and may be even lower. This produces more difficulty in cold starting, and increased combustion noise, HC, and NOx due to the increased ignition delay.

Increased aromatic content is also correlated with higher particulate emissions. Aromatic hydrocarbons have a greater tendency to form soot in burning, and the poorer combustion quality also appears to increase particulate SOF emissions. Increased aromatic content may also be correlated with increased SOF mutagenicity, possibly due to increased PNA and nitro-PNA emissions. There is also some evidence that more highly aromatic fuels have a greater tendency to form deposits on fuel injectors and other critical components. Such deposits can interfere with proper fuel-air mixing, greatly increasing PM and HC emissions.

Other Fuel Properties

Diesel fuel consists of a mixture of hydrocarbons having different molecular weights and boiling points. As a result, as some of it boils away on heating, the boiling point of the remainder increases. This fact is used to characterize the range of hydrocarbons in the fuel in the form of a "distillation curve" specifying the temperature at which 10%, 20%, etc. of the hydrocarbons have boiled away. A low 10% boiling point is associated with a significant content of relatively volatile hydrocarbons. Fuels with this characteristic tend to exhibit somewhat higher HC emissions than others. Formerly, a relatively high 90% boiling point was considered to be associated with higher particulate emissions. More recent studies (Wall and Hoekman, 1984) have shown that this effect is spurious--the apparent statistical linkage was due to the higher sulfur content of these high-boiling fuels.

Other fuel properties may also have an effect on emissions. Fuel density, for instance, may affect the mass of fuel injected into the combustion chamber, and thus the air-fuel ratio. This is because fuel injection pumps meter fuel by volume, not by mass, and the denser fuel contains a greater mass in the same volume. Fuel viscosity can also affect the fuel injection characteristics, and thus the mixing rate. The corrosiveness, cleanliness, and lubricating properties of the fuel can all affect the service life of the fuel injection equipment--possibly contributing to excessive in-use emissions if the equipment is worn out prematurely.

Fuel Additives

Several generic types of Diesel fuel additives can have a significant effect on emissions. These include cetane enhancers, smoke suppressants, and detergent additives. In addition, some additive research has been directed specifically at emissions reduction in recent years. Although some moderate emission reductions have been demonstrated, there is yet no consensus on the widespread applicability or desirability of such products.

Cetane enhancers are used to enhance the self-ignition qualities of Diesel fuel. These compounds (generally organic nitrates) are generally added to reduce the adverse impact of high-aromatic fuels on cold starting and combustion noise. These compounds also appear to reduce the aromatic hydrocarbons' adverse impacts on HC and PM emissions, although PM emissions with the cetane-improver are generally still somewhat higher than those from a higher-quality fuel able to attain the same cetane rating without the additive.

Smoke suppressant additives are organic compounds of calcium, barium, or (sometimes) magnesium. Added to Diesel fuel, these compounds inhibit soot formation during the combustion process, and thus greatly reduce emissions of visible smoke. Their effects on the particulate SOF are not fully documented, but one study (Draper et al, 1988) has shown a significant increase in the PAH content and mutagenicity of the SOF with a barium additive. Particulate sulfate emissions are greatly increased with these additives, since all of them readily form stable solid metal sulfates, which are emitted in the exhaust. The overall effect of reducing soot and increasing metal sulfate emissions may be either an increase or decrease in the total particulate mass, depending on the soot emissions level at the beginning and the amount of additive used.

Detergent additives (often packaged in combination with a cetane-enhancer) help to prevent and remove coke deposits on fuel injector tips and other vulnerable locations. By thus maintaining new-engine injection and mixing characteristics, these deposits can help to decrease in-use PM and HC emissions. A recent study for the California Air Resources Board (Weaver and Klausmeier, 1988) estimated the increase in PM emissions due to fuel injector problems from trucks in use as being more than 50% of new-vehicle emissions levels. A significant fraction of this excess is unquestionably due to fuel injector deposits.

3. DIESEL ENGINE TECHNOLOGY

Diesel engine emissions are determined by the combustion process within the cylinder. This process is central to the operation of the Diesel engine. Virtually every characteristic of the engine affects combustion in some way, and thus has some direct or indirect effect on emissions. Some of the engine systems affecting Diesel emissions are the fuel injection system, the engine control system, air intake and combustion chamber, and the air charging system. Actions to reduce lubricating oil consumption can also impact HC and PM emissions. Finally, exhaust aftertreatment systems such as trap-oxidizers and catalytic converters may play a significant role in reducing emissions in the future.

This section is intended as background information for the discussion of emissions control programs and scenarios in Sections 4 and 5. It briefly outlines the functions and basic types of each of the technologies and systems listed above, and describes their current status and any ongoing developments.

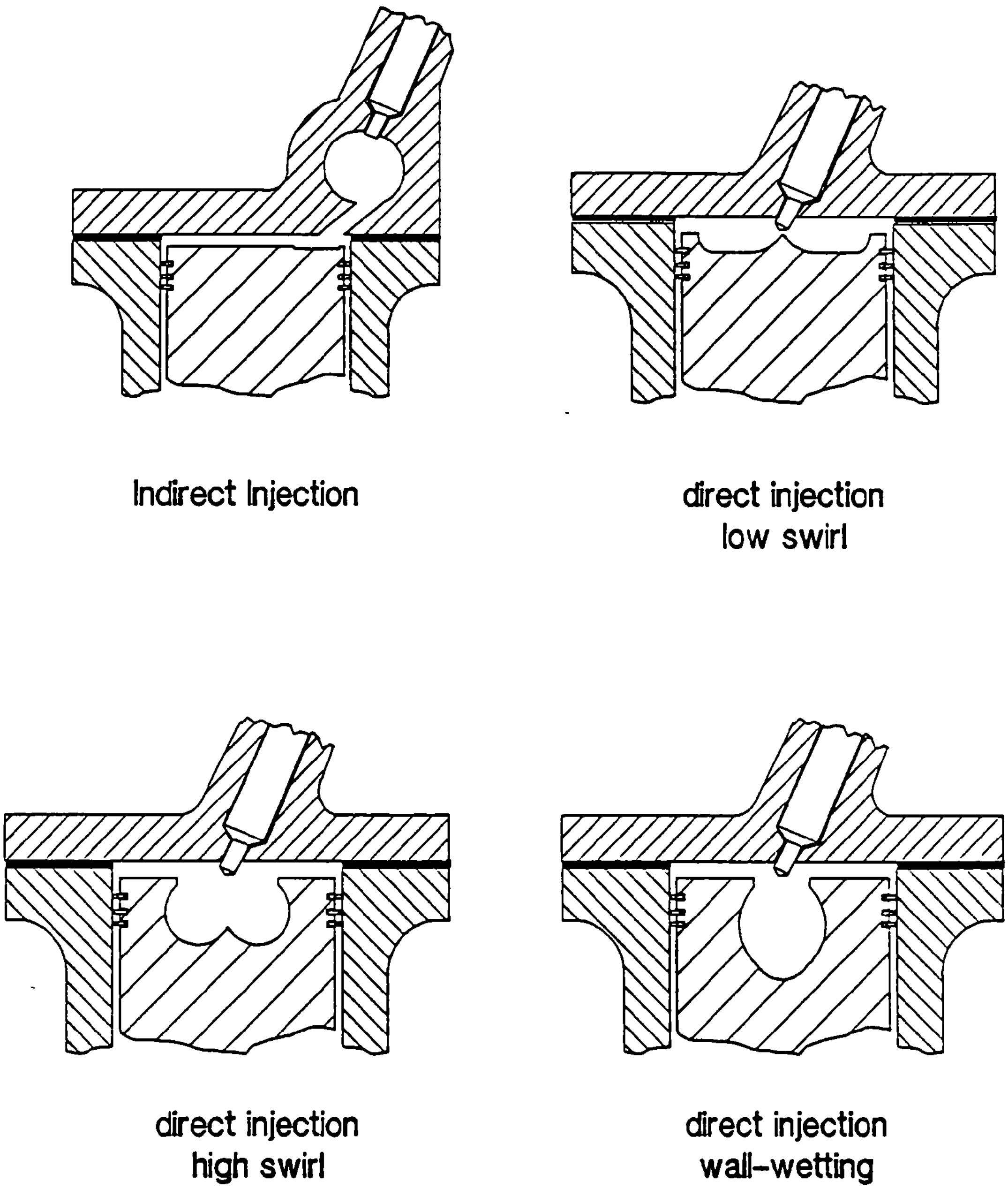
3.1 Air Motion and Combustion Chamber Design

The geometries of the combustion chamber and the air intake port control the air motion in the Diesel combustion chamber, and thus play an important role in air-fuel mixing and emissions. A number of different combustion chamber designs, corresponding to different basic combustion systems, are in use in heavy-duty Diesel engines at present. This section outlines the basic combustion systems in use, their advantages and disadvantages, and the effects of changes in combustion chamber design and air motion on emissions.

Combustion Systems

Diesel engines used in heavy-duty vehicles use several different types of combustion systems. The most fundamental difference is between direct injection (DI) engines and indirect injection (IDI) engines. In an indirect-injection engine, fuel is injected into a separate "prechamber," where it mixes and partly burns before jetting into the main combustion chamber above the piston. In the more common direct-injection engine, fuel is injected directly into a combustion chamber hollowed out of the top of the piston. DI engines can be further divided into high-swirl, low-swirl (quiescent chamber), and wall-wetting designs. The latter, used by some German manufacturers, has many characteristics in common with indirect injection systems. Figure 4 shows a typical combustion chamber of each type.

Figure 4
Different Types of Diesel Combustion Chambers



Fuel-air mixing in the direct-injection engine is limited by the fuel injection pressure and any motion imparted to the air in the chamber as it entered. In high-swirl DI engines, a strong swirling motion is imparted to the air entering the combustion chamber by the design of the intake port. These engines typically use moderate-to-high injection pressures, and three to five spray holes per nozzle. Low-swirl engines rely primarily on the fuel injection process to supply the mixing. They typically have very high fuel injection pressures and six to nine spray holes per nozzle. Wall-wetting DI engines also have fairly high swirl, but the injection system is designed to deposit the fuel on the combustion chamber wall, where it vaporizes and burns relatively slowly.

In the indirect-injection engine, much of the fuel-air mixing is due to the air swirl induced in the prechamber as air is forced into it during compression, and to the turbulence induced by the expansion out of the pre-chamber during combustion. These engines typically have better high-speed performance than direct-injected engines, and can use cheaper fuel-injection systems. Historically, uncontrolled IDI Diesel engines have also exhibited lower emission levels than uncontrolled DI engines. With recent developments in DI engine emission controls, however, this is no longer the case. Disadvantages of the IDI engine are the extra heat and frictional losses due to the prechamber. These result in a 5-10 percent reduction in fuel efficiency compared to a DI engine.

The wall-wetting DI design also shows a disadvantage in fuel economy compared to other DI engine designs, and the further disadvantage of high HC emissions. Its advantages include low combustion noise, and the ability to use a cheaper fuel injection system.

Presently, all light-duty and most light-heavy-duty Diesels in the U.S. use IDI engines, but all medium-heavy and heavy-heavy engines are direct-injected. The same pattern is found in the rest of the world, although the incidence of DI engines in the light-heavy-duty class tends to be greater. Most European and Japanese truck engines, and most medium-heavy U.S. truck engines are of the high swirl type, while most heavy-heavy U.S. engines are low-swirl designs. A number of advanced, low-emitting and fuel-efficient high-swirl DI engines have recently been introduced in the light-heavy duty category as well, and it appears that these engines will completely displace the existing IDI designs. Small, low-emitting, high-speed DI engines (of the high-swirl design) are also being developed for light-duty trucks and passenger cars, but their penetration into this market segment is still very small.

DI Combustion Chamber Design

Changes in the engine combustion chamber and related areas have demonstrated a major potential for emission control. Design changes to reduce the crevice volume in DI Diesel cylinders increase the amount of air available in the combustion chamber. Changes in combustion chamber geometry--such as the use of a reentrant lip on the piston bowl--can markedly reduce emissions by improving air-fuel mixing and minimizing wall impingement by the fuel jet. Optimizing the intake port shape for best swirl characteristics has also yielded significant benefits. Several firms are considering variable swirl intake ports, to optimize swirl characteristics across a broader range of engine speeds.

Crevice volume--The crevice volume is that part of the compression volume which lies outside the combustion chamber. This includes the clearance between the top of the piston and the cylinder head, and the "top land"--the space between the side of the piston and the cylinder wall above the top compression ring. The air in these volumes contributes little to the combustion process. The smaller the crevice volume, the larger the combustion chamber volume can be for a given compression ratio. Thus, reducing the crevice volume effectively increases the amount of air available for combustion.

The major approaches to reducing the crevice volume are to reduce the clearance between the piston and cylinder head through tighter production tolerances, and to move the top compression ring toward the top of the piston. This increases the working temperature of the top ring, and poses mechanical design problems for the piston top and cooling system as well. These problems have been addressed through redesign and the use of more expensive materials. The higher piston ring temperature may also make additional demands on the oil.

Combustion chamber shape--Numerous test results indicate that, for high swirl DI engines, a reentrant combustion chamber shape (in which the lip of the combustion chamber protrudes beyond the walls of the bowl) provides a substantial improvement in performance and emissions over the previous straight-sided bowl designs. Researchers at AVL (Cartellieri and Wachter, 1987) found that the use of a reentrant bowl gave a 20 percent reduction in PM emissions from those measured with a straight-sided bowl at the same compression ratio. NOx emissions were increased 3 percent, but the reentrant bowl combustion chamber is also more tolerant of retarded injection timing than the straight-sided bowl.

Because of the superiority of the reentrant bowl design for high-swirl engines, most manufacturers of such engines are developing or already using this approach. Similar improvements in the performance of low-swirl DI engines may also be possible through modifications to combustion chamber geometry, but there is much less unanimity as to what the optimal shape may be. A number of different variations on the classic "Mexican hat" combustion chamber shape have been tried, with some success.

Intake air swirl--Optimal matching of intake air swirl ratio with combustion chamber shape and other variables is critical for emissions control in high-swirl engines. The swirl ratio is the ratio of the rotational speed of the air charge in the cylinder to the rotational speed of the engine, which is determined by the design of the air intake port. Unfortunately, the selection of a fixed swirl ratio involves some tradeoffs between low-speed and high-speed performance.

At low speeds, a higher swirl ratio provides better mixing, permitting more fuel to be injected and thus greater torque output at the same smoke level. However, this can result in too high a swirl ratio at higher speeds, impairing the airflow to the cylinder. Too high a swirl ratio can also increase HC emissions, especially at light loads.

Attaining an optimal swirl ratio is most difficult in smaller light-heavy and medium-heavy DI engines, as these experience a wider range of engine speeds than do heavy-heavy engines. One solution to this problem is to vary the swirl ratio as a function of engine speed. A two-position variable swirl system has been developed and applied to some Diesel engines in Japan (Shimada et al, 1986). This system is being considered for engines used in the U.S. as well. Test data using this system show a noticeable reduction in PM and NOx emissions due to optimization of the swirl ratio at different speeds.

3.2 Fuel Injection

The fuel injection system in a Diesel engine includes the machinery by which the fuel is transferred from the fuel tank to the engine, then injected into the cylinders at the right time for optimal combustion, and in the correct amount to provide the desired power output. The quality, quantity, and timing of fuel injection determine the engine's power, fuel economy, and emissions characteristics, so that the fuel injection system is one of the most important components of the engine.

The fuel injection system normally consists of a low-pressure pump to transfer fuel from the tank to the system, one or more high-pressure fuel pumps to create the pressure pulses that actually send the fuel into the cylinder, the injection nozzles through which fuel is injected into the cylinder, and a governor and fuel metering system. These determine how much fuel is to be injected on each stroke, and thus the power output of the engine.

The major areas of concentration in fuel injection system development have been on increased injection pressure, increasingly flexible control of injection timing, and more precise governing of the fuel quantity injected. Systems offering electronic control of these quantities, as well as fuel injection rate, have been introduced. Some manufacturers are also pursuing technology to vary the rate of fuel injection over the injection period, in order to reduce the amount of fuel burning in the premixed combustion phase. Reductions in NOx and noise emissions and maximum cylinder pressures have been demonstrated using this approach (Gill, 1988). Other changes have been made to the injection nozzles themselves, to reduce or eliminate sac volume and to optimize the nozzle hole size and shape, number of holes, and spray angle for minimum emissions.

Injection System Types

Fuel injection systems used in heavy-duty Diesel vehicles can be divided into two basic types. The most common type consists of a single fuel pump (typically mounted at the side of the engine) which is driven by gears from the crankshaft, and connected to individual injection nozzles at the top of each cylinder by special high-pressure fuel lines. These pump-line-nozzle (PLN) injection systems can be further divided into two subclasses: "distributor" fuel pumps, in which a single pumping element is mechanically switched to connect to the high-pressure fuel lines for each cylinder in turn; and "in-line" pumps having one pumping element per cylinder, each connected to its own high-pressure fuel line. The latter type is much more common in heavy-duty trucks.

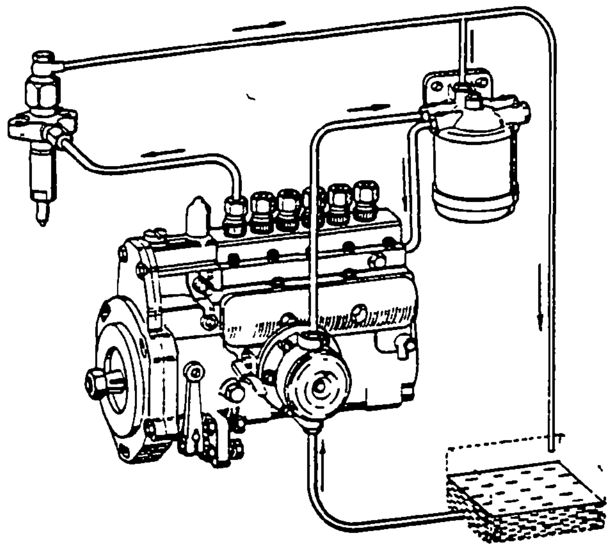
The most common alternative to the pump-line nozzle injection systems are systems using unit injectors, in which the individual fuel metering and pumping element for each cylinder is combined in the same unit with the injection nozzle at the top of the cylinder. The pumping elements in a unit injector system are generally driven by the engine camshaft. Figure 5 shows some typical examples of pump-line nozzle and unit injector fuel injector systems.

Worldwide, many more engines are made with pump-line-nozzle injection systems than with unit injectors. This is primarily due to the higher cost of unit injector systems. Presently, three U.S. engine manufacturers (accounting for more than half of U.S. heavy-heavy-duty engine production) produce unit-injector-equipped truck engines. Due to the absence of high-pressure fuel lines, however, unit injectors are capable of higher injection pressures than pump-line-nozzle systems. With improvements in electronic control, these systems offer better fuel economy at low emission levels than the pump-line-nozzle systems. For this reason, many heavy-duty engine models sold in the U.S. will be equipped with unit injectors for the 1991 model year.

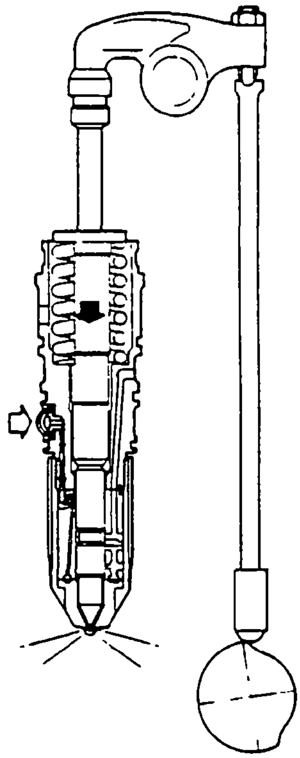
Fuel injection pressure and injection rate--High fuel injection pressures are desirable in order to improve fuel atomization and fuel-air mixing, and to offset the effects of retarded injection timing by increasing the injection rate. A number of workers have published data on the effects of higher injection pressures on PM and/or smoke emissions. All show marked reductions as injection pressure is increased. High injection pressures are most important in low-swirl, direct-injection engines, since the fuel injection system is responsible for most of the fuel-air mixing in these systems. For this reason, low-swirl engines tend to use unit injector systems, which can achieve peak injection pressures in excess of 1,500 bar.

The injection pressures achievable in pump-line-nozzle fuel injection systems are limited by the mechanical strength of the pumps and fuel lines, as well as by pressure wave effects, to about 800 bar. Improvements in system design to minimize pressure wave effects, and increases in the size and mechanical strength of the lines and pumping elements have increased the injection pressures achievable in pump-line nozzle systems substantially from those achievable a few years

Figure 5
Typical Diesel Fuel Injection Systems
(Source: Lilly, 1984)



Pump-Line-Nozzle System
(only one of six injectors shown)



Unit Injector System

ago. It now appears that a point of diminishing returns may have been reached in this area--further increases in injection pressure in some experimental systems have not greatly improved emissions.

The pumping elements in all current fuel injection systems are driven through a fixed mechanical linkage from the engine crankshaft. This means that the pumping rate, and thus the injection pressure, are strong functions of engine speed. At high speeds, the pumping element moves rapidly, and injection pressures and injection rates are high. At lower speeds, however, the injection rate is proportionately lower, and injection pressure drops off rapidly. This can result in poor atomization and mixing at low speeds, and is a major cause of high smoke emissions during lugdown. Increasing the pumping rate to provide adequate pressure at low speeds is impractical, as this would exceed the system pressure limits at high speed.

A new type of in-line injection pump has recently been developed which provides a partial solution to this problem (Ishida et al., 1986). The cam driving the pumping elements in this pump has a non-uniform rise rate, so that pumping rate at any given time is a function of the cam angle. By electronically adjusting a spill sleeve, it is possible to select the portion of the cam's rotation during which fuel is injected, and thus to vary the injection rate. Injection timing varies at the same time, but the system is designed so that desired injection rate and injection timing correspond fairly well. Ishida and coworkers obtained a 25 percent reduction in PM emissions and a 10 percent reduction in HC using this system, with virtually no increase in NOx. The same approach could easily be applied to a unit injector system, using an electronically controlled spill valve.

Another approach to increasing injection pressure at low engine speeds is the use of electro-hydraulic actuators for injection instead of mechanically-driven pumping elements. Through appropriate design and control schemes, such systems can control and maintain fuel injection pressures nearly independently of engine speed. A number of such systems have been described in the technical literature, but--to date--none has actually been implemented on commercial engines. At least one major engine manufacturer plans to introduce such systems in the U.S. in 1991, however.

Initial injection rate and premixed burning--Reducing the amount of fuel burned in the premixed combustion phase can significantly reduce total NOx emissions. This can be achieved by reducing the initial rate of injection, while keeping the subequent rate of injection high to avoid high PM emissions due to late burning. This requires varying the rate of injection during the injection stroke. This represents a difficult design problem for mechanical injections systems, but should be possible using electro-hydraulic injectors. Another approach to the same end is split injection, in which a small amount of fuel is injected in a separate event ahead of the main fuel injection period.

Data published by a U.S. manufacturer (Gill, 1988) show a marked beneficial effect from reducing the initial rate of injection. Based on these data, it appears likely that a 30 to 40 percent reduction in

NOx emissions could be achieved through this technique, without significant adverse impacts on fuel consumption, HC, or PM emissions. As a side benefit, engine noise and maximum cylinder pressures (for a given power output) are also reduced.

Low sac/sacless nozzles--The nozzle sac is a small internal space in the tip of the injection nozzle. The nozzle orifices open into the sac, so that fuel flowing past the needle valve first enters the sac, and then sprays out the orifices. The small amount of fuel remaining in the sac tends to burn or evaporate late in the combustion cycle, resulting in significant PM and HC emissions. The sac volume can be minimized or even eliminated by redesigning the injector nozzle. One manufacturer reported nearly a 30 percent reduction in PM emissions through elimination of the nozzle sac. It is also possible to retain some of the sac while designing the injector nozzle so that the tip of the needle valve covers the injection orifices when it is closed. This valve-covers-orifice or VCO injector design is used in some production engines, and in many engines being developed for compliance with the U.S. 1991 emissions standards.

3.3 Engine controls

Traditionally, Diesel engine control systems have been closely integrated with the fuel injection system, and the two systems are often discussed together. These earlier control systems (still in use on most engines) are entirely mechanical. The last few years have seen the introduction of an increasing number of computerized electronic control systems for Diesel engines. With the introduction of these systems, the scope of the engine control system has been greatly expanded.

Mechanical Controls

Most current Diesel engines still rely on mechanical engine control systems. The basic functions of these systems include basic fuel metering, engine speed governing, maximum power limitation, torque curve "shaping", limiting smoke emissions during transient acceleration, and (sometimes) limited control of fuel injection timing. Engine speed governing is accomplished through a spring-and flyweight system which progressively (and quickly) reduces the maximum fuel quantity as engine speed exceeds the rated value. The maximum fuel quantity itself is generally set through a simple mechanical stop on the rack controlling injection quantity. More sophisticated systems allow some "shaping" of the torque curve to change the maximum fuel quantity as a function of engine speed.

Acceleration smoke limiters are needed to prevent excessive black smoke emissions during transient acceleration of turbocharged engines. Most are designed to limit the maximum fuel quantity injected as a function of turbocharger boost, so that full engine power is developed only after the turbocharger comes up to speed.

Many pump-line-nozzle fuel injection systems incorporate mechanical injection timing controls. Since the injection pump is driven by a special shaft geared to the crankshaft, injection timing can be adjusted within a limited range by varying the phase angle between the two shafts, using a sliding spline coupling. A mechanical or hydraulic linkage slides the coupling back and forth in response to engine speed and/or load signals.

In mechanical unit injector systems, the injectors are driven by a direct mechanical linkage from the camshaft, making it very difficult to vary the injection timing. Cummins, in its California engines, has introduced a mechanical timing control which operates by moving the injector cam followers back and forth with respect to the cam. Although effective in limiting light-load HC and PM emissions under the stringent California NOx standards, these systems have proven very troublesome and unpopular among users.

Computerized Electronic Controls

The advent of computerized electronic engine control systems has greatly increased the potential flexibility and precision of fuel metering and injection timing controls. In addition, it has made possible whole new classes of control functions, such as road-speed governing, alterations in control strategy during transients, synchronous idle speed control, and adaptive learning--including strategies to identify and compensate for the effects of wear and component-to-component variation in the fuel injection system.

By continuously adjusting the fuel injection timing to match a stored "map" of optimal timing vs. speed and load, an electronic timing control system can significantly improve on the NOx/particulate and NOx/fuel-economy tradeoffs possible with static or mechanically-variable injection timing. Most electronic control systems also incorporate the functions of the engine governor and the transient smoke limiter. This helps to reduce excess particulate emissions due to mechanical friction and lag-time during engine transients, while simultaneously improving engine performance. Potential reductions in PM emissions of up to 40% been documented with this approach by Wade and coworkers (1983).

A potential drawback of the increasing use of electronic controls is the demand that it places on the emissions test procedure. As discussed in Section 2.3, such a control system could easily be programmed to defeat a simple steady-state test procedure such as the 13-mode by maintaining optimal emission control only near the test points, not across the entire range. A similar problem is possible in the Federal Transient Test, given the apparent mismatch between the operating conditions emphasized in the test and those found in long-distance truck operation. The earlier mechanical controls were incapable of such sophisticated control strategies.

Other electronic control features, such as cruise control, upshift indication, and communication with an electronically controlled transmission will also help to reduce fuel consumption, and will thus likely reduce in-use emissions. Since the effect of these technologies is to reduce the number of BHP-hrs per mile, rather than the amount of pollution per BHP-hr, their effects will not be reflected in dynamometer emissions test results, however.

3.4 Turbocharging and Intercooling

A turbocharger consists of a centrifugal air compressor feeding the intake manifold, mounted on the same shaft as an exhaust gas turbine in the exhaust stream. By increasing the mass of air in the cylinder prior to compression, turbocharging correspondingly increases the amount of fuel that can be burned without excessive smoke, and thus increases the potential maximum power output. The fuel efficiency of the engine is improved as well. The process of compressing the air, however, increases its temperature, increasing the thermal load on critical engine components. By cooling the compressed air in an intercooler before it enters the cylinder, the adverse thermal effects can be reduced. This also increases the density of the air, allowing an even greater mass of air to be confined within the cylinder, and thus further increasing the maximum power potential.

Increasing the air mass in the cylinder and reducing its temperature can reduce both NOx and particulate emissions, as well as permitting greater fuel economy and more power output from a given engine displacement. Most heavy-duty Diesel engines are presently equipped with turbochargers, and most of these have intercoolers. In the U.S., virtually all engines will be equipped with these systems by 1991. Recent developments in air charging systems for Diesel engines have been primarily concerned with increasing the turbocharger efficiency, operating range, and transient response characteristics; and with improved intercoolers to further reduce the temperature of the intake charge. Tuned intake air manifolds (including some with variable tuning) have also been developed, to maximize air intake efficiency in a given speed range.

Turbocharger refinements

Turbochargers for heavy-duty Diesel engines are already highly developed, but efforts to improve their performance continue. The major areas of emphasis are improved matching of turbocharger response characteristics to engine requirements, improved transient response, and higher efficiencies. Engine/turbocharger matching is especially critical, because of the inherent conflict between the response characteristics of the two types of machines. Engine boost pressure requirements are greatest near the maximum torque speed, and most turbochargers are matched to give near-optimal performance at that point. At higher speeds, however, the exhaust flowrate is greater, and the turbine power output is correspondingly higher. Boost pressure under these circumstances can exceed the engine's design limits, and the excessive turbine backpressure increases fuel consumption. Thus, some compromise between adequate low-speed boost and excessive high-speed boost must be made.

Variable geometry turbochargers

Because of the inherent mismatch between engine response characteristics and those of a fixed-geometry turbocharger, a number of engine manufacturers are considering the use of variable geometry turbines instead (Wallace et al., 1986). In these systems, the turbine nozzles can be adjusted to vary the turbine pressure drop and power level in order to match the engine's boost pressure requirements. Thus, high boost pressures can be achieved at low engine speeds, without wasteful overboosting at high speed. The result is a substantial improvement in low-speed torque, transient response, and fuel economy, and a reduction in smoke, NOx, and PM emissions.

Prototype variable geometry turbochargers (VGT) have been available for some time, but they have not been used in production vehicles up to this point. The major reasons for this are their cost (which could be 50% more than a comparable fixed-geometry turbocharger), reliability concerns, and the need for a sophisticated electronic control system to manage them. With the forthcoming deployment of electronic engine controls on virtually all vehicles in the U.S., these latter arguments have lost much of their force, and the fuel economy and performance advantages of the VGT are great enough to outweigh the costs in many applications. As a result, variable geometry turbochargers should be available on a number of production heavy-duty Diesel engines in the relatively near future.

Other types of superchargers

A number of alternative forms of supercharging have been considered, with a view to overcoming the mismatch between turbocharger and engine response characteristics. The two leading candidates at present are the Sulzer Comprex (tm) gas-dynamic supercharger, and mechanically-assisted turbochargers such as the "three-wheel" turbocharger developed by General Motors. The major advantages of these systems are superior low-speed performance and improved transient response. These advantages would be expected to yield some improvement in PM emissions, as well as driveability and torque rise.

Intercoolers

As discussed in Section 2.2, charge air cooling helps to reduce both NOx and PM emissions, while increasing maximum power and decreasing fuel consumption and the thermal loading on engine components. Because of these advantages, intercoolers are almost universally used on highly-rated turbocharged engines. Presently, most intercoolers rely on the engine cooling water as a heat sink, since this minimizes the components required. The relatively high temperature of this water (about 90° C) limits the benefits available, however. For this reason, an increasing number of heavy-duty Diesel engines are being equipped with low-temperature charge-air cooling systems.

The most common type of low-temperature charge-air cooler rejects heat directly to the atmosphere through an air-to-air heat exchanger mounted on the truck chassis in front of the radiator. Although bulky and expensive, these charge-air coolers are able to achieve the lowest charge-air temperatures--in many cases, only ten or 15 degrees C above ambient. An alternative approach is low-temperature air-to-water intercooling, which has been pursued by Cummins Engine in the U.S. Cummins has chosen to retain the basic water-air intercooler, but with drastically reduced radiator flowrates to reduce the water temperature coming from the radiator. This water is then passed through the intercooler before it is used for cooling the rest of the engine.

Intake manifold tuning

Tuned intake manifolds have been used for many years to enhance airflow rates on high-performance gasoline engines, and are being considered for some heavy-duty Diesel engines. A tuned manifold provides improved airflow and volumetric efficiency at speeds near its resonant frequency, at the cost of reduced volumetric efficiency at other speeds. At least one medium-heavy-duty manufacturer is considering a variable-resonance manifold, in order to improve airflow characteristics at both low and high speeds.

3.5 Exhaust Gas Recirculation

EGR is a time-proven NOx control technique for light-duty gasoline and Diesel vehicles, but has been little used in heavy-duty Diesel engines. In heavy-duty Diesel engines, EGR has been shown to increase wear rates and oil contamination, resulting in higher maintenance expenses and shorter engine life (Cadman and Johnson, 1986). For this reason, engine manufacturers have avoided it, and little research on its effects has been performed. In the past, a few California-model medium-heavy engines used EGR to meet the California NOx standard. Considerable adverse experience with these engines has reinforced the existing prejudice against EGR use in heavy-duty Diesels.

Another reason for avoiding EGR is that it was considered to have little advantage over other NOx control techniques such as retarding injection timing, at least in DI engines. Yu and Shahed (1981) found little difference in the NOx/smoke tradeoff curves for EGR and for injection timing. EGR has a lesser impact on fuel economy than retarded timing (moderate EGR actually improves fuel economy slightly), but this has been outweighed by its perceived adverse effects on durability.

Some recent research results suggest that a re-evaluation of this technique may be in order, however. This research indicates that properly modulated EGR does not necessarily increase PM emissions significantly, even though NOx may be dramatically reduced. EGR often (but not always) increases soot emissions, but gaseous HC and particulate SOF are generally reduced. In some cases, soot emissions may be reduced by EGR as well (Shiga et al., 1985). The effect of EGR on overall PM emissions may thus be positive or negative, depending on the specific operating mode.

Data from a number of manufacturers (e.g. Wade et al., 1985) have shown that exhaust gas recirculation can reduce NOx emissions from light-duty Diesel vehicles by 50% or more, without adverse effects on PM emissions or fuel economy. These results cannot be translated directly to heavy-duty engines, however, due to the differences in emission test cycles between the light-duty FTP and the heavy-duty test procedures. Compared to the light-duty cycle, the heavy-duty procedures involve much more high-power operation, which would limit the amount of EGR that could be tolerated. Nonetheless, these data strongly suggest that the properly modulated EGR could result in a major reduction in NOx emissions, with minimal impacts on PM, fuel economy, or driveability.

To obtain a rough quantification of the potential impact of EGR in a heavy-duty engine, Weaver and Klausmeier (1987) developed a rough model of EGR effects, using published modal emissions data for a modern low-emission heavy-duty engine. For this engine, good correlation had been demonstrated between transient cycle emissions and emissions in a specialized steady-state cycle constructed to mimic the operating conditions in the transient cycle (Cartellieri and Wachter, 1987). The effects of EGR on emissions in this steady-state cycle were estimated by assigning an EGR rate to each operating mode, then estimating the resultant effects on soot, SOF, and NOx emissions.

The results of this calculation showed a 27% reduction in NOx emissions (from 6.0 to 4.3 g/BHP-hr), at the cost of a 14% increase in PM (from 0.242 to 0.276 g/BHP-hr). Although very rough, these results may be considered as an approximate indicator of EGR's potential for heavy-duty Diesel engines. Compared to the effects of injection timing retardation at similar NOx levels, the tradeoff ratio of 1.7 g/BHP-hr NOx reduction to 0.034 g/BHP-hr PM increase is an extremely favorable one.

3.6 Lubricating Oil Control

A significant fraction of Diesel particulate matter consists of oil-derived hydrocarbons and related solid matter. The long-chain (typically 20-carbon) hydrocarbons in the oil readily condense to form liquid particles in the dilute exhaust, and are subsequently collected on the particulate filter. A number of researchers have estimated the oil contribution to particulate emissions by assigning all of the heavy-hydrocarbon fraction of the SOF to the oil. Estimates of the oil contribution to overall PM emissions by this means range from 10 to 50%. More accurate measurements using a radioactive tracer technique show a somewhat smaller--but still very significant--contribution by the lube oil to total SOF. The difference between the two methods may be due to pyrosynthesis of high molecular weight hydrocarbons from the lower molecular weight hydrocarbons in the fuel.

Reduced oil consumption has been a design goal of heavy-duty Diesel engine manufacturers for some time, and the current generation of Diesel engines already uses fairly little oil compared to their predecessors. Further reductions in oil consumption are possible through careful attention to cylinder bore roundness and surface finish, optimization of piston ring tension and shape, and attention to valve stem seals, turbocharger oil seals, and other possible sources of oil loss. Some oil consumption in the cylinder is required with present technology, however, in order for the oil to perform its lubricating and corrosion-protective functions.

Advances in piston/cylinder tribology could potentially eliminate or greatly reduce oil consumption in the cylinder. Areas such as boundary lubrication and development of low-friction ceramic coatings are presently the subjects of much research. The potential for transforming this research into durable and reliable engines on the road remains to be demonstrated, however.

Some manufacturers have measured emissions from engines modified for ultra-low oil consumption. Oil consumption in each case was reduced to an extent that was expected to result in unacceptable long-term durability. These tests have shown a reduction of 0.07 to 0.10 g/BHP-hr in particulate matter due to the reduced oil consumption.

3.7 Aftertreatment Systems

The preceding discussion has dealt entirely with measures to reduce pollutant concentrations in the exhaust before it leaves the engine. An alternative approach is to use a separate processing system to eliminate pollutants from the exhaust after it leaves the engine, but before it is emitted from the tailpipe into the ambient air. Possibilities for such aftertreatment systems include particulate trap-oxidizers, Diesel catalytic converters, electrostatic agglomerators, and various techniques for reducing NOx to oxygen and nitrogen gases.

Trap-Oxidizers

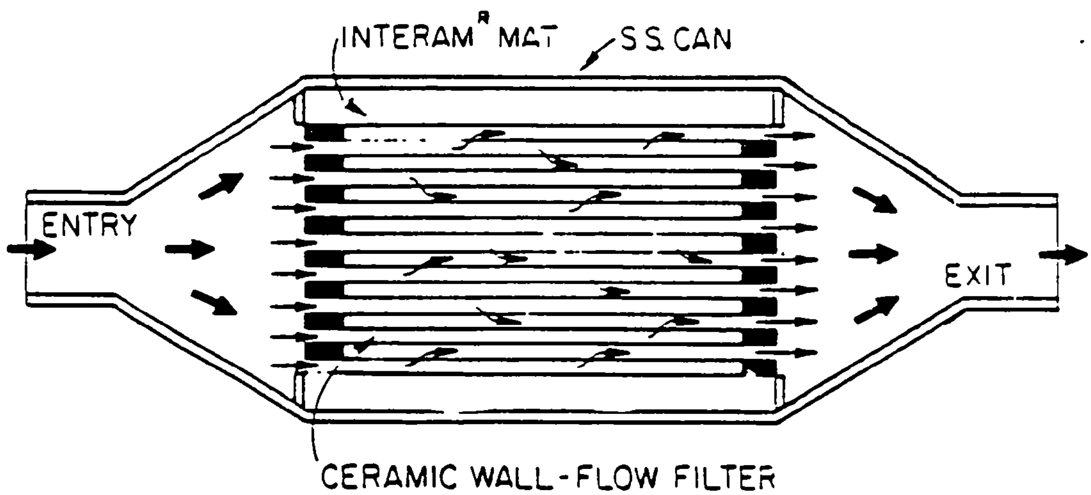
A trap-oxidizer system consists of a durable particulate filter (the "trap") positioned in the engine exhaust stream, along with some means for cleaning the filter by burning off ("oxidizing") the collected particulate matter. The construction of a filter capable of collecting Diesel soot and other particulate matter from the exhaust stream is a straightforward task, and a number of effective trapping media have been developed and demonstrated. The great problem of trap-oxidizer system development has always been with the process of "regenerating" the filter by burning off the accumulated particulate matter.

As discussed in Section 2.1, Diesel particulate matter consists primarily of a mixture of solid carbon coated with heavy hydrocarbons. The ignition temperature of this mixture is about 500-600° C, which is above the normal range of Diesel engine exhaust temperatures. Thus, special means are needed to assure regeneration. Once ignited, however, this material burns to produce very high temperatures, which can easily melt or crack the particulate filter. Initiating and controlling the regeneration process to ensure reliable regeneration without damage to the trap is the central engineering problem of trap-oxidizer development.

Compared to the in-cylinder emission control technologies discussed in the preceding sections, trap-oxidizer technology has progressed more slowly and in a more predictable manner. This is partly due to the simpler and more predictable physical and chemical phenomena involved, and partly due to the much lower priority accorded it in most manufacturers' research and development efforts. Despite the relatively slow general rate of progress, several manufacturers have fielded successful prototype trap-oxidizer systems.

Traps--Presently, most of the trap-oxidizer systems under development are based on the cellular cordierite ceramic monolith traps produced by Corning Glassworks and NGK-Locke. Figure 6 shows the principal of operation and a typical example of such a trap. These traps can be formulated to be highly efficient (collecting essentially all of the soot, and a large fraction of the particulate SOF), and they are relatively compact, having a large surface area per unit of volume. Because of their relatively simple production process, they could also be produced fairly inexpensively. They can also be coated or impregnated with catalyst material to assist regeneration.

Figure 6
Principle of the Ceramic Monolith Trap
(Source: Gulati and Merry, 1984)



The high concentration of soot per unit of volume with the ceramic monolith makes these traps rather sensitive to regeneration conditions. Trap loading, temperature, and gas flow rates must be maintained within a fairly narrow window. Otherwise, the trap fails to regenerate fully, or cracks or melts due to overheating.

An alternative trap technology is provided by the ceramic fiber coil traps developed by Mann and Hummel and Daimler Benz in West Germany. These traps are composed of a number of individual filtering elements, each of which consists of a number of thicknesses of silica-fiber yarn wound on a punched metal support. A number of these filtering elements are suspended inside a large metal can to make up a trap. Daimler-Benz has deployed prototype traps of this design in more than 50 city buses in West Germany (Hardenberg, 1987).

The advantages of the ceramic fiber coil trap include high filtering efficiency and immunity to thermal cracking. In addition, its low ratio of filtering area to volume (which results in a low volumetric soot loading) and the heat capacity and thermal conductivity of the materials make this trap nearly impossible to melt. Its primary disadvantages are the relatively large volume required and a fairly rapid increase in backpressure with increasing particulate loading. The silica yarn coils can also be mechanically cut or frayed by sharp objects, or loosened by repeated thermal cycling (Hardenberg et al., 1987a). The trap is also relatively complex structurally--implying that it could be expensive to manufacture.

Numerous other trapping media have been tested or proposed. These include ceramic foams, corrugated mullite fiber felts, and catalyst coated stainless steel wire mesh. Traps based on the latter technology were demonstrated in a number of U.S. and European programs, most of which showed rather poor performance. Presently, all of the most successful trap-oxidizer systems under development are based on either the ceramic monolith or the silica fiber coil traps.

<u>Regeneration</u>--Numerous techniques for regenerating particulate trap-oxidizers have been proposed, and a great deal of development work has been invested in many of these. These approaches can generally be divided into two groups: passive systems and active systems. Passive systems rely on attaining the conditions required for regeneration as a result of the normal operation of the vehicle. This requires the use of a catalyst (either as a coating on the trap or as a fuel additive) in order to reduce the ignition temperature of the collected particulate matter. Regeneration temperatures as low as 420° C have been reported with catalytic coatings, and even lower temperatures are achieveable with fuel additives.

Active systems, on the other hand, monitor the buildup of particulate matter in the trap and trigger specific actions intended to regenerate it when needed. A wide variety of approaches to triggering regeneration have been proposed, from Diesel fuel burners and electric heaters to catalyst injection systems.

Passive regeneration systems face special problems on heavy-duty vehicles. Regeneration temperatures must be attained in normal operation, even under lightly loaded conditions. Because of the variability in their loading and use patterns, trucks may sometimes operate for long periods at very light loads. Exhaust temperatures from heavy-duty Diesel engines are already fairly low, and recent developments such as charge-air cooling and increased turbocharger efficiency are reducing them still further. Under some conditions, therefore, it would be possible for a truck to drive for many hours without exceeding the exhaust temperature (around 400-450° C) required to trigger regeneration.

Presently, no purely passive systems appear to be under serious consideration for heavy-duty applications. However, some manufacturers are working on quasi-passive systems, in which the system will usually regenerate passively without intervention, but the active regeneration system remains as a backup.

Active regeneration systems can be classified as either in-line or bypass-type systems. In the in-line system, exhaust continues to flow through the trap during regeneration, while with the bypass system the exhaust is bypassed around the trap. The exhaust stream from a vehicle engine varies rapidly and unpredictably in both temperature and flowrate, depending on the demands of the driving cycle. This variability would pose impossible control problems for systems such as Diesel fuel burners and electric heaters. The need to heat the entire exhaust stream would also be very wasteful of energy, and would be well beyond the capacity of a truck's electrical system. For these reasons, burner and electric heater-based regeneration systems usually bypass the exhaust around the trap during regeneration.

Engine and catalyst manufacturers have experimented with a wide variety of catalytic material and treatments to assist in trap regeneration. Good results have been obtained both with precious metals (platinum, palladium, rhodium, silver) and with base metal catalysts such as vanadium and copper. Precious metal catalysts are effective in oxidizing gaseous HC and CO, as well as the particulate SOF, but are relatively ineffective at promoting soot oxidation. Unfortunately, these metals also promote the oxidation of NO in the exhaust to the more toxic NO_2, and of SO_2 to particulate sulfates such as sulfuric acid (H2SO4). The base-metal catalysts, in contrast, are effective in promoting soot oxidation, but have little effect on HC, CO, NO, or SO_2.

To date, no catalytic coating has sufficiently reduced the trap regeneration temperature to permit reliable passive regeneration in heavy-duty Diesel service. Catalyst coatings also have a number of advantages in active systems, however. The reduced ignition temperature and increased combustion rate due to the catalyst mean that less energy is needed from the regeneration system. Regeneration will also occur spontaneously under most duty cycles, greatly reducing the number of times the regeneration system must operate. The spontaneous regeneration capability also provides some insurance against a regeneration system failure. Finally, the use of a catalyst may make possible a simpler regeneration system.

Although normal heavy-duty Diesel exhaust temperatures are not high enough under all operating conditions to provide reliable regeneration for a catalyst-coated trap, the exhaust temperature can readily be increased by changes in engine operating parameters. Retarding the injection timing, bypassing the intercooler, throttling the intake air (or cutting back on a variable geometry turbocharger), and/or increasing the EGR rate all markedly increase the exhaust temperature. Applying these measures all the time would seriously degrade fuel economy, engine durability, and performance. The presence of an electronic control system, however, would make it possible to apply them briefly, and only when needed to regenerate the trap. Since they would be needed only at light loads, the effects on durability and performance would be imperceptible. One engine manufacturer has successfully accumulated more than 145,000 miles on a prototype system of this type.

Catalytic converters

Recent dramatic progress in in-cylinder particulate control has greatly reduced engine-out particulate levels. This progress has been most effective in reducing the solid soot fraction of the particulate, so that the soluble organic fraction (SOF) of the particulate matter now accounts for a much larger share than previously. Depending on the engine and operating conditions, the SOF may account for from 30 to more than 70 percent of the engine-out particulate matter.

Like a catalytic trap, a Diesel catalytic converter oxidizes a large part of the hydrocarbon constituents of the SOF, as well as gaseous HC, CO, odor, and mutagen emissions. Unlike a catalytic trap however, a flow-through catalytic converter does not collect any of the solid particulate matter, which simply passes through in the exhaust. This eliminates the need for a regeneration system, with its attendant technical difficulties and costs. The particulate control efficiency of the catalytic converter is, of course, much less than that of a trap. However, a particulate control efficiency of even 25 to 35 percent is enough to bring many current development engines within the target range for the U.S. 1991 emissions standard.

Diesel catalytic converters have a number of advantages. In addition to reducing particulate emissions enough to comply with the 1991 standard, the oxidation catalyst greatly reduces HC, CO, and odor emissions. The catalyst is also very efficient in reducing emissions of gaseous and particle-bound toxic air contaminants such as aldehydes, PNA, and nitro-PNA. While a precious-metal catalyzed particulate trap would have the same advantages, the catalytic converter is much less complex, bulky, and expensive. Unlike the trap, the catalytic converter has little impact on fuel economy or safety, and it will probably not require replacement as often. Also, unlike the trap-oxidizer, the catalytic converter is a relatively mature technology--millions of catalytic converters are in use on gasoline vehicles, and Englehard Corporation PTX (tm) Diesel catalytic converters have been used in underground mining applications for more than 20 years.

The disadvantages of the catalytic converter are the same as those of the precious-metal catalyzed particulate trap: sulfate emissions and conversion of NO to the more toxic NO_2. The NO to NO_2 conversion occurs naturally in the atmosphere, so the only differences in NO_2 exposure would occur where people are exposed to relatively fresh exhaust. The increase in the toxic effects of NO_2 under these circumstances should be more than counterbalanced by the decrease in CO, aldehydes, PNA, and nitro-PNA. However, the tendency of the precious-metal catalyst to convert SO_2 to particulate sulfates requires the use of low-sulfur fuel: otherwise, the increase in sulfate emissions would more than counterbalance the decrease in SOF. As discussed in Section 5.4, however, low-sulfur fuel appears to be a cost-effective emissions control measure in any case. Regulations mandating low-sulfur fuel (0.05 wt. percent sulfur maximum) in the U.S. have been proposed (in early 1989) and will probably be finalized in 1990. The implementation date is proposed to be October 1993.

Electrostatic Agglomerator/Precipitators

Electrostatic precipitators have been used in a number of novel approaches to particulate emissions control. An electrostatic agglomerator has been used as the front end in an experimental system for removing Diesel particles by cyclone collection developed by Robert Bosch AG (Polach and Hagele, 1984), and a similar system has been proposed by Kittelson and coworkers (1986).

The Bosch researchers developed a fairly compact agglomerator system using serrated "spray disks" to increase the corona discharge and charging rate of the particles. This system was developed as a "pre-agglomerator" for a cyclone collection system. A prototype of the Bosch system was tested on a light-duty vehicle using the U.S. Federal Test Procedure. The particulate mass collection efficiency on this test was measured at 58 percent. The system was reported to give the same muffling capability as a muffler, while occupying the space required by 1 1/2 mufflers. It was also indicated that the system resulted in a 3 percent increase in fuel consumption.

A similar system has been proposed by Kittelson and coworkers (1986). In this approach, particles are collected and agglomerated by a multiplate electrostatic precipitator. Kittelson et al. discovered that Diesel particles have a significant charge as they leave the engine; therefore, no separate charging system is needed. After sufficient particulate matter has built up on the plates, the agglomerated particles begin to be reintrained by the exhaust gas. They can then be collected downstream by a cyclone or other inertial filter.

The key problem with both the Bosch system and the approach of Kittelson et al. lies in disposing of the collected particulate matter. In the Bosch system, a high-particulate gas stream is recycled into the engine and burned. This would be infeasible in a turbocharged engine, due to the potential fouling of the compressor and intercooler with particulate matter. All of the engine manufacturers' reservations about EGR systems would also apply to this system as well. Unless this problem can be resolved, the electrostatic collection approach to particulate control is unlikely to proceed beyond the laboratory.

NOx Reduction Techniques

Under appropriate conditions, NOx can be chemically reduced to form oxygen and nitrogen gases. This process is used in modern closed-loop, three-way catalyst equipped gasoline vehicles to control NOx emissions. However, the process of catalytic NOx reduction used on gasoline vehicles is inapplicable to Diesels. Because of their heterogeneous combustion process, Diesel engines require substantial excess air, and their exhaust thus inherently contains significant excess oxygen. The three-way catalysts used on automobiles require a precise stoichiometric mixture in the exhaust in order to function--in the presence of excess oxygen, their NOx conversion efficiency rapidly approaches zero.

A number of aftertreatment NOx reduction techniques which will work in an oxidizing exhaust stream are currently available or under development for stationary pollution sources. These include selective catalytic reduction (SCR), selective non-catalytic reduction (Thermal Denox(tm)), and reaction with cyanuric acid (RapReNox(tm)). However, each of these systems requires a continuous supply of some reducing agent such as ammonia or cyanuric acid to react with the NOx. Because of the need for frequent replenishment of this agent, and the difficulty of ensuring that the replenishment is performed when needed, such systems are considered impractical for vehicular use. Even if the replenishment problems could be resolved, these systems would raise serious questions about crash safety and possible emissions of toxic air contaminants. They will not be considered further in this report, therefore.

4. EMISSION CONTROL STRATEGIES FOR NEW DIESELS

Emission control requirements for heavy-duty Diesel engines have grown increasingly stringent over the last 20 years, and will continue to do so for at least the next decade. Technology for Diesel emissions control, in consequence, has grown ever more sophisticated and expensive, and emissions requirements have come to play an increasing role in overall engine design. As a result one can define a number of different levels of Diesel emission control, arranged in ascending order of effectiveness, complexity, and cost.

Due to differences in local air-quality requirements, economic capacities, and politically-determined tradeoffs between environmental and economic goals, different levels of emissions control may be appropriate for different jurisdictions. The focus of this section is therefore not to lay out one preferred level of emissions control, but to present a menu of differing control levels, in ascending order of complexity, cost, and effectiveness. These range from simple limits on excessive smoke emissions through sophisticated in-cylinder control strategies to trap-oxidizer systems. Table 3 summarizes the emission control levels considered. Each of these is discussed separately below.

Table 3
Emissions Control Levels Considered

	Emissions (g/BHP-hr)[1]				Smoke		
Emissions Level	HC	CO	NOx	PM	A	B	C
1 Smoke Controls	--	--	--	--	25%	10%	40%
2 First-level controls	1.0[2]	4.0[2]	8.0[2]	0.50[2]	15%	7%	25%
3 Current Technology	1.0	4.0	6.0	0.50	15%	7%	25%
4 Best engine-out technology	0.5	3.0	5.0	0.25	--	--	--
5 Best non-trap technology	0.2	0.5	5.0	0.15	--	--	--
6 Maximum Control	0.2	0.5	4.0	0.08	--	--	--

[1] U.S. Heavy-duty transient test or similar, except as noted.
[2] 13-mode, steady state test.

The costs of controlling emissions from Diesel engines can include one or more of the following:

- Research and development costs;

- Emissions certification and other costs of demonstrating compliance with regulations;

- Additional manufacturing cost for the engine;

- Additional maintenance costs; and

- Increased fuel consumption.

In this section, we develop rough estimates of each of these quantities (where applicable) for each of the emissions control levels considered. Because of country-to-country variations (e.g. in duty cycles, fuel costs, and interest rates) no attempt has been made to combine these separate cost estimates into an overall lifecycle cost or cost-effectiveness. These calculations are left to be carried out by national authorities, using economic parameters appropriate to each nation.

The costs of research and development, certification, and manufacturing are paid directly by the engine manufacturer. Depending on competitive conditions, the manufacturer may or may not be able to recover these costs by increasing the price paid by the buyer. Due to the variation in competitive conditions, we have not attepted to estimate the effect of these cost elements on the ultimate price paid -- the cost estimates shown are the added costs to the manufacturer. The development cost estimates also reflect the cost to a manufacturer undertaking such development now, with the benefit of the substantial body of research that has already been done in the area. This is probably less than the cost to the first manufacturers undertaking development in this field.

The cost of additional maintenance and fuel consumption are paid by the vehicle owner, not the manufacturer. The costs given for maintenance are the estimated average annual cost to the vehicle owner. In addition, we have estimated the percentage increase or decrease in fuel consumption due to each emissions control level. Due to the wide country-to-country variation in fuel consumption and fuel prices, no attempt has been made to attach a monetary value to the change in fuel consumption.

4.1 Smoke Controls

The first Diesel emissions regulations were established to limit emissions of visible smoke. These regulations are still in force in both the U.S. and the EEC. The advent of strict Diesel PM regulations in 1991 and 1994 will render the U.S. standards more or less irrelevant, however. As the first step in Diesel PM emissions control, smoke limits are both inexpensive and very cost-effective. Table 4 summarizes the emissions characteristics and costs of this level of emissions control.

Table 4
Estimated Emissions and Cost Impacts of
Emissions Control Level One: Smoke Controls

	Emissions (g/BHP-hr)				Smoke		
	HC	CO	NOx	PM	A	B	C
Emissions Standards	--	--	--	--	20%	10%	35%
Estimated Emissions[1]							
uncontrolled	1.0	4.0	11.0	1.2			
with smoke control	1.0	3.0	11.0	0.8			
reduction	0.0	1.0	0.0	0.4			
% reduction	0%	25%	0%	33%			

Economic Effects	Light-Heavy	Medium-Heavy	Heavy-Heavy
Change in fuel consumption (%)	0%	0%	0%
Change in cost per vehicle ($)			
Initial cost	0-100	0-150	0-150
Maintenance cost/year	0-20	0-20	0-20
Additional cost per engine family (1000s of $)			
Development/testing	0-100	0-100	0-100
Certification	10	10	10

[1] U.S. Heavy-duty transient test or similar.

Technology

Technology for controlling excessive visible smoke emissions is well-developed. Excessive smoke is the result of injecting too much fuel for the existing air supply and fuel-air mixing conditions. This generally occurs under one of three conditions: full-load operation in naturally-aspirated engines, transient acceleration in turbocharged engines, and "lug-down"--operation at low engine speeds and high loads.

Excessive full-load smoke in naturally-aspirated engines can be prevented by limiting the maximum fuel quantity to a level which does not exceed the smoke limit. This will normally mean a reduction in engine power output. Alternatively, steps to improve engine "breathing" and air-fuel mixing (e.g. increasing injection pressure) may permit a reduction in smoke at the same power output.

Excessive lug-down smoke occurs as a result of poor mixing. In present production fuel injection systems, the fuel injection pump is geared to the crankshaft. A reduction in engine speed thus reduces the injection rate and thus (since injector orifice area is constant) the injection pressure. At sufficiently low speeds, this impairs atomization and mixing enough to cause heavy smoke at high loads. This can be prevented by "shaping" the engine governor curve to reduce the maximum fuel quantity permitted at low speeds. Although this reduces emissions, it also impairs low-speed torque, and may thus require more frequent gear shifting--or a larger engine--in some applications.

Transient smoke emissions from turbocharged engines can be controlled through the use of an acceleration smoke limiter. These are of two types: simple time-delays and boost-pressure sensors, which limit the maximum fuel quantity permitted as a function of turbocharger boost. Both have the effect of reducing the maximum fuel quantity during transient accelerations--thus limiting smoke from overfueling, but also impairing acceleration performance to some degree. The boost sensors are preferable, since they automatically adjust for variations in turbocharger performance, and generally allow better acceleration performance for the same smoke level.

Reliable measurements of the impact of Diesel smoke control measures on total emissions are scarce. However, Weaver and Klausmeier (1988) evaluated the impact of tampering with maximum fuel settings and acceleration smoke limiters on emission-controlled engines. For a heavy-duty truck engine, measurements by an engine manufacturer showed that disabling the acceleration smoke limiter increased PM emissions by roughly 50%. The increase in PM emissions from a naturally-aspirated engine on which the maximum fuel limit had been increased was also estimated at 50%. Assuming that these emissions were characteristic of uncontrolled levels, the institution of smoke controls should reduce emissions by about one-third. The effects of smoke control will be heavily dependent on the specific duty cycle. Where (as in bus operation) the duty cycle includes mostly full-power accelerations, uncontrolled emissions are likely to be much higher, and the effect of smoke controls will be proportionately greater.

Emissions Standards and Test Procedures

Smoke emissions standards can be defined in terms either of smoke opacity (as in the U.S.) or in terms of a smoke "number" such as the Bosch or Hartridge number, which measures the optical absorbtion per unit volume. Since, for a given smoke concentration, opacity varies as a function of the optical path length, the U.S. procedure requires that the path length be specified. In the U.S. procedure, longer path lengths (corresponding to greater exhaust pipe diameters) are used for more powerful engines. This recognizes the fact that--at the same soot concentration--an engine producing a greater volume of exhaust creats a darker and thus more offensive smoke plume.

The smoke emissions test procedure used in the U.S. is performed on an engine dynamometer, equipped with either a flywheel or dynamometer controls to simulate vehicle inertia. The engine is operated through a test cycle consisting of two accelerations (simulating acceleration from stop with a gear change) followed by "lugging down" at full load from the rated power point to the maximum torque point. Average smoke opacity is computed for each half-second interval during the cycle, and the cycle itself is repeated three times.

Three smoke opacity values are computed: "A" or average acceleration; "B", or lug-down peak; and "C" or acceleration peak. The A smoke opacity is the average of the 15 highest opacity values in the acceleration phases of each test cycle. The B opacity value is the average of the 5 highest values from the lug-down phase of each cycle. The C opacity, finally, is the average of the 1/2 second intervals with the highest opacity in each test cycle. The maximum smoke opacity levels permitted in the U.S. are A smoke, 20%; B smoke, 15%; and C smoke, 50% opacity. Smoke of 15% opacity is clearly visible, but "thin", and can still be seen through easily. This opacity level is about the threshold at which smoke becomes noticeable to many people. Smoke of 50% opacity appears "thick" and dark, and most people would consider it visually offensive at this level.

The U.S. smoke standards have not changed since 1973, and appear to be substantially more lenient than necessary. In reviewing smoke certification data for the last 15 years, average A and B smoke for naturally aspirated engines are both around 10%, while for turbocharged engines average A smoke is around 15-18%, and B smoke around 5-9%. Average peak smoke is about 25%, and seldom exceeds 35% opacity. Therefore, smoke opacity standards of 20%, 10%, and 35% for A, B, and C smoke, respectively, appear readily attainable.

Costs

The costs of establishing smoke emission limits would be relatively small. Since such limitations are already in place in the largest Diesel engine markets, nearly all engine manufacturers have already developed the requisite technology and calibrations. The costs of substituting a smoke-controlled model for a non-smoke-controlled model would then consist of only the additional manufacturing costs, plus the costs of testing and filing a certificate of compliance. Manufacturing costs would be nil for naturally-aspirated engines, and would range from around $50 to $150 for turbocharged engines. In the case where the manufacturer chooses to upgrade technology in response to the smoke limits (eg. by installing a turbocharger), the additional manufacturing costs would be higher, but in this case, these costs would be ascribable to improved engine performance, rather than the smoke standard per se.

The costs of enforcing smoke standards for new engines would also be fairly low. The major expense would be in setting up and maintaining an office to keep track of emissions certification records. Occasional spot-checking of actual compliance would also be desirable (a smoke enforcement or inspection/maintenance program, if one were established, would be useful in suggesting specific engine models to be checked). This would require an engine dynamometer and associated facilities, at a capital cost of $100,000 to $300,000, depending on land, building, and labor costs. Operating expenses for a moderate spot-checking program for smoke emissions would probably be about $100,000 per year.

Other Effects

The steps taken to limit smoke emissions will reduce acceleration performance in both turbocharged and naturally-aspirated engines. In addition, maximum steady-state power output from naturally aspirated engines would be reduced somewhat (perhaps as much as 10-15%). To recover the same vehicle performance, engine manufacturers would need to increase engine displacement and/or improve engine breathing and fuel injection to lower smoke at the same power level.

In-Use Maintenance and Enforcement Requirements

Changes in maximum fuel settings to limit smoke would not increase maintenance requirements. Acceleration smoke limiters do require some periodic maintenance, but this is minor. The cost of this added maintenance is estimated at $20 per year. To the extent that manufacturers upgrade technology to meet smoke limits (e.g. by substituting in-line for distributor-type injection pumps), the maintenance costs for the new technology may be higher.

The reduced engine performance resulting from smoke limitations will create an incentive for vehicle owners and drivers to tamper with the maximum fuel settings. To counteract this, manufacturers should be required to make these settings tamper-resistant to the degree practical (bearing in mind that there is a legitimate need to adjust them in some cases, such as when recalibrating an injection pump). Presently, manufacturers and injection service shops generally seal these adjustments, in order to protect themselves against warranty claims caused by tampering. Tampering is widespread nevertheless. A smoke enforcement program and/or inspection/maintenance program aimed at smoke opacity would be desirable to limit the amount of tampering as well.

4.2 First-level Emissions Control

This first level of emissions control comprises only the most basic emission reduction strategies. The technology required is comparable to that required by pre-1988 U.S. Federal emissions standards, or the present requirements of ECE R.49, with the exception that particulate emissions are regulated as well. Using this basic technology, emissions can be reduced significantly from uncontrolled levels, at relatively low costs. The cost-effectiveness of this level of control is excellent, therefore. Table 5 summarizes the estimated emissions effects and costs of this level of control.

Table 5
Estimated Emissions and Cost Impacts of
Emissions Control Level Two: First Level Controls

	Emissions (g/BHP-hr)				Smoke		
	HC	CO	NOx	PM	A	B	C
Emissions Standards[1]	1.0	4.0	8.0	0.50	15%	7%	25%
Est. Transient Emissions[2]	0.8	2.5	7.5	0.65			
Red. from previous level							
g/BHP-hr[2]	0.2	0.5	3.5	0.15			
percent	20%	17%	32%	19%			
Red. from uncontrolled level							
g/BHP-hr	0.2	1.5	3.5	0.55			
percent	20%	38%	32%	46%			

Economic Effects	Light-Heavy	Medium-Heavy	Heavy-Heavy
Change in fuel consumption (%)	2%	1%	0%
Change in cost per vehicle ($)			
Initial cost	0-50	0-100	0-200
Maintenance cost/year	0	0	0
Additional cost per engine family (1000s of $)			
Development/testing	0-400	0-500	0-600
Certification	50	50	50

[1] 13-mode steady-state test.
[2] U.S. Heavy-duty transient test or similar.

Technology

The technology needed for first-level emissions control is approximately the lowest common level of Diesel engine technology worldwide. The basic approach to compliance with these emission levels involves retarding injection timing somewhat to reduce NOx, use of low-sac injection nozzles to reduce HC and PM, and smoke controls as discussed in the last section to limit both PM and visible smoke. Some minimal optimization of engine breathing and the combustion chamber may also be required, but is likely to have been performed in any case in the search for better fuel economy. Due to the moderately retarded injection timing, mechanical variable timing devices may be beneficial in improving cold-start performance and light-load HC emissions.

Emissions Standards and Test Procedures

As this level of emissions control is intended to require only simple and inexpensive technology, the use of expensive and sophisticated test methods such as the U.S. Transient Test would be inappropriate. So long as only simple mechanical emission controls are in use, gaseous and steady-state particulate emissions can be controlled with sufficient accuracy by a steady-state test procedure such as the 13-mode test. Transient particulate emissions can then be kept within reasonable limits by the application of stringent standards for visible smoke. Where electronic controls are used, some additional testing and regulations would be required to ensure that emissions calibrations are applied across the entire range of engine operation, not just in the vicinity of the steady-state test points.

The emissions standards recommended for this level of control technology are shown in Table 5. The gaseous and particulate emissions standards shown in the table are based on a steady-state test procedure similar to the U.S. or ECE 13-mode tests. The recommended NOx emissions standard of 8.0 g/BHP-hr represents a significant reduction from uncontrolled levels, but not so much as to have a significant effect upon fuel economy or PM emissions. The CO and HC emissions standards are rather lenient, considering the inherently low emissions of these pollutants from Diesel engines. The steady-state PM standard of 0.6 g/BHP-hr is also considered readily attainable using conventional technology. The recommended smoke emissions standards of 15% A smoke, 7% B smoke, and 25% C smoke are relatively stringent, but well within the present state of the art as demonstrated in U.S. certification data.

Costs

Imposition of emissions controls at this level will probably result in some upgrading of marginal fuel injection equipment to provide higher injection pressures and variable injection timing, especially in the heavier end of the Diesel market. Most engines would not require such upgrades, however, since they are already sold in markets requiring at least this level of control. The costs of these incremental changes are estimated at up to $200 for heavy-heavy engines, but considerably less for medium-heavy and light-heavy engines.

For most engine models, no development and only minimal testing would be required to assure compliance with these standards. Engine models not already being sold in jurisdictions where they are subject to emission controls would require some development and testing effort, however. Since only steady-state emissions and smoke tests are required, the costs of this effort would be moderate--in the range of $400,000 to $600,000, much of which would be for durability testing. Certification, since it could be carried out using steady-state test data, would not be very costly.

Other Effects

The retarded fuel injection timing necessary to limit NOx emissions is likely to have an adverse effect on fuel economy, especially in naturally aspirated engines. For the relatively lenient 8 g/BHP-hr standard shown in the table, however, this effect is unlikely to be more than two or three percent. In heavier engines, increased fuel injection pressure is likely to offset any adverse effects of NOx control at this level. Retarded injection timing should help to reduce combustion noise somewhat, while the use of low-sac nozzles will help cut odor and aldehyde emissions as well as HC.

The strict smoke emissions standards recommended for this control level would require manufacturers to calibrate their naturally aspirated engines for reduced power output, and turbocharged engines for reduced acceleration performance, compared to the more lenient smoke standards recommended for the previous level. Engine modifications to reduce PM emissions should also improve smoke, however, so the net effect is likely to be small.

In-Use Maintenance and Enforcement Requirements

Achieving these emission levels will require no new components beyond those required for compliance with smoke limitations alone. The detailed changes in calibration, injection nozzle design, combustion chamber, etc. are not expected to result in maintenance requirements different from those for smoke-controlled engines.

The degree of injection timing retardation required at this emissions control level is not enough to provide significant incentive to tamper with injection timing. The strict smoke controls will result in some temptation to tamper with maximum fuel and acceleration smoke limiter settings, however. Requiring tamper-resistant designs, and tying the warranty coverage to maintaining intact seals on the adjustments should reduce this tampering to some degree. As an additional deterrent, however, an in-use smoke enforcement program and/or inspection/maintenance program would be desirable.

4.3 Existing Technology

This level of emissions control is intended to reflect current (1988-1990) Diesel engine technology in the U.S. While this level of technology is required in the U.S., it is not unique to that country--many premium engines in Europe and Japan are built to similar standards, primarily for reasons of power output and fuel economy. Table 6 summarizes the emissions levels achievable and the cost estimated for this technology.

Technology

To attain this level of emissions control in the U.S., most manufacturers have chosen to reduce NOx and PM via turbocharging with

Table 6
Estimated Emissions and Cost Impacts of
Emissions Control Level Three: Existing Control Technology

	Emissions (g/BHP-hr) HC	CO	NOx	PM	Smoke A	B	C
Emissions Standards[1]	1.0	4.0	6.0	0.50	15%	7%	25%
Est. Transient Emissions[1]	0.5	2.5	5.5	0.4			
Red. from previous level							
g/BHP-hr[1]	0.3	0.0	2.0	0.3			
percent	38%	0%	27%	38%			
Red. from uncontrolled level							
g/BHP-hr[1]	0.5	1.5	5.5	0.8			
percent	50%	38%	50%	67%			

Economic Effects	Light-Heavy	Medium-Heavy	Heavy-Heavy
Change in fuel consumption (%)	-5 TO 3%	-5 TO 3%	0 TO 3%
Change in cost per vehicle ($)			
Initial cost	400-1500	0-1600	0-1500
Maintenance cost/year	50-200	0-200	0-300
Additional cost per engine family (1000s of $)			
Development/testing	0-2000	0-2000	0-2000
Certification	270	300	350

[1] U.S. Heavy-duty transient test or equivalent.

air-to-air or low-temperature air-water aftercooling. Further NOx control to meet the standards is provided with moderately retarded fuel injection timing. Increased fuel injection pressure and variable injection timing are used to minimize the effect of the retarded timing on fuel consumption and PM emissions. Further control of PM emissions comes from detailed optimization of air swirl patterns and combustion chamber geometry, use of low-sac or VCO injection nozzles, limited control of lube oil consumption, and changes in engine calibration to reduce transient smoke.

For the most part, this has involved only incremental changes to the existing technology, rather than major redesign. The same technological changes (except for the retarded injection timing) have also been employed in many premium European and Japanese engines, for reasons of power and fuel economy rather than emissions. Thus, the effect of regulations in the premium segment of the engine market has probably been fairly small. However, these regulations have resulted in the near-disappearance of low-cost, naturally-aspirated, low-BMEP engines from the marketplace, to be replaced with more expensive (albeit more efficient and powerful) turbocharged engines.

Emissions Standards and Test Procedures

At this level of emissions control, compliance requires fairly sophisticated and expensive technology. The use of similarly sophisticated and expensive technology for verifying compliance is therefore not unreasonable. The emissions test procedure recommended for this level of emissions control is the U.S. Heavy-Duty Transient Test, or some other, similar test procedure involving real-time simulation of transient operation. Emissions durability requirements should be set to cover 70-80% of the engine's full "useful life" before overhaul (recognizing that the increase in PM and HC emissions due to lube-oil consumption near the end of an engine's life is beyond the manufacturer's control).

Achievable emissions standards for this level of control are shown in Table 6. The NOx standard of 6.0 g/BHP-hr is identical to the current California NOx standard, and to the U.S. Federal standard for 1990. This level was originally established for the 1988 model year, but a lawsuit on procedural grounds resulted in a two-year delay at the Federal level.

The achievable PM emissions standard shown in Table 6 is 0.50 g/BHP-hr on the U.S. Transient Test. This is somewhat less than the current U.S./California standard of 0.60 g/BHP-hr. Since that standard was set in 1984, progress in PM emissions control has been unexpectedly rapid, and the lower standard is now clearly feasible. Indeed, most Diesel engines certified to the U.S. standards have demonstrated PM emissions below 0.50 g/BHP-hr--considerably below, in some cases.

The HC and CO emissions standards shown in Table 6 are capping rather than technology-forcing standards, as Diesel CO emissions are already quite low, while HC emissions have been reduced considerably by the changes made to reduce PM emissions. These standards are considerably below the present U.S. standards, however, as those were designed with gasoline engines in mind. The recommended standards are the same, numerically, as the steady-state HC and CO standards recommended for first-level emissions control, but the fact that they are measured on a transient test cycle makes them (especially the HC standard) considerably more stringent.

The smoke emissions standards shown in Table 6 are intended primarily to maintain visual esthetics, rather than particulate emissions control (although some additional PM control would likely result). At this level of PM emissions, significant short-term acceleration smoke could still occur. To ensure public support for an emissions control program (as well as to limit high short-term exposures to Diesel PM concentrations) it would be desirable to maintain at least the preceding level of smoke emissions control.

Costs

Costs of meeting these emission standards will vary, depending on the level of technology already in use. For naturally aspirated engines (found on most light-heavy and many medium-heavy vehicles) the costs could include a turbocharger with air-air charge air cooling, and an upgraded fuel injection system. In this case, the loss in fuel economy would be nil--fuel economy could even improve. Selection of less-expensive technologies would result in reduced power output and some loss in fuel-economy. For premium engines already equipped with air-air aftercooling and high-pressure injection, the additional hardware costs would be small, but a small fuel economy loss would be incurred.

The costs of developing engines to meet these emissions levels would vary, depending on the degree of development that had been done already. For engines sold in the U.S., the incremental development costs would be small or zero, as these engines are already meeting similar standards. For engines not sold in the U.S., however, these costs could range to two million dollars or more, depending on the degree of development required.

Depending on the specific test procedure chosen, certification costs could also be small, as U.S. certification results might be applicable. Otherwise, the costs of durability testing to full life, with periodic emissions testing, would probably run about $300,000 per engine family.

Other Effects

Depending on the emissions control strategy used, the effects of this level of emissions control on fuel economy could range from a small penalty (especially in heavy-heavy engines, which are typically turbocharged and intercooled anyway) to a small benefit (where a naturally aspirated engine is replaced with a more efficient turbocharged/intercooled one). At any given technology level, however, advancing injection timing is likely to improve fuel economy several percent, thus introducing a motive for tampering.

Extensive use of turbocharging and charge air cooling will increase maximum power levels, providing better vehicle performance, or making it possible to use a smaller engine.

In-Use Maintenance and Enforcement Requirements

Incremental maintenance costs at this level would range from zero to a few hundred dollars per year, depending on the approach taken. Additional maintenance costs would be due to turbocharger and aftercooler maintenance, and more expensive and precise fuel injection systems.

4.4 Near-term Technology (U.S. 1991 Standards)

This level of emissions control reflects essentially the current state-of-the-art in Diesel engine technologies--those being developed for compliance with the U.S. 1991 emissions standards. These standards represent roughly the limits of feasibility for in-cylinder emissions control alone (using currently available technology). Table 7 outlines the achievable emissions levels and estimated costs for this level of emissions control.

Technology

Recent progress in in-cylinder emissions control has been made possible, in large part, by improved understanding of the Diesel combustion process, and of the factors affecting pollutant formation and destruction. Pollutant formation and destruction in the cylinder are determined by the specific course of the Diesel combustion

Table 7
Estimated Emissions and Cost Impacts of
Emissions Control Level Four: Best In-Cylinder Control Technology

	Emissions (g/BHP-hr)				Smoke		
	HC	CO	NOx	PM	A	B	C
Emissions Standards[1]	0.50	4.0	5.0	0.25	--	--	--
Est. Transient Emissions[1]	0.35	2.5	4.7	0.20			
Red. from previous level							
g/BHP-hr[1]	0.15	0.0	0.8	0.20			
percent	30%	0%	15%	50%			
Red. from uncontrolled level							
g/BHP-hr[1]	0.65	1.5	6.3	1.00			
percent	65%	38%	57%	83%			

Economic Effects	Light-Heavy	Medium-Heavy	Heavy-Heavy
Change in fuel consumption (%)	0%	0%	0%
Change in cost per vehicle ($)			
Initial cost	400-1000	600-1400	800-2000
Maintenance cost/year	50-200	100-300	150-400
Additional cost per engine family (1000s of $)			
Development/testing	5000-10000	5000-10000	5000-10000
Certification	270	300	350

[1] U.S. Heavy-duty transient test or equivalent.

process. Modifying this process to minimize pollution involves a complex multi-dimensional tradeoff between NOx, HC, and PM emissions, fuel economy, power output, smoke, cold startability, cost, and many other considerations.

Most engine manufacturers have followed a broadly similar approach to in-cylinder control, although the specific techniques used differ considerably from one manufacturer to the next. This typical approach includes the following major elements:

- Minimize parasitic HC and PM emissions (those not directly related to the combustion process) by minimizing nozzle sac volume and reducing oil consumption to the extent possible.

- Reduce PM emissions at constant NOx by refining the turbocharger/engine match and improving engine "breathing" characteristics. Many manufacturers are also experimenting with variable-geometry turbochargers to improve the turbocharger match over a wider speed range.

- Reduce PM and NOx (with some penalty in HC) by cooling the compressed charge air as much as possible, via air-air or low-temperature air-water aftercoolers.

- Further reduce NOx to meet regulatory targets by severely retarding fuel injection timing over most of the speed/load range. Minimize the adverse effects of retarded timing on smoke, starting, and light-load HC emissions via a flexible timing system to advance the timing under these conditions.

- Recover the PM increase due to retarded timing by increasing the fuel injection pressure and injection rate.

- Improve air utilization (and reduce HC and PM emissions) by minimizing parasitic volumes such as piston/cylinder head clearance and piston top land volume.

- Optimize in-cylinder air motion through changes in combustion chamber geometry and intake air swirl to provide adequate mixing at low speeds (to minimize smoke and PM) without over-rapid mixing at high speeds (which would increase HC, NOx, and fuel consumption).

- Control smoke and particulate emissions in full-power operation and transient accelerations through improved governor curve shaping and transient smoke limiting (generally through electronic governor controls).

Taken together, these changes amount to a complete redesign of large portions of the engine and combustion system, and the costs are correspondingly high.

In addition to these generally used approaches, a number of other promising in-cylinder control techniques are under development by various manufacturers. These include variable air swirl devices for improved control of in-cylinder air motion over a range of speeds; fuel injection pumps with electronic control of the fuel injection rate; proprietary technology to minimize the initial fuel injection rate, thus reducing premixed burning and therefore NOx emissions; and innovative supercharging technologies to minimize or eliminate turbocharger lag. These technologies will be applied to the extent that individual manufacturers consider them desirable or cost-effective.

Emissions Standards and Test Procedures

The recommended test procedure for this level of emissions control is the U.S. Heavy-Duty Transient Test or a similar test which more accurately reflects actual operating patterns present Diesel vehicles in the applicable jurisdiction. As discussed in Section 2.3, the representativeness of the test cycle becomes an important concern at these advanced levels of emissions control, due to the potential for manufacturers to calibrate their control systems to exploit any differences between testing and actual operation.

Emissions standards recommended for this emissions control level are shown in Table 7. The recommended NOx and PM emissions standards are identical to the U.S. 1991 levels. The present consensus among U.S. manufacturers appears to be that these levels are difficult, but achievable given low-sulfur fuel in 1991. The CO standard recommended is the same as the earlier standards, and is intended only as a cap. The HC standard of 0.5 g/BHP-hr also serves essentially a capping function: to reduce particulate SOF to the required levels, most manufacturers will have to control HC to well below 0.5 g/BHP-hr. At this low level of PM emissions control, no separate smoke standard is required.

Costs

The incremental costs of this level of emissions control over the previous one are difficult to assess, due to lack of experience with the technologies involved. The costs of electronic fuel injection control--the major technological change--are estimated at around $200-800 per unit, depending on what functions and sensors are incorporated. Improved piston and liner materials, required to help control oil consumption, will also increase costs significantly. Variable-geometry turbocharging could add $500-800 to the cost of an engine. Other technological changes would have their costs as well. Altogether, likely ranges for the incremental costs of this emissions control level are from around $400 to $1,000 in light-heavy engines to around $800 to $2,000 in heavy-heavy engines.

Testing and development costs to meet this level of emissions control will also be high. As noted above, what is required is essentially the complete redesign of the engine and combustion system. Many new technologies must be incorporated, and existing technologies extended beyond known limits. To assure reasonable durability and reliability in use, engine manufacturers will need to test extensively, both in the laboratory and in the field. The costs of this intensive testing and development program are estimated at roughly five million to ten million dollars per engine family.

For engines being developed for the U.S. 1991 emissions standards, a significant portion of these costs has already been incurred, or would be incurred in any event, in order to market the engines in the U.S. Thus, for these engines, incremental development and testing costs will be small. For engines not marketed in the U.S., however, the full costs of development and testing would still apply.

Other Effects

The universal use of electronic engine control systems should add significantly to engine performance and driveability, especially in combination with variable-geometry turbochargers. Other desirable functions such as road-speed governing, cruise control, driver performance monitoring, etc. could easily be added as well. The more sophisticated control strategies possible with these technologies would probably have a net beneficial effect on vehicle fuel consumption, even given the lower NOx limit. Vehicle performance and driver satisfaction should be enhanced as well. Reliability (especially of the electronic control systems) will be a significant concern, however, until sufficient experience is accumulated with onboard electronics in heavy-duty truck applications to provide some assurance of durability.

In-Use Maintenance and Enforcement Requirements

The widespread use of computerized electronic engine controls in light-duty vehicles has led to somewhat of a crisis in vehicle maintenance in the U.S. Many mechanics, especially those working in non-dealer shops, are simply unable to diagnose or repair these systems. Similar problems can be expected with widespread use of electronics in heavy-duty engines. Due to the greater reliance on manufacturer-authorized service centers and generally superior mechanic training in the heavy-duty field, this problem will probably not be as severe, but it will certainly occur. Presently, all U.S. heavy-duty engine manufacturers are engaged in intensive mechanic training programs to combat this problem.

Due to the great number of new systems and technologies, overall engine maintenance costs will probably increase considerably at this level of control. Durability and reliability of the newly introduced systems may not be as great as those of the older mechanical systems, especially at first. In addition, engine durability with the low oil-consumption levels required for PM compliance has not been fully demonstrated. On the other hand, use of low-sulfur fuel and low-soot combustion systems should reduce engine oil contamination and could thus improve durability.

The implementation of such sophisticated emission control techniques may lead to correspondingly sophisticated attempts to tamper with them. One problem that has already occurred in light-duty vehicles is the marketing of replacement computer PROMs containing engine maps optimized for optimum performance and/or fuel economy, rather than for emissions compliance. Tamper-resistant designs, tie-ins with warranty coverage, and extended warranty periods may help to reduce this problem. An effective anti-tampering inspection program, or an I/M program including gaseous emissions measurements would be helpful in deterring such tampering as well.

4.5 Most Stringent Non-Trap Technology

This level of emissions control consists essentially of a Diesel catalytic converter added on to the in-cylinder emissions control technologies discussed in Section 4.4. This represents approximately the maximum level of Diesel emissions control possible without the use of a trap-oxidizer system. Table 8 summarizes the emissions effects and estimated costs of this level of emissions control.

Technology

Technology for Diesel catalytic converters was summarized in Section 3.7. The use of precious-metal catalyzed particulate traps and catalytic converters has been demonstrated to reduce particulate SOF by 60-80%, HC by 40-80%, and CO by 50-90%. With the use of low-sulfur fuel and low-soot engines to reduce fouling of the converter,efficiencies near the upper ends of this range can be expected. Low-sulfur fuel will also be required to limit sulfate emissions, due to the conversion of gaseous SO_2 to particulate sulfates.

Emissions Standards and Test Procedures

Test procedures for this emissions level would be the same as for the best engine-out technology. Due to the presence of the catalyst, however, special attention would have to be paid to the operating conditions during durability testing, to ensure that they realistically reflect the conditions the catalyst is likely to see in use.

Feasible emissions standards for this technology are listed in Table 8. HC and CO emissions standards have been set at levels which will require an oxidation catalyst to attain. The PM limit reflects a 40% reduction from the limit achieavable with in-cylinder controls alone. The NOx standard, on the other hand, has not changed from the previous emissions control level, as NOx would not be affected by an oxidation catalyst.

Table 8
Estimated Emissions and Cost Impacts of
Emissions Control Level Five: Best Non-Trap Control Technology

	Emissions (g/BHP-hr) HC	CO	NOx	PM	Smoke A	B	C
Emissions Standards[1]	0.20	1.0	5.0	0.15	--	--	--
Est. Transient Emissions[1]	0.12	0.5	4.7	0.12			
Red. from previous level							
g/BHP-hr[1]	0.23	2.0	0.0	0.08			
percent	66%	80%	0%	40%			
Red. from uncontrolled level							
g/BHP-hr[1]	0.88	3.5	6.3	1.08			
percent	88%	88%	57%	90%			

Economic Effects	Light-Heavy	Medium-Heavy	Heavy-Heavy
Change in fuel consumption (%)	0.5%	0.5%	0.5%
Change in cost per vehicle ($)			
Initial cost	150-300	300-500	500-800
Maintenance cost/year	20-40	40-80	40-80
Additional cost per engine family (1000s of $)			
Development/testing	500-1000	500-1000	500-1000
Certification	270	300	350

[1] U.S. Heavy-duty transient test or equivalent.

Costs

The costs of a Diesel catalytic converter system would be moderate. Weaver and Klausmeier (1987) estimated the increase in new-vehicle costs for this technology at around $186 for a light-heavy, $323 for a medium-heavy, and $589 for a heavy-heavy-duty vehicle. Actual costs would depend on the results of further development, but are likely to fall within a range surrounding these values. The costs of research and development on catalytic converter systems should also be fairly moderate, in the range of $500,000 to one million dollars per engine family. Certification costs would the same as for the in-cylinder controls alone, or about $300,000 per family.

Other Effects

Added backpressure from the catalytic converter would tend to increase fuel consumption slightly, but this would be offset to some extent by its muffling effect. Overall, an increase of about 0.1-0.5% in fuel consumption appears likely. Beneficial effects of the catalytic converter would include reductions in aldehydes, odor, and mutagenic compounds, as well as regulated emissions of HC, CO, and PM.

In-Use Maintenance and Enforcement Requirements

Since catalytic converters would have little adverse impact on vehicle performance, there would be little incentive to tamper with them. Periodic replacement would be necessary, however, in intensively used vehicles such as long-distance trucks and buses. To ensure that replacements are performed when necessary, it would be desirable to add some measurement of catalytic converter efficiency to the inspection/maintenance program required for in-cylinder emission controls. Free catalyst replacements (in effect, incorporating the cost of the replacement into the initial price) and incentives for having it performed could also help to ensure replacement when needed.

4.6 Maximum Emissions Control: Catalytic Trap-oxidizers

This emissions control level would consist of a catalytic trap-oxidizer system, added onto the advanced in-cylinder emissions controls discussed in Section 4.4. As such, it represents the maximum level of emissions control achievable with a Diesel engine, using reasonably well-demonstrated technology. Table 9 summarizes the emission levels achievable and the estimated costs for this level of emissions control.

Technology

The current state of trap-oxidizer technology was discussed in Section 3.7. For maximum effectiveness in controlling particulate SOF (as well as gaseous emissions) it would be desirable to have a precious-metal catalyst coating on the trap or a separate catalytic converter. Regeneration, using one of the active or semi-passive techniques described in Section 3.7, would be under the control of the engine's electronic control system.

Emissions Standards and Test Procedures

The emissions test procedure for this control level would be essentially the same as for in-cylinder controls alone--the U.S. Transient Test or equivalent. Modifications to the test procedure would be needed to ensure the inclusion of regeneration emissions on a pro-rata basis. Special attention to the durability test cycle would also be required, to ensure that the conditions experienced by the trap in durability testing are reasonably representative of those in actual service.

Achievable emissions standards for this level of control are listed in Table 9. The HC and CO standards of 0.2 and 1.0 g/BHP-hr, respectively, are the same as those for the catalytic converter technology, and are intended to force the use of an oxidation catalyst. The PM standard of 0.08 g/BHP-hr is somewhat lower than the U.S. 1994 standard level, but should be readily achievable by a catalytic trap-oxidizer on low-sulfur fuel. The NOx standard of 4.5 g/BHP-hr is somewhat lower than for the in-cylinder control case, reflecting the change in emissions tradeoffs with the trap-oxidizer present. Although retarding injection timing to reduce NOx tends to increase soot and PM emissions, the trap is extremely efficient in collecting soot. Thus, a lower NOx emissions level is achievable without significantly increasing PM emissions.

Table 9

Estimated Emissions and Cost Impacts of
Emissions Control Level Six: Maximum Emissions Control

	Emissions (g/BHP-hr)				Smoke		
	HC	CO	NOx	PM	A	B	C
Emissions Standards[1]	0.20	1.0	4.5	0.08	--	--	--
Est. Transient Emissions[1]	0.07	0.5	4.2	0.04			
Red. from previous level							
g/BHP-hr[1]	0.05	0.0	0.5	0.08			
percent	42%	0%	11%	67%			
Red. from uncontrolled level							
g/BHP-hr[1]	0.93	3.5	6.8	1.16			
percent	93%	88%	62%	97%			

Economic Effects	Light-Heavy	Medium-Heavy	Heavy-Heavy
Change in fuel consumption (%)	3%	2%	1.5%
Change in cost per vehicle ($)			
Initial cost	400-1000	800-1400	1200-2000
Maintenance cost/year	40-80	100-200	200-300
Additional cost per engine family (1000s of $)			
Development/testing	3000-10000	3000-10000	3000-10000
Certification	300	340	400

[1] U.S. Heavy-duty transient test or equivalent.

Costs

The capital costs of different trap-oxidizer system designs were estimated by Weaver and Klausmeier (1987) at around $400 to $600 for light-heavy vehicles; $800 to $1,000 for medium-heavy vehicles; and $1,200 to $1,500 for heavy-heavy vehicles. Other cost estimates by engine manufacturers have ranged as high as $5,000 for a heavy-heavy-duty vehicle, but these must be viewed with some skepticism. Our cost estimates in Table 9 basically follow Weaver and Klausmeier, but include a higher upper range to reflect the possibility of higher costs in some specialized applications.

System development and testing costs for trap-oxidizer systems would be very high, due to the novel nature of the technology and the need to demonstrate great reliability under a wide variety of operating patterns. Development and testing costs are roughly estimated at around three to ten million dollars per engine family, depending on the complexity of the application and the availability of "packaged" trap-oxidizer system designs from outside vendors. Certification costs would be similar to but somewhat higher than those for in-cylinder controls alone, due to the higher cost of multiple tests to account for regeneration emissions.

Other Effects

Depending on their design, trap-oxidizer systems would increase fuel consumption by between 0.5 and 5%. Their size and potential fire hazard would impose additional problems for vehicle designers. Power output might also be reduced somewhat by backpressure from the trap. The trap's effectiveness in collecting soot emissions might make it possible to relax somewhat on air-fuel ratio control, however, allowing for increased power output and better acceleration.

In-Use Maintenance and Enforcement Requirements

Maintenance costs for trap-oxidizers are likely to be significant. Given the complexity of the system, the need for periodic inspection and checking, replacement of trapping elements in intensively-used vehicles, and the inevitable system failures could add up to several hundred dollars per year. This would depend on the vehicle size and intensity of usage--some rough cost estimates are shown in Table 9.

Trap-oxidizers are likely to encounter resistance from the user community, due to their (perceived or actual) disadvantages for fuel economy, power output, and safety. As the trap would also be easy to remove (or bypass, in the case of active systems using bypass regeneration) tampering with these systems could be expected to be widespread in the absence of an effective inspection/maintenance program. For bypassable traps, even a scheduled I/M program might be inadequate, since it would be easy to reverse tampering with the bypass valve immediately before the inspection, restoring it to its tampered condition afterward. Thus, some form of in-use anti-tampering and/or smoke inspection would be required to supplement a scheduled I/M program.

4.7 Advanced Technologies

A number of advanced engine technologies hold promise for additional emissions control beyond the levels discussed above. These include low-heat rejection engines, turbocompounding, closed-loop fuel injection controls, advanced combustion technologies, exhaust gas recirculation, and advanced aftertreatment technologies.

Low heat rejection engines

Considerable effort is being devoted to the development of low heat rejection Diesel engines. The major benefit of such engines would be the elimination of the engine cooling system, with its attendant power losses and reliability problems. Another likely benefit would be the elimination of lubricating oil for the piston/cylinder contact, and thus a major source of the oil contribution to particulate SOF. Higher in-cylinder temperatures would help to reduce HC emissions, but NOx would probably increase some (this might be offset by a reduction in ignition delay, however). Some test data suggest that soot emissions might increase, however, due to the higher charge temperature. Overall, it appears that the technology of low heat rejection engines is too immature for any final judgement to be made concerning its emission effects.

Turbocompounding

Several manufacturers are developing turbocompound engines for use in line-haul trucks (Holtman, 1987). The primary advantage of these engines is their increased fuel efficiency, due to their ability to extract work from some of the waste exhaust heat. Other things being equal, this should result in a small corresponding decrease in emissions. Another possible emissions-related advantage would be the potential to bypass the power recovery turbine at low engine speeds, thus increasing the pressure drop across the compressor turbine and thus providing more power to the compressor. This should markedly improve low-speed smoke emissions and transient response.

Fuel injection rate shaping

Technology for reducing the fuel that burns in the premixed burning phase is not yet completely demonstrated. Some research results, however, suggest that NOx emissions might be reduced by 30-50% using this technique, with little or no adverse impact on PM emissions or fuel consumption. This can be expected to be an area of very active development in the next few years. If successful, it could make possible the attainment of PM and HC emissions comparable to those of levels four through six above (Tables 7 to 9), in combination with NOx levels of three g/BHP-hr or less.

Exhaust gas recirculation

The use of EGR could also have a major impact on NOx emissions, with minimal degradation in fuel economy and PM. Researchers at Ford were able to reduce NOx emissions from a light-duty DI engine by more than 50 percent (to about two g/BHP-hr in light-duty test cycle) using an optimized EGR schedule, while maintaining PM emissions comparable to light-duty IDI engines without EGR. EGR would be less effective in a heavy-duty engine, due to their more heavily loaded test cycles. The available data suggest that NOx emissions in the 3-4 g/BHP-hr range might be achievable without greatly degrading fuel economy or PM emissions, however.

The major drawback to EGR is its detrimental effect on engine durability and maintenance costs. The reasons for this effect are not well understood, however. Some data (and some manufacturers) suggest that the sulfur dioxide in the exhaust is the major culprit, while others focus on the role of recycled carbon particles. If sulfur is the major problem, its effects could be greatly reduced by the use of low-sulfur fuel--a measure which will probably be required for the 1994 PM standard in any case. If recycled carbon is the problem, its effects should be virtually eliminated by taking the recycle stream after the trap-oxidizer. Thus, EGR's effects on engine wear might be greatly alleviated by emission control measures undertaken for other reasons. More research is needed to establish the real causes and potential cures for excessive engine wear due to EGR.

Closed-loop control

Technology for feedback control of heavy-duty Diesel injection timing, fuel quantities, etc. is still in its infancy. By actually measuring outputs such as injector needle lift and rates of change in engine angular velocity, feedback control systems could help to balance fuel injection quantities between cylinders, compensate for wear or improper setting of the injection linkage, etc. etc. The major benefit of such technologies is likely to come from a reduction in in-use emissions deterioration, as the control system will actually be able to compensate for wear. Some reduction in the "slippage" between the performance of certification engines and those actually produced on the assembly line can also be expected.

Advanced combustion technologies

Diesel NOx and soot formation are inherent in the heterogeneous combustion process. Some research (Wood, 1988) is now focussed on ways to make Diesel combustion more homogeneous (i.e. more like that in an Otto-cycle engine) without giving up the fuel economy and other advantages of the Diesel. As discussed in Section 6, lean homogeneous combustion can achieve very low emissions of both NOx and PM. Techniques for approaching this condition using Diesel or a similar fuel are still research curiosities rather than the subject of serious development efforts, however.

Advanced aftertreatment

Beyond trap-oxidizer systems, potential aftertreatment controls include electrostatic collection techniques and various approaches to reducing NOx emissions to harmless nitrogen and oxygen. Currently, all known NOx reduction techniques require that a chemical reductant such as ammonia or cyanuric acid be supplied separately. This makes them infeasible for use in motor vehicles, except under special circumstances. A system to use Diesel fuel directly as a reductant, or the use of direct electrochemical reduction, could make aftertreatment NOx controls feasible.

5. EMISSION CONTROL STRATEGIES FOR DIESELS ALREADY IN USE

Programs to control in-use emissions form an important complement to new-vehicle emissions standards. Programs such as smoke enforcement and inspection/maintenance may be required to ensure that the anticipated emissions benefits of new-vehicle control technologies are not lost through the effects of poor maintenance and/or tampering with emission controls. Proper maintenance, encouraged by an effective inspection/maintenance program, can go far to limit emissions even from uncontrolled vehicles. Retrofit programs to install emission controls on existing vehicles can help reduce emissions over the short term, contributing to more rapid improvement in the environment. Finally, transportation control measures may also contribute to improved air quality in specific areas.

5.1 Maintenance

Even in the absence of specific emissions controls, well-maintained and properly-adjusted Diesel engines usually emit only relatively small quantities of unburned hydrocarbons and CO, and moderate amounts of particulate matter. Incorrect adjustment, poor maintenance, or excessive wear can increase emissions of these pollutants many-fold, however. NOx emissions, in contrast, are not very sensitive to maintenance conditions.

In extreme cases, PM and HC emissions in malfunctioning Diesel engines may be increased by a factor of 10 or 15 over the levels experienced with proper maintenance. Emission-controlled engines, since they have lower emissions to start with, may experience an even greater percentage increase. While the most severe emissions problems tend to degrade power output and fuel consumption, and are thus likely to be fixed eventually, this is by no means certain. Increases of up to a factor of two in HC, CO, and PM have be measured even in the absence of a significant effect on power or fuel consumption (Ullman et al., 1984).

The engine systems most likely to contribute to high HC, CO, and PM emissions are the air induction system (including the turbocharger), and the fuel injection system. Problems in these areas are generally due to neglect of routine maintenance, and can be corrected fairly cheaply. Tampering and improper adjustment of engine controls such as governor settings, maximum fuel limits, and acceleration smoke limiters may also result in substantially increased emissions. Major engine mechanical problems and/or excessive wear may also result in very high emissions (especially lube-oil emissions).

The effects of poor maintenance practices on Diesel emissions have received little quantitative study. One study performed for the California Air Resources Board (Weaver and Klausmeier, 1988) attempted to estimate the impact of common emissions-related defects by estimating the frequency of occurrence of each defect in the truck fleet and the emissions impact of vehicles having that defect. Defect frequencies and emissions impacts were different for different classes of trucks, and for different levels of emission control. Table 10 shows the estimates developed for medium-heavy duty trucks built to U.S. Federal pre-1988 emissions standards. This emission control technology is also representative of most European truck engines built to comply with ECE regulation R.49.

Fuel injection problems

As Table 10 indicates, the most important causes of excess PM and HC emissions are fuel injection system problems such as leaky, worn, or clogged injector nozzles. Injector problems range in severity from minor to very severe. Minor injector problems are likely to go unrepaired until the next routine maintenance interval, even in well-maintained fleets. These are not severe enough to impair engine operation noticeably, even though emissions are increased noticeably.

Moderate injector problems could include clogging with deposits or significant wear. These problems are severe enough to degrade engine performance and fuel economy noticeably, and are typically accompanied by considerable excess smoke. These problems would typically be repaired at the first convenient opportunity in a well-maintained fleet. Where maintenance is less scrupulous, however (that is, in most vehicle fleets worldwide), they are likely to go unrepaired for some time.

Severe injector problems often involve mechanical damage to the injector, or else extreme wear or deposit fouling. These problems are serious enough to degrade engine performance and fuel economy significantly, and are generally characterized by very heavy smoke. Problems of this magnitude should cause all but the most marginal operators to pull the vehicle out of service for repairs. Based on visual observations, however, such vehicles may constitute as many as 2 to 3 percent of trucks and buses on the road.

Particulate emissions in excess of 50 g/mile have been measured in city buses with severe injector problems (unpublished New York City Dept. of Environmental Protection data, summarized in Weaver and Klausmeier, 1988). The buses were nonetheless driveable, and capable of performing in service.

Improper fuel injection timing may also result in significant excess emissions in some circumstances. In fuel injection systems with mechanical controls, the angular relationship between the fuel pump and the pump driveshaft is very important. An error of a few degrees in either direction can significantly increase NOx emissions (if timing is advanced) or PM emissions (if it is retarded). Where

Table 10
Estimated Effects of Tampering and Malfunctions on Heavy-Duty Diesel Emissions

Type of Defect	Pct. Aff.	Oxides of Nitrogen		Unburned Hydrocarbons		Particulate Matter		Fuel Consumption	
		Ind. Veh.	Fleet Avg.	Ind. Veh.	Fleet Avg.	Ind. Veh.	Fleet Avg.	Ind. Veh.	Fleet Avg.
Timing Advanced	10%	50%	5.0%	20%	2.0%	10%	1.0%	0%	0.0%
Timing Retarded	6%	-20%	-1.2%	-10%	-0.6%	30%	1.8%	7%	0.4%
Minor Injector Problems	20%	0%	0.0%	10%	2.0%	35%	7.0%	2%	0.4%
Moderate Injector Problems	15%	-5%	-0.8%	150%	22.5%	200%	30.0%	5%	0.8%
Severe Injector Problems	5%	-10%	-0.5%	500%	25.0%	500%	25.0%	10%	0.5%
Smoke Limiter Misset	18%	0%	0.0%	0%	0.0%	20%	3.6%	1%	0.2%
Smoke Limiter Disabled	15%	0%	0.0%	-20%	-3.0%	50%	7.5%	2%	0.3%
Maximum Fuel High	14%	10%	1.4%	0%	0.0%	30%	4.2%	2%	0.3%
Clogged Air Filter	23%	0%	0.0%	0%	0.0%	50%	11.5%	2%	0.5%
Wrong/Worn Turbo	10%	0%	0.0%	0%	0.0%	40%	4.0%	1%	0.1%
Intercooler Clogged	1%	10%	0.1%	-20%	-0.2%	40%	0.4%	2%	0.0%
Other Air Problems	14%	0%	0.0%	0%	0.0%	40%	5.6%	1%	0.1%
Engine Mechanical Failure	2%	-10%	-0.2%	200%	4.0%	150%	3.0%	7%	0.1%
Excess Oil Consumption	8%	0%	0.0%	300%	24.0%	150%	12.0%	0%	0.0%
% All Defects Combined			3.9%		75.2%		140.4%		3.7%

stringent NOx controls are in place, injection timing is likely to be significantly more retarded than would be optimal for performance and fuel economy. In this case, vehicle owners and drivers will be tempted to tamper with the injection timing to improve performance.

Air-fuel ratio problems

Operating with the air-fuel ratio below the smoke limit is another common cause of excessive PM emissions. This may occur as the result either of tampering or of neglect of routine maintenance. In naturally aspirated engines, the maximum power level is generally smoke-limited. To increase the power output from the engine, it is very common for owners of such engines to "turn up" the maximum fuel stop to increase power. This results in a very large increase in black smoke and particulate emissions at full load.

A similar problem occurs with acceleration smoke limiters used on turbocharged engines. By limiting maximum fuel flow during engine transients, they act to limit smoke emissions. But this also reduces the engine power output during the transient, and thus impairs the vehicle's acceleration performance. Smoke limiter settings are commonly adjustable, and it is very common for vehicle owners or drivers to adjust them to provide better acceleration, at the cost of a substantial increase in smoke and PM emissions.

Other causes of air-fuel ratios below the smoke limit include dirty air filters, which restrict the airflow to the engine; worn-out or incorrect turbochargers; intercoolers clogged with deposits; and miscellaneous air intake problems such as air and exhaust leaks in turbocharged systems, collapsed air intake hoses, crimped exhaust pipes, etc.

Engine mechanical problems

Vehicles suffering from excessive emissions due to engine mechanical failures or excessive oil consumption make up a fairly small fraction of the vehicle fleet. The increase in emissions from these vehicles is so large, however, that they represent a significant fraction of total Diesel emissions. Unlike the other problems leading to high emissions, these defects are very expensive to correct--typically requiring that the engine be rebuilt, at a cost of $3,000 to $10,000.

Total impact

The emissions impacts of different types of defects are not necessarily additive--some defects can interact with others to create an even greater increase in emissions. For this reason, Weaver and Klausmeier (1988) estimated the combined impact of all defects by multiplying the fleet-average impacts of defects in each group. The results, shown in Table 10, indicate that average HC emissions in this vehicle class are approximately 75% higher and PM emissions 140%

higher than they would be if all vehicles were well-maintained. Similar estimates for heavy-heavy and for light-heavy-duty trucks showed similar effects. For advanced-technology emission-controlled vehicles, the effects of tampering and poor maintenance were estimated to be even larger in percentage terms, although the actual increase in g/BHP-hr was projected to be smaller.

Figure 7, reproduced from Weaver and Klausmeier (1988), shows the estimated impact of poor maintenance and tampering with emissions controls on total Diesel emissions in California through the year 2000 (in the absence of an inspection/maintenance program). As these figures show, baseline PM and HC emissions (those which would be experienced if all vehicles were well maintained) are projected to decrease markedly in the 1990s, as engines built to the stringent California/U.S. emissions standards replace older models. Excess emissions of these pollutants are also expected to decline, but by a much smaller percentage.

Due to the scarcity of data, the estimates of emissions impact and total emissions developed by Weaver and Klausmeier (1988) include considerable uncertainty (estimated as -30 to +70 percent for the excess emissions). Despite this range of uncertainty, it is clear from the foregoing that poor maintenance has a very large impact in increasing Diesel HC and PM emissions in California. Since there is no reason to believe that trucks in other areas receive significantly better maintenance than those in California, the same conclusion is doubtless valid elsewhere as well.

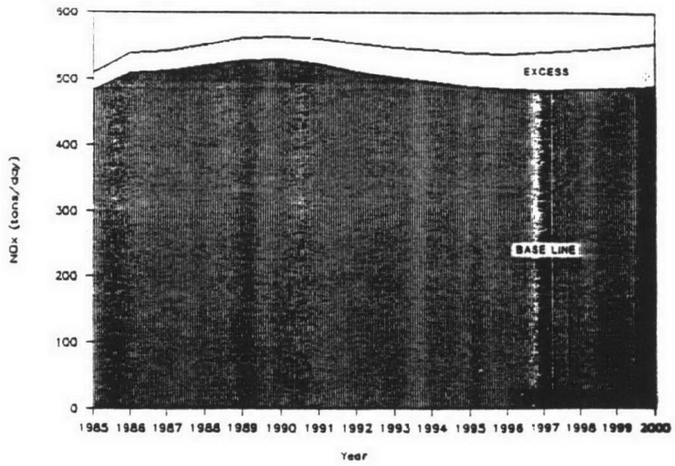
5.2 Smoke Enforcement

One approach to reducing the incidence of the most severe emissions problems in the heavy-duty vehicle fleet is a smoke enforcement program, in which traffic police or other designated personnel identify and cite heavily smoking trucks on the highways. Due to the public offense from excessive Diesel smoke, many jurisdictions have established such programs.

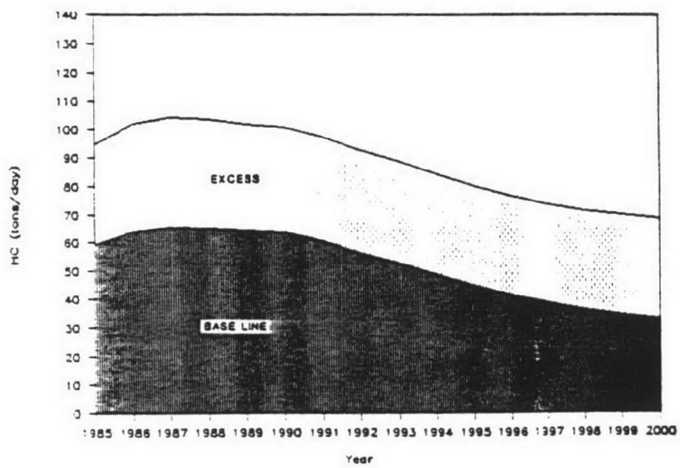
Most of the programs implemented to date have relied on visual estimates of smoke opacity, using the Ringelmann scale or some analogous measure. These measures have generally proven very difficulty to enforce, due to the need for properly trained observers and good observing conditions. Smoke opacity estimates based on Ringelmann Charts have been shown to vary considerably from chart to chart and observer to observer (Engine Manufacturer's Association, 1983). In some cases, lack of credence in such a "naked-eye" measurement has led judges to dismiss such citations.

Another problem contributing to the ineffectiveness of most smoke enforcement programs has been a lack of vigorous enforcement. Smoke, often, is viewed as less significant than speeding or other traffic violations, and receives lower priority. Lack of suitable test procedures, failure to recognize the differences in Diesel smoke emissions in different operating modes, and excessively lax failure

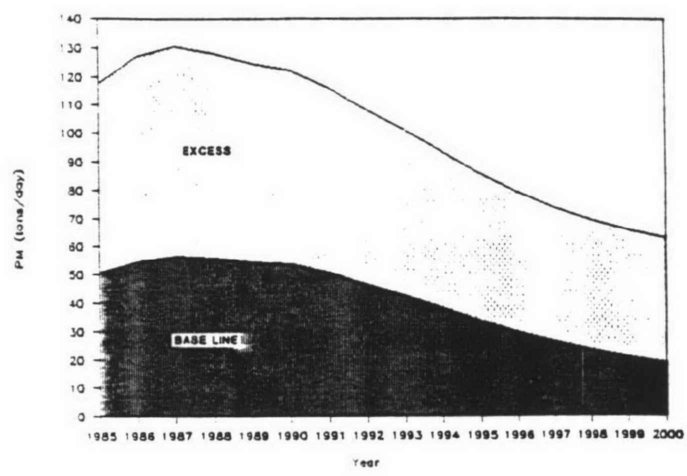
Figure 7
Estimated Impact of Poor Maintenance and Tampering with Emission Controls on Heavy-Duty Diesel Emissions in California 1985-2000
(Source: Weaver and Klausmeier, 1988)



Oxides of Nitrogen



Unburned Hydrocarbons



Particulate Matter

criteria have also led to frustration on the part of those charged with enforcing the programs, and thus to their failure.

Smoke enforcement programs could potentially be an effective spur to improved maintenance, and thus to reduced Diesel emissions. Proper program design is essential, however. Recommended elements for an effective smoke enforcement program are the following.

1. Dedicated enforcement personnel. Especially when a program is just starting, it is important that the personnel assigned to smoke enforcement have that as their sole (or at least primary) responsibility. This will allow for concentration of effort, for effective training in smoke observation, and for intensive practice to maintain the skills developed.

2. Suitable test procedures. Although vehicles to be subjected to enforcement action can be picked out by eye on the road, the variety of possible operating conditions makes it impractical for a single standard to apply to all cases. If the vehicle is made to undergo a standard test, a single standard becomes feasible. Weaver and Klausmeier (1988) evaluated a number of short roadside opacity tests, ultimately recommending one based on full-power acceleration from a stop.

3. Instrumental backup. Much experience has shown that observers can be trained to judge smoke opacity accurately and repeatably. Nonetheless, such judgements often lack credibility in court. Such skills also atrophy quickly if not used. The use of an inexpensive end-of-stack opacity meter to confirm an officer's judgement in doubtful or disputed cases can significantly improve the credibility of the program.

4. Stringent standards. Standards should be set at the lowest level that will ensure that properly maintained and adjusted vehicles will pass. A truck need not be continuously belching opaque black smoke to be emitting far more particulate matter than it should. The actual standard levels feasible will vary depending on the level of particulate emissions control in place. As a general rule, however, no Diesel engine should emit visible smoke in straight and level cruise at less than full power; and Diesels subject to level 4 or higher controls (U.S. 1991 standards or equivalent) should emit no more than a trace of visible smoke under any condition.

5. Effective public relations. The public, and especially the trucking community, should understand the operation of the program and the reasons for adopting it, and should be convinced of its fairness. Truck owners should be provided with adequate time and guidance to bring their vehicles into compliance before the program goes into effect. Initial enforcement efforts should concentrate on ticketing the worst offenders, letting marginal cases go for the time being.

5.3 Inspection/Maintenance Programs

Inspection and maintenance (I/M) represents the next step beyond an on-road smoke enforcement program for reducing in-use emissions from heavy-duty vehicles. As discussed in Section 4, some form of I/M program is likely to be essential to reap the full benefits of emission controls such as smoke limiters and trap-oxidizers.

Design of an inspection and maintenance program for heavy-duty Diesel vehicles presents many difficult issues. Because of the differences in technology, ownership, and operating patterns, existing I/M programs for light-duty vehicles may not be a good model for heavy-duty Diesel I/M. Other existing enforcement programs aimed at heavy-duty trucks (such as truck weight and safety enforcement programs) should be considered as well.

To reduce emissions, while minimizing the burden on vehicle owners, the primary goals of a heavy-duty Diesel I/M program should be the following:

- deter tampering with emission controls;
- detect tampering which is not deterred, and require that it be corrected;
- identify gross-emitting vehicles, and require that they be repaired; and
- encourage proper maintenance and awareness of the importance of emission controls in the bulk of the heavy-duty Diesel fleet.

Program Designs

One approach to designing a heavy-duty Diesel I/M program is to model it after existing light-duty I/M programs. In these programs, vehicles owners are required to present them for periodic inspections and emissions measurements, generally on an annual basis. Inspections may be performed either at a centralized, government-operated facility, or at specially licensed garages.

For heavy-duty Diesel vehicles, this type of program has several drawbacks. The costs of truck and driver time lost in bringing the vehicle in for inspection are likely to be significant (unless the emissions test can be combined with a required safety inspection). In addition, heavy-duty vehicles travel much greater distances annually than passenger cars, and require correspondingly more frequent maintenance. An annual inspection will thus have less impact on the incidence of emissions-related defects in the vehicle fleet.

Another important drawback to periodic inspections is that the scheduled inspection will be less effective in deterring tampering than one which is not predictable in advance. Many forms of tampering with heavy-duty emissions controls (e.g. maximum fuel stops, acceleration smoke limiters, injection timing, and trap-oxidizer bypasses) are reversible. If the inspection time is known, the tampering can be restored to its original condition immediately before the inspection, then returned to its tampered condition immediately afterward.

An alternative to periodic inspections is a program of in-use inspection for heavy-duty vehicles. Many jurisdictions already perform truck weight checks and safety inspections on this basis, and the addition of an emissions check and/or anti-tampering inspection to these programs would be straightforward. Random anti-tampering inspections (possibly in conjunction with smoke enforcement) could also serve as a useful adjunct to a periodic inspection/maintenance program.

Existing Programs

Inspection/maintenance programs for Diesel vehicles are already operating in a number of jurisdictions. In West Germany and several U.S. I/M programs, Diesel trucks are subject to the same idle tailpipe emission tests used for passenger cars, or to an idle smoke opacity test. These tests are generally justified on grounds of "fairness"--since gasoline vehicles are required to be tested, Diesels should too. Such measurements provide no meaningful test of actual Diesel emissions performance, however, and are essentially a waste of time and money. Failure rates in these programs are extremely low, as only a grossly malfunctioning engine could possibly fail.

A few jurisdictions have established meaningful Diesel I/M programs. One, established in the U.S. cities of Tucson and Phoenix, Arizona, measures Diesel smoke opacity under peak torque conditions on a chassis dynamometer. The maximum opacity level is 20%, or 5% over the U.S. smoke emissions standard. The failure rate in this program is about 7.5%.

Another successful program, in Santiago, Chile, is combined with a periodic safety inspection. Trucks are required to be tested every seven months, and buses every three months. Emissions testing in this program is performed by placing the drive wheels on a set of free rollers, placing the engine in gear, and then loading the engine down to the peak torque point using the vehicle's service brake. Smoke is measured using a Bosch smokemeter. To minimize potential problems with reversible tampering, smoke inspection facilities are required to seal the maximum fuel adjustment after the vehicle passes.

The Chilean program is a good example of the potential benefits of an effective I/M program, as well as some of the potential problems. Buses in Santiago are privately owned and operated, and maintenance practices are generally poor. However, Santiago's buses--unlike those in nearly every other third-world city--do <u>not</u> emit excessive quantities of black smoke. While about 25% of the buses emit visible smoke, the smoke is bluish or grayish--characteristic of unburned lubricating oil, rather than soot. The Bosch smoke test method used in the Chilean program is effective in measuring soot emissions, but is insensitive to oil smoke. It thus appears that the program is successfully controlling only those smoke emissions measured in the test. Chile has begun a the transition to a light-transmission opacity measuring technique, which will allow oil smoke to be detected as well. This will presumably result in decreased oil smoke emissions.

Test Procedures

The Diesel emissions of greatest concern from an I/M standpoint are particulate matter and hydrocarbons. Where (as in the U.S.) NOx emissions controls are stringent enough to affect fuel economy significantly, measurement of NOx emissions as well may be needed to deter tampering. While direct measurement of Diesel particulate matter under I/M conditions is impractical, smoke opacity provides an excellent proxy measurement. Smoke opacity can be measured using Bosch, Hartridge, or similar test apparatus, or by an inexpensive end-of-stack light-transmission opacity meter. The latter has the advantage that it registers light-colored blue or gray smoke, as well as the black smoke resulting from soot emissions.

Diesel HC and NOx concentrations can be measured directly by sampling the exhaust gas, using readily available detectors. Because of the higher molecular weight of Diesel HC emissions, they cannot be measured using the same unheated infrared-type analyzers used for gasoline engine HC measurements, however. Instead, a flame-ionization type detector (with heated sample lines to prevent HC condensation in the line) is required. NOx can be measured by chemilumenescent or IR techniques.

Meaningful Diesel emissions measurements can only be performed with the engine under load. Alternatives for supplying this load include use of a chassis dynamometer, the vehicle's own inertia and/or that of its drivetrain, the hydraulic torque converter on a vehicle so equipped, or the vehicle's service brake. The specific speed and load conditions during the test have an important effect on the emission levels. The choice of transient versus steady-state test conditions is also significant--many turbocharged Diesels have low emissions in steady-state operation, but smoke heavily during transients.

In work for the California Air Resources Board, Weaver and Klausmeier (1988) analyzed the results of a number of different test modes, using both chassis dynamometer and in-motion tests with a portable opacity meter. NOx, HC, and PM emissions were also measured during the chassis dynamometer tests. Weaver and Klausmeier also analyzed a database compiled by the New York City Department of Environmental Protection, consisting of smoke and chassis transient emissions measurements for several hundred trucks and buses.

Based on these analyses, Weaver and Klausmeier recommended measuring smoke opacity under full-power acceleration from stop as the most effective and practical roadside test for high emissions. For vehicles with hydraulic torque converters, an alternative test--accelerating the engine from idle to full load against the stalled torque converter (with the vehicle in gear, but held stationary by the brakes) gave similar results, and was also recommended. The recommended failure level for both test modes was 35% opacity (for engines built to the pre-1988 U.S. standards). Initial smoke opacity screening can be done by eye, with doubtful or disputed cases resolved by a portable end-of-stack opacity meter. California now plans to implement an in-use I/M program based on these recommendations.

For chassis dynamometer testing, Weaver and Klausmeier recommended smoke opacity measurements in transient acceleration, steady-state operation at peak torque, and at rated engine speed and three-quarters power. The latter condition (corresponding to highway cruise) is a very favorable one for emissions, and the recommended failure criterion is correspondingly stringent--4% opacity. Recommended failure criteria for the acceleration and peak torque test modes were 35% and 15% opacity, respectively.

Weaver and Klausmeier also found good correspondence between HC and NOx emissions in specific operating modes and overall emissions. For NOx, the best correspondence was found at 50% and 75% power at rated speed (the latter mode being the same as for highway cruise opacity measurement). For HC, a weighted combination of emissions at 100% power/rated speed and no-load/governor speed gave the best correlation with overal emissions. Further research (with reference to the specific emissions standards involved) would be required to establish failure criteria for NOx and HC concentrations, however.

Chassis dynamometer testing, as investigated by Weaver and Klausmeier (1988), is quite expensive, due to the cost of the dynamometer itself (generally $100,000 to $200,000 installed), and the time required to mount and secure the truck safely. Where these costs are prohibitive, the free-roller technique as used in Santiago may be an attractive alternative. The rollers are much less costly than dynamometer units, and the time requirements are less. Since no horizontal force is transmitted to the rollers, it is unnecessary to secure the truck in place before testing, and it can simply be driven on and off by locking the rollers. This has the disadvantage that it is difficult to measure transient smoke emissions, however.

Cost-Effectiveness

The cost-effectiveness of a heavy-duty Diesel I/M program will depend heavily on the degree to which it can be combined with existing activities, and on the effectiveness of the emissions tests and anti-tampering inspections in identifying high-emitting vehicles. In their study for the California Air Resources Board, Weaver and Klausmeier (1988) estimated the costs of a periodic I/M program using chassis dynamometers at around $5,500 per ton of PM eliminated. This estimate included a large credit for reducing NOx and HC emissions, however--without these credits, the cost would have been more than $12,000 per ton. More than a third of this cost was due to truck and driver time lost in going to and from the inspection.

For an in-use inspection program, using roadside smoke opacity tests and anti-tampering inspections combined with California's existing safety and truck weight inspections, the cost-effectiveness was estimated at only about $1,500 per ton of PM eliminated. Without the NOx and HC credits, this would have been $4,000 per ton instead. This greater cost-effectiveness is due to a reduction in time wasted in the inspection process, and to increased program effectiveness due to the more effective inspection frequency for the roadside program.

5.4 Fuel Modification

Modifications to Diesel fuel composition have drawn considerable attention in the United States as a quick and cost-effective means of reducing emissions from existing vehicles. The two modifications which show the most promise are a reduction in sulfur content, and in the fraction of aromatic hydrocarbons in the fuel. Of the two, the sulfur reduction is by far the cheaper and more cost-effective. Current proposals being studied by the U.S. EPA would reduce sulfur content in Diesel fuel to a maximum of 0.05% by weight. Possible limits on the cetane index or aromatic content of the fuel are also under consideration. The State of California has already adopted regulations mandating 0.05% sulfur in the Los Angeles area, and is presently considering limits of 0.05% sulfur and 10% aromatic hydrocarbons, statewide.

Sulfur Content

The effects of Diesel fuel sulfur and aromatic hydrocarbon content on emissions were addressed in a previous report by one of the authors and others (Weaver et al., 1986). Based on the limited data then available, this report concluded that reducing the fuel aromatic content would significantly reduce Diesel NOx, HC, and PM emissions; while reducing the sulfur content would reduce PM emissions and corrosive wear, thus increasing engine life. The savings due to extended engine life were projected to more than compensate for the increased refining cost to remove the sulfur, resulting in net economic benefits to society, as well as substantial environmental benefits. These conclusions proved highly controversial.

Since the publication of the 1986 report, many new data have come to light on the relationship between fuel sulfur and engine wear. In submissions to EPA, virtually every heavy-duty engine manufacturer has stated that reducing fuel sulfur will beneficially affect engine life (although the magnitude of these benefits is uncertain, and may have been overestimated by Weaver et al.). Preliminary results from a study of oil analyses in Southern California RTD buses show roughly a 30 percent reduction in wear metals in switching from the previous fuel to fuel containing 0.05 percent sulfur. Tests by a major engine manufacturer using a low-emission engine with air-to-air intercooling showed more than a two-thirds reduction in piston ring wear rate in going from 0.27 percent to 0.05 percent sulfur in the fuel. Low-emission engines would be expected to be more susceptible to corrosive wear, since their low exhaust temperatures and high boost pressures would make it easier for sulfuric acid to condense on the cylinder walls. It appears clear from the available data, therefore, that a reduction in fuel sulfur content is likely to result in measurable benefits in engine life.

Fuel sulfur may also be a major reason for the increase in Diesel engine wear due to EGR, as discussed in Section 3.6. If so, low sulfur fuel would be required in order for EGR to become a practical emission control technique for heavy-duty Diesel engines.

In addition to a direct reduction in emissions of SO_2 and sulfate particles, reducing the sulfur content of Diesel fuel would reduce the indirect formation of sulfate particles from SO_2 in the atmosphere. In Los Angeles, it is estimated that each pound of SO_2 emitted results in roughly one pound of fine particulate matter in the atmosphere. In this case, therefore, the indirect PM emissions due to SO_2 from Diesel vehicles are roughly as great as their direct particulate emissions. SO_2 conversion to particulate matter is highly dependent on local meteorological conditions, however, so the effects could be greater or less in other cities.

The sulfur content of Diesel fuel can be reduced to 0.05% or less by weight through hydrotreatment under moderate pressures in the presence of a catalyst. This process is widely used in the U.S. Cost estimates for adding this capability to a refinery without it range from around $0.01 to $0.05 per gallon of Diesel fuel treated, depending on the specific refinery and the availability of surplus hydrogen for treatment. Even taking the upper end of this range, and neglecting maintenance and engine life benefits, the cost-effectiveness of reducing sulfur from 0.3 to 0.05% would be about $6,000 per ton of PM eliminated, assuming the same SO_2 to particulate conversion rate as Los Angeles. This is competitive with trap-oxidizers. Factoring in maintenance benefits would reduce the net cost considerably, as would a lower desulfurization cost.

Regulations limiting Diesel fuel sulfur content to 0.05% in the Los Angeles area of California have been in force for several years. Spot-market prices for such low-sulfur fuel (CIF Los Angeles Harbor) are typically $0.02 per gallon higher than for standard distillate (max 0.5% sulfur by weight). This suggests that the actual costs of producing desulfurized fuel in a modern refinery are probably much closer to $0.02 per gallon or lower, rather than $0.05.

<u>Aromatic Hydrocarbons</u>

A reduction in the aromatic hydrocarbon content of Diesel fuel may also help to reduce emissions, especially where fuel aromatic levels are high (as they are in the U.S. and Canada). For existing (pre-1988) Diesel engines, a reduction in aromatics from 35% to 20% by volume would be expected to reduce transient particulate emissions by 10 to 15% and NOx emissions by 5 to 10%. HC emissions, and possibly the mutagenic activity of the particulate SOF, would also be reduced. Modelling studies of the refining industry have shown that aromatic reductions of this magnitude can often be obtained through alterations in Diesel fuel production and blending strategy, without a need for major new investments in additional processing capacity.

The costs of reducing fuel aromatic content to 20% in the U.S. have been estimated in EPA studies at $0.018 to $.033 per gallon, assuming sulfur controls are in place. Studies conducted for industry have estimated costs in the neighborhood of $0.08 per gallon. If the cost were $0.03 per gallon, and PM emissions were reduced 10%, the cost-effectiveness of this measure (for vehicles using pre-1991 technology) would be about $20,000 per ton of PM eliminated, which is more than the cost of other PM controls that have been adopted in the U.S. Vehicles with advanced emissions controls would show a smaller benefit, so that the costs per ton would be even higher. If half of the cost were assigned to the NOx, HC, and mutagenicity benefits, however, the resulting cost-effectiveness for pre-1991 vehicles would be comparable to that for other emission control measures.

Reduced Diesel fuel aromatic content would have other environmental and economic benefits which, if factored in, might help to improve its cost-effectiveness. The reduced aromatic content would improve the fuel's ignition quality, improving cold-starting and idling performance and reducing engine noise. The reduction in the use of catalytically cracked blending stocks should also have a beneficial effect on deposit-forming tendencies in the fuel injectors, reducing maintenance costs. On the negative side, however, the reduced aromatics might result in some impairment of cold-flow properties, due to the increased paraffin content of the fuel.

Fuel Additives

A number of well-controlled studies have demonstrated the ability of detergent additives in Diesel fuel to prevent and remove injector tip deposits, thus reducing smoke levels. The reduced smoke probably results in reduced PM emissions as well, but this has not been demonstrated as clearly, due to the great expense of PM emissions tests on in-use vehicles. Cetane-improving additives are also likely to result in some reduction in HC and PM emissions in marginal fuels. Claims for emissions benefits with specific fuel additives abound, and a moderate (perhaps 10 to 20 percent) reduction in PM emissions with a well-formulated cetane and detergency improving additive appears credible. Hard experimental data in heavy-duty engines to support these claims have been difficult to find, however. Therefore, while fuel additives may offer a modest but cost-effective reduction in Diesel emissions, such claims for any particular additive formulation should be supported by actual test data, preferably long-term comparative tests in heavy-duty DI engines.

5.5 Retrofitting Emission Controls

Attempts to retrofit emissions controls to light-duty vehicles in consumer service have been notably unsuccessful. Heavy-duty vehicles, due to their more intensive usage, represent a more attractive target for retrofits. A successful retrofit requires considerable care and engineering development work, however--it is not enough simply to "bolt on" some emissions control technology in the expectation that it will be effective. Proper design, prototype testing (including emissions testing), and manufacturing are required. Design and development will require at least the services of an experienced engine emissions laboratory, and preferably the assistance of the original equipment manufacturer. In most cases, the systems developed will be unique to a single engine or vehicle type.

Due to the expense involved in development, retrofits will generally be cost-effective only where a large number of vehicles of similar type and design are available for retrofit. Examples include transit bus fleets, garbage collection fleets, urban delivery fleets, etc. The highest priority for retrofit programs should probably go to transit buses and to other vehicles operating in congested urban areas, especially those with high-emission stop-and-go driving cycles. Such programs could best be undertaken, at least initially, on a voluntary or quasi-voluntary basis. Because of this, government-owned vehicle fleets are especially suitable. Given the present state of the technology, enforcement of a mandatory retrofit program for privately owned vehicles would be very difficult.

Engine Technologies

Possible engine retrofits to reduce emissions range from simple changes in settings to addition of new turbochargers and replacement of fuel injection systems.

Maximum fuel rate--Particulate emissions from naturally aspirated Diesel engines can often be reduced by simply derating the engine. The extent to which PM emissions are reduced depends on the initial smoke level and the extent of the derating. Where engines are not subject to smoke or PM emissions limits, manufacturers may establish maximum power ratings which require operation beyond the smoke limit. Smoke levels at high altitudes may be excessive even where sea-level smoke is low. In most cases, derating the engine by as little as 10% is enough to produce a drastic reduction in smoke and PM. The impact of this derating on the vehicle's intended use may be significant, however, and must be assessed on a case-by-case basis.

Turbocharger--An alternative to derating a naturally aspirated engine to reduce its smoke levels is to equip it with a turbocharger to provide extra air for combustion. This requires some care, however. Although many manufacturers produce both turbocharged and naturally aspirated versions of the same engine, the turbocharged engines often differ in compression ratio, injection timing, and piston design from their naturally aspirated brethren. Simply bolting a turbocharger onto the naturally aspirated version may unduly increase maximum cylinder pressures and possibly damage the engine. In most cases, it will be necessary to rebuild the engine with pistons, etc. intended for the turbocharged model. If the engine is in need of rebuilding anyway, the incremental cost to rebuild it in turbocharged form will generally be only about $500 to $1,500. Otherwise, the costs will be much higher.

One situation where it will often be feasible to "bolt on" a turbocharger without other modifications is where naturally aspirated engines are used exclusively at high altitude. In this case, the effect of the turbocharger is simply to restore the intake air pressure for which the engine the engine was designed for.

Fuel/air ratio controls--Fuel-air ratio controls are of two types: limits on the maximum fuel quantity injected, and acceleration smoke limiters in turbocharged engines. Maximum fuel quantity levels are adjustable on most types of fuel injection equipment, and could readily be reduced to limit excess smoke and PM emissions at full load. The cost of this adjustment would be very low, but it would result in some loss of power--possibly impairing the vehicle's ability to perform its intended functions.

Many turbocharged engines are already equipped with acceleration smoke limiters for reasons of consumer acceptance, even where these are not required by regulations. Where this is the case, more stringent smoke standards could be achieved simply by adjusting the control settings, at minimal cost. Even where acceleration smoke limiters have not been installed as original equipment, most fuel injection equipment manufacturers offer them as a standard option on their pumps. In many cases, therefore, it would be possible to retrofit smoke limiters to engines already in use. The cost of the additional parts required would be of the order of up to $150. Since it would be necessary to remove, disassemble, reassemble, and recalibrate the pump, labor costs would be fairly high, however, unless the pump needed to be removed and serviced anyhow.

Injection timing--Except where they are subject to stringent NOx controls (as in California), Diesel engine fuel injection timing is generally set to provide optimum fuel economy. Base injection timing on most Diesel engines is adjustable to some degree. By retarding the injection timing a few degrees, NOx may often be reduced 30 to 40%, at some cost in fuel economy and particulate emissions. The relationship between NOx and fuel economy/particulates depends on the specific engine model and calibration. Typically, however, the first few increments of NOx reduction have comparatively little impact, with the effects growing rapidly more severe after some point. By resetting the injection timing to optimize between NOx and PM emissions, it may be possible to obtain significant NOx reductions at relatively little cost.

Fuel injection system--As discussed in previous chapters, fuel injection technology has advanced considerably in recent years. Fuel injection pumps and nozzles suffer wear, and must be rebuilt or replaced every few years. By replacing the pump with a unit capable of higher injection pressures, and injection nozzles with improved designs, it may be possible to retard injection timing to reduce NOx while still reducing PMand HC emissions and possibly fuel consumption. Further benefits may be obtainable during engine overhaul by replacing the pistons with updated models optimized for use with the new injection system. Some U.S. engine manufacturers now offer standard "updating" kits to bring their older engine models up to the technology and performance levels of their current production.

Aftertreatment Technologies

Because they require little or no modification to the engine itself, aftertreatment technologies may be more cost-effective than in-cylinder emission controls in retrofit applications. The two aftertreatment technologies that appear most promising as retrofits are catalytic converters and particulate trap-oxidizers.

Catalytic converters--The advantages of catalytic converters for Diesel engines have already been discussed. Although ineffective in oxidizing Diesel soot, they can sharply reduce emissions of particulate SOF, HC, CO, aldehydes, and mutagenic compounds such as PNA and nitro-PNA. To avoid an increase in sulfate emissions, low-sulfur fuel would be required. As discussed above, however, low-sulfur fuel appears to be a highly cost-effective emissions control measure in any case.

Due to the lower temperature and combustible content of Diesel engine exhaust, catalytic converter temperatures would be much lower than in conventional gasoline engines, and thermal protection requirements would be minimal. The major cost in a retrofit program would be the catalytic converter itself, therefore. Given large scale production, this would probably be about $400 to $800 for typical heavy-duty Diesel vehicles.

Trap-oxidizers--A number of programs have been undertaken to retrofit trap-oxidizers to existing vehicles, with varying degrees of success. One successful program has occurred in Athens, Greece, where a number of buses have successfully been retrofitted with ceramic monolith traps and a manually controlled throttling regeneration system. Where (as in buses and other centrally-serviced fleets) periodic manual control of regeneration is possible, the difficult control and reliability problems that have plagued trap-oxidizer development can be significantly alleviated.

Even where manual control is not feasible, it appears likely that some manufacturers will soon be able to offer more-or-less stand-alone trap-oxidizer systems--including the trap, regeneration hardware, sensors, and control unit--in a form which could be suitable for retrofit applications. Much work is presently being done in this area, and the fruits of this work should be commercially available within a few years. The cost of such systems is presently unknown, but a range of about $1200 to $3000--depending on size and production level--appears reasonable.

Alternative Fuels

Diesel engines can be modified to burn ignition-improved methanol by replacing the fuel injection pump with one sized for the larger methanol quantities required, and resistant to methanol's corrosive effects. With somewhat more effort, spark ignition or glow-plug ignition may be used to ignite the methanol instead of additives. Diesel-derived methanol engines produce very little PM, and less NOx than a standard Diesel, but may produce unacceptable levels of aldehydes and unburned methanol. Diesel engines can also be modified fairly readily to utilize natural gas or LP gas, in either spark-ignition or dual-fuel modes. The combination of spark-ignition, very lean combustion, and an oxidation catalyst in the exhaust results in very low emissions of all pollutants. These technologies are discussed at greater length in Section 6.

5.6 Transportation Control Measures

Measures to reduce vehicle traffic should be considered in any program to reduce mobile-source emissions. Unfortunately, the scope for such measures is very limited where heavy-duty vehicles are concerned. Trucks are an essential component of urban commerce, and there is no obvious transportation mode available to replace them. The high costs of truck operation have already prodded most truck operators to eliminate unnecessary trips, and to use the smallest vehicle that can do the job effectively. The situation for buses is much the same--indeed, many programs to control light-duty vehicle traffic are likely to increase, not decrease, the use of transit buses. Replacement of buses with electric rail vehicles or trolley buses is seldom cost-effective. Alternative fuel vehicles using compressed natural gas or methanol are likely to prove a more economic alternative.

Changes in traffic patterns to improve the flow of traffic, and reduce time and fuel-consuming stop-and-go operation have some potential for heavy-duty Diesel emission reductions. For buses, establishment of special priority bus lanes, limitations on private car access to congested areas, and other traffic improvements have often proven very effective in reducing traffic congestion and delays (World Bank, 1988). By reducing stop-and-start operations as well as congestion, these measures can help considerably in reducing emissions as well.

In the case of heavy-duty trucks, regulations prohibiting operation during peak traffic hours could possibly be justified. Such regulations are now under consideration in Los Angeles. A requirement that truck deliveries to the most congested city areas be made only at night could also prove effective. A similar requirement has been in effect in New York for some time.

Changes in transportation patterns that reduce Diesel fuel consumption are also likely to reduce emissions. Since one large truck uses less fuel (and emits less) than two small ones, governments may wish to review truck size and weight regulations to assure that they are actually justified. Changing to alternative transport modes (such as piggyback rail service instead of long-distance trucking) may help to reduce the regional impacts of Diesel emissions. By concentrating trucking activity around one central point, however, such measures may significantly increase the local emissions impact.

6. ALTERNATIVE FUELS

The possibility of substituting cleaner-burning alternative fuels for Diesel fuel has drawn increasing attention during the last decade. Motivations advanced for this substitution include conservation of oil products and energy security, as well as the reduction or elimination of certain pollutant emissions such as particulate matter and visible smoke. Care is necessary in evaluating the air-quality claims for alternative fuels, however. While many alternative fuel engines do display greatly reduced particulate and SOx emissions, emissions of other gaseous pollutants such as unburned hydrocarbons, CO, and in some cases NOx and aldehydes may be much higher than from Diesels.

The principal alternative fuels presently under consideration are natural gas and methanol made from natural gas. Other fuels having present or potential local applications in heavy-duty vehicles include liquified petroleum gas (LPG) and ethanol from biomass. Table 11 compares some of the key physical and combustion properties of these fuels with those of gasoline and Diesel fuel.

This section provides an overview of all four alternatives as fuels for heavy-duty vehicles. The properties and characteristics of the fuels themselves are discussed, and the key issues surrounding their utilization are summarized. These issues include fuel cost and availability, utilization technologies, emissions tradeoffs, timing, and economics.

6.1 Natural Gas

Natural gas has many desirable qualities as an alternative to Diesel fuel in heavy-duty vehicles. Clean-burning, cheap, and abundant in many parts of the world, it already plays a significant vehicular role in a number of countries. Buses equipped with natural gas engines are now in series production in Brazil, and numerous heavy-duty vehicles around the world have been retrofitted to use this fuel. The major disadvantage of natural gas as a motor fuel is its gaseous form at normal temperatures.

Fuel Properties

Pipeline-quality natural gas is a mixture of several different gases. The primary constituent is methane, which typically makes up 90-95% of the total volume. Other, minor constituents include nitrogen, carbon dioxide, higher hydrocarbons such as ethane and propane, and traces of hydrogen sulfide and water. The presence of these minor constituents has some effect on the actual properties of the gas, but for most

Table 11
Properties of Alternative and Conventional Fuels

	Diesel	Gasoline	Methanol	Ethanol	Propane	Methane
Energy Content (HHV MJ/kg)	45.15	43.65	23.86	29.73	50.37	55.53
Liquid Density (kg/l)	.843-.848	~.735	.7914	.7843	.5077	.4225
Energy Density of Liquid (MJ/l)	38.16	32.1	18.9	23.32	25.6	23.46
Energy Density of Gas (MJ/l)						
@ STP*	---	---	---	---	---	0.036
@ 200 BAR	---	---	---	---	---	7.47
Normal Boiling Point °C	140-360	37-205	65	79	-42.15	-161.6
Research Octane No.	~25	91-97	112	111	125	130
Cetane No.	45-55	0-5	5	5	~2	0

*standard temperature and pressure

practical purposes natural gas can be treated and analyzed as pure methane.

Methane is a nearly ideal fuel for Otto-cycle (spark-ignition) engines. As a gas under normal conditions, it mixes readily with air in any proportion, eliminating cold-start problems and the need for cold-start enrichment. It is flammable over a fairly wide range of air-fuel ratios. With a research octane number of 130 (the highest of any commonly used fuel), it can be used with engine compression ratios as high as 15:1 (compared to 8-9:1 for gasoline), thus giving greater efficiency and power output. The low lean flammability limit permits operation with extremely lean air-fuel ratios--having as much as 60% excess air. On the other hand, its high flame temperature tends to result in high NOx emissions, unless very lean mixtures are used.

Because of its gaseous form and poor self-ignition qualities, methane is a poor fuel for Diesel engines. Since Diesels are generally somewhat more efficient than Otto-cycle engines, natural gas engines are likely to use somewhat more energy than the Diesels they replace.

The high compression ratios achievable with natural gas limit this efficiency penalty to about 10% of the Diesel fuel consumption, however. In many cases, the increase in energy consumption is more than offset by the lower cost of gas, resulting in a net savings in fuel costs.

The fact that methane is a gas under normal conditions creates significant problems with fuel storage aboard the vehicle. At present, natural gas is stored either as a gas in high-pressure cylinders or as a cryogenic liquid in an insulated tank. Both forms of storage are considerably heavier, more expensive, and bulkier than storage for an equivalent amount of Diesel fuel. The costs of compressing or liquifying natural gas in order to store it are also substantial, in some cases more than offsetting its lower cost.

Engine Technology and Emissions

Although an excellent fuel for Otto-cycle engines, natural gas is not suitable by itself as a fuel for Diesels. Options for using natural gas in heavy-duty vehicle engines are thus limited to the following:

- Fumigation, or mixing the gas with the Diesel intake air to be ignited by Diesel fuel injected in the conventional way;

- Conversion of the existing Diesel engine to Otto cycle operation; or

- Replacement of the Diesel engine with a conventional spark-ignition engine.

These options are discussed below.

Fumigation--The simplest way to use natural gas in a Diesel engine is simply to mix it with the intake air. Injection and combustion of the Diesel fuel then ignites and burns the alternate fuel as well. Since the gas supplies much of the energy for combustion, the Diesel fuel delivery for a given power level is reduced. This results in reduced smoke and particulate (PM) emissions at high load, and can increase the smoke-limited power of the engine. However, incomplete combustion (especially at light loads) usually increases CO and HC emissions considerably. The increased HC emission are of less concern with natural gas than with other hydrocarbon fuels, since the principal component, methane, is non-toxic and has very low photochemical reactivity. On the other hand, methane is a very active greenhouse gas, and the other, minor components of the HC emissions include some formaldehyde as well as higher hydrocarbons.

Fumigated engines are normally set up to idle on Diesel fuel only, with the gas being added in increasing amounts at higher loads, and the amount of Diesel fuel injected per stroke (the "pilot" fuel quantity) kept constant. The pilot fuel quantity required to ensure good combustion in a fumigated engine is of the order of 5 to 20% of the full-load energy consumption of the engine. Near full load, up to 95% of the total fuel energy can be supplied by the gas, but at lower loads, much more Diesel energy is required to ensure good combustion. Because idling and light-load operation account for a large part of total engine fuel consumption, it is typically possible to substitute natural gas for only about 40-70% of the total energy consumption.

The major advantage of the fumigation technique is the fact that no major modifications are required to the engine, making it easy to install in an existing vehicle. A number of commercial kits for converting Diesel engines to dual fuel operation are available. The major disadvantages of the fumigation approach are the fact that only partial substitution is possible, and the large increases in HC and CO emissions that may result. The need for two fuel supply systems adds cost and weight, and creates additional safety hazards. The fact that a large part of the energy is still provided by Diesel fuel also limits the emissions benefits. Although fumigation greatly reduces smoke and particulate emissions at full load, the interaction between the gaseous fuel and the pilot may actually increase particulate production at lower loads. Thus, the net effect on particulate emissions will depend on the duty cycle.

Spark-ignition engines--Natural gas fueled, spark-ignition versions of heavy-duty truck Diesel engines have been used for stationary applications for many years, and a number of similar conversions have been carried out with vehicular engines. The modifications required to convert a Diesel engine to Otto-cycle operation are machining the cylinder head to accept a spark plug instead of a fuel injector; redesign of the pistons to reduce the compression ratio; replacement of the fuel injection pump with an ignition system and distributor; replacement of exhaust valves and valve seats with wear resistant materials; and addition of a carburetor (or fuel injection system) and throttle assembly.

For new engines, these changes involve only minor changes in the existing Diesel manufacturing process, and would be economic even on a very small scale. MAN, Saab-Scania, Daimler-Benz, Caterpillar, and Cummins, among others, have produced such engines on a demonstration or small-volume production basis. This conversion can also be performed on an existing Diesel engine, at a cost comparable to that of a major overhaul. A number of such conversions have been performed in New Zealand, Australia, and Brazil.

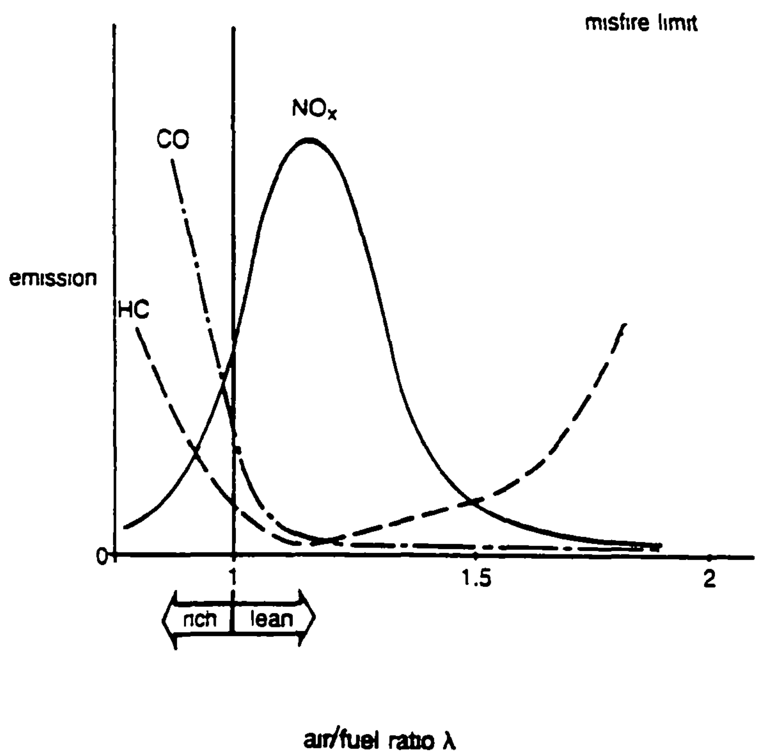
Current heavy-duty Otto-cycle engines can be divided into two groups: "rich burn" and "lean-burn". Conventional stoichiometric or "rich burn" engines operate with the air-fuel ratio λ close to or even somewhat less than 1.0. The rich-burn approach provides the maximum power output for a given engine displacement and turbocharging level, at some cost in fuel economy.

"Lean-burn" engines operate with λ in the range of 1.4 to 1.6, or even higher where stratified-charge techniques are used. Since lean mixtures knock less readily than stoichiometric ones, these engines can use higher compression ratios. Throttling losses in the lean-burn engine are also lower at a given power level, since a given amount of fuel occupies a larger volume of mixture. All of these effects help to increase the thermodynamic efficiency of the lean-burn engine compared to a rich-burn type. Lean-burn natural gas engines used in stationary applications commonly attain thermal efficiencies at full load comparable to those of Diesels.

The choice between lean-burn and rich-burn has an important effect on emissions. Figure 8 shows the typical relationship between HC, CO, and NOx and λ for Otto-cycle engines. CO emissions are governed by oxygen availability, while NOx emissions are primarily a function of flame temperature. For natural gas engines, the peak NOx emissions at λ = 1.1 are in the range of 20 to 30 grams per BHP-hr. Typical NOx emissions at stoichiometry (λ = 1) are about 10 to 15 g/BHP-hr. This can be reduced to less than 2 g/BHP-hr, however, through the use of a three-way catalyst and closed-loop mixture controls like those on light-duty passenger cars. The durability of such catalysts under the high temperatures experienced in heavy-duty operation is doubtful, however. The durability of electronic control systems under heavy-duty conditions is also unproven.

Figure 8

Typical Variation of Emission Levels with Air-Fuel Ratio λ
for an Otto-Cycle Engine
(Source: Bergmann and Busenthur, 1986)



An alternative approach to NOx control is to operate very lean. At $\lambda = 1.5$, which is about the limit for smooth running with normal ignition systems, the lower flame temperature results in NOx levels around 3.5 to 4.5 g/BHP-hr. Through the use of high-energy ignition systems and careful optimization, homogeneous mixtures with λ as lean as 1.6 can be burned. NOx emissions from such engines are typically in the 2 g/BHP-hr range. The drivability of such engines under transient conditions has not yet been demonstrated, however. The lean combustion limit can be extended even further by using a stratified charge. Stationary engines using this technique have demonstrated NOx emissions less than one g/BHP-hr.

To avoid excessive smoke, Diesel engines are designed to run at rather lean air-fuel ratios, with λ typically in the range of 1.5 to 1.8 at full power. They are well-adapted, therefore, to lean-burn operation on natural gas, and can typically match or exceed their Diesel power rating. Stoichiometric operation, with its higher exhaust temperatures, is likely to lead to valve and turbocharger problems, however.

Existing Otto-cycle engines, on the other hand, are designed for near-stoichiometric operation. Lean-burn operation in these engines is likely to result in a significant power loss. In addition, these engines typically lack the mechanical strength and other design features required to take full advantage of the high compression ratios possible with natural gas. Thus, the fuel efficiency of gasoline-type engines converted to natural gas is likely to be considerably less than that of a Diesel-engine-based lean-burn engine.

Fuel Storage and Refueling

Natural gas may be stored on-board a vehicle either as a compressed gas in high-pressure cylinders or as a cryogenic liquid. Although both processes are expensive and energy-intensive, compression is much less so than liquefaction. The current maximum working pressure for CNG cylinders is 3,000 PSIG (200 bar). The volumetric energy content of natural gas at this pressure is about one-fifth that of Diesel fuel, while that of LNG is a little over half that of Diesel.

The high-pressure cylinders needed for CNG weigh more and occupy more space than the vacuum-insulated tanks used for LNG, but the cost of the two storage systems is about the same. The lesser weight and volume required by LNG tanks is a critical advantage in some applications (e.g., long-distance hauling). For typical urban vehicles, however, there is sufficient unused space between the frame rails to accommodate enough CNG cylinders for a full day's operation with some reserve.

A major drawback of LNG storage is the need to provide for venting of gas. As the tanks are not perfectly insulated, some heat leaks in. During normal operation, this heat is removed by drawing off the vapor above the tank, thus cooling the liquid by evaporation. Upon prolonged standing, however, pressure builds up in the tank. While the tank is capable of withstanding 20-40 atmospheres, it must eventually vent the excess vapor. For available tank designs, the standing time before this occurs is of the order of a week (Deluchi et al., 1988).

Two types of CNG refueling systems are in common use: slow-fill and quick-fill. In the slow-fill approach, the fuel tanks of all vehicles at a given facility are connected to a common fuel manifold. A compressor pumps high-pressure gas through the manifold into all of the tanks simultaneously (usually overnight). This system is well suited to the operating patterns of buses and other fleet vehicles which return to the same location each night. In the alternative, quick-fill system, the compressor is connected to one vehicle at a time, in sequence, in the same way as a Diesel refueling pump. The refueling rate is then limited by the capacity of the compressor. As compressor capacity is the major cost in a CNG system, rapid refueling by this means can be very expensive. Often, quick-fill systems will include a small amount of high-pressure gas storage, arranged in a "cascade" system. With this approach, vehicles can be refueled quickly from the cascade, which is then recharged more slowly by the compressor.

Fuel Supply and Costs

After coal, natural gas is the most abundant fossil fuel. The ratio of proven gas reserves to annual production is double that of petroleum, and a larger fraction of world gas reserves than petroleum reserves are found outside the Middle East. Today, most major urban centers and many minor ones in industrial countries are served by a large network of gas pipelines.

Transport and distribution of natural gas by pipeline is a well-developed and relatively low-cost technology. Use of compressed natural gas (CNG) from pipelines as a vehicular fuel is also well-developed in Italy (where it has been used for more than 40 years), Canada, and New Zealand. Other technologies for natural gas transportation and distribution include liquefaction and shipment in liquid form (LNG), and short-distance transport of CNG in large banks of cylinders. Japan and many countries of Western Europe now import significant quantities of natural gas in the form of LNG.

Owing to the difficulty of transportation, the costs of natural gas vary greatly from country to country, and even within countries. Where gas is available by pipeline from the field, its price is normally set by competition with residual fuel oil or coal as a burner fuel. The market-clearing price of gas under these conditions is typically about $3.00 per million BTU (equivalent to about $0.41 per gallon of Diesel fuel equivalent). Compression costs for CNG use can add another $0.50 to $2.00 per million BTU, however, depending on the size of the facility and the natural gas supply pressure. The higher the pipeline supply pressure of the gas, the lower the capital and operating costs of the compression facility.

The cost of LNG varies considerably, depending on specific contract terms (there is no effective "spot" market for LNG). The cost of small-scale liquefaction of natural gas is about $2.00 per million BTU, making it uneconomic in comparison to CNG in most cases. Where low-cost remote gas is available, however, LNG production can be quite economic. Typical 1987 costs for LNG delivered to Japan were stated as about $3.20 to $3.50 per million BTU (Oil and Gas Journal, 1988). The costs of terminal receipt and transportation would probably add another $0.50 or so to this cost at the wholesale level. Compression costs would be nil, however, since LNG could either be used directly, or converted directly to CNG by allowing it to vaporize under pressure. The costs of LNG for vehicular fuel (given that a nation was importing LNG anyway) would thus be comparable to those of CNG.

Capital and Maintenance Costs

Lean-burn natural gas engines based on Diesel engine designs should cost no more to manufacture than the parent Diesel, if produced in moderate quantity. Additional capital costs for new vehicles, therefore, would be limited essentially to the extra costs of the fuel storage. For heavy-duty vehicles using CNG, the additional cost of the cylinders would amount to about $2,000 to $5,000, depending on vehicle size and range requirements. The costs of LNG tanks would probably be similar, but such tanks are not commercially available at present.

To retrofit an existing Diesel vehicle for lean-burn operation using CNG would be more expensive. Assuming that a large number of vehicles were to be converted, the costs per vehicle would probably range from about $5,000 to $10,000, with about half of the cost being due to the CNG storage system.

Maintenance costs for natural gas engines based on Diesel engine components should be lower than those for the parent Diesel. Due to the clean-burning nature of the fuel, oil-change intervals can be extended, and the engine life is likely to be considerably longer than with Diesel fuel. The added costs of maintaining spark plugs, ignition systems, and fuel storage systems would be offset by the avoided costs of fuel injection system maintenance. Other maintenance costs should be essentially the same between the two technologies.

Current Activities

The use of natural gas in heavy-duty vehicle engines is the subject of a fair amount of activity around the world. Commercial kits for converting Diesels to dual fuel operation are available in the U.S. and Europe. A number of heavy-duty truck and bus engines have been converted to natural gas spark-ignition operation in New Zealand, Australia, and Brazil. In Brazil, Daimler-Benz AG is producing new natural-gas fueled engines and buses on its production lines for domestic use. Cummins Engine Co. in the U.S. is developing a lean-burn, spark-ignition conversion of its L-10 bus engine, with a view toward compliance with the U.S. 1991 transit bus emissions regulations. Several other heavy-duty Diesel engine manufacturers have demonstrated spark-ignition conversions of their existing Diesel engine models, although only Daimler-Benz is currently producing such engines for vehicular use.

6.2 Liquified Petroleum Gas (LPG)

Liquified petroleum gas is already widely used as a vehicle fuel in the U.S., Canada, the Netherlands, and elsewhere. As a fuel for spark-ignition engines, it has many of the same advantages as natural gas, with the additional advantage of being easier to carry aboard the vehicle. Its major disadvantage is the limited supply, which would rule out any large-scale conversion to LPG fuel.

Fuel Properties

Liquified petroleum gas or LPG is typically a mixture of several gases in varying proportions. Major constituent gases are propane (C_3H_8) and normal butane (C_4H_{10}), with minor quantities of propylene and other hydrocarbon gases. Because of its superior knock-resistance, propane is preferred to butane or propylene as an automotive fuel.

Propane presents a useful combination of combustion and storage properties. Like methane, it is a gas at normal temperatures and pressures, and thus mixes readily with air in any proportion. Cold starting is not a problem, therefore, and cold-start enrichment is unnecessary. Propane's research octane rating of 125, while somewhat lower than that of methane, is still much higher than gasoline, and permits the use of compression ratios in the range of 11-12:1. The lean combustion limit of propane-gasoline mixtures is also considerably leaner than for gasoline, allowing the use of lean-burn calibrations which increase efficiency and reduce emissions. These mixtures are also more resistant to knocking, permitting the use of still higher compression ratios. This is risky, however, as inadvertent contamination with butane (which is denser and has a lower octane value) can cause destructive detonation in the engine.

Engine Technology and Emissions

The technologies available for LPG are the same as those available for natural gas: fumigation, or spark ignition using either stoichiometric or very lean mixtures. Due to the lower octane value of LPG, the compression ratio (and thus the thermal efficiency) possible with this fuel in spark-ignition operation is lower than with natural gas, although still considerably higher than with gasoline. Aside from this, the engine technologies involved are very similar. Due to the lower octane value (and higher photochemical reactivity) of LPG, however, it is not as good a candidate for use in fumigation as natural gas.

Like natural gas, LPG in spark-ignition engines is expected to produce essentially no particulate emissions (except for a small amount of lubricating oil), very little CO, and moderate HC emissions. NOx emissions are a function of the air-fuel ratio, λ. LPG does not burn as well under very lean conditions as natural gas, so the NOx levels achievable through lean-burn technology are expected to be somewhat higher--probably in the range of 3 to 5 g/BHP-hr. For stoichiometric LPG engines, the use of a three-way catalyst and closed-loop air-fuel mixture control results in very low NOx emissions (Van der Weide et al., 1988), assuming that such systems can be made sufficiently durable.

Fuel Storage and Handling

Propane is stored on the vehicle as a liquid under pressure. Propane tanks, since they must contain an internal pressure of 20-40 atmospheres, are generally cylindrical with rounded ends, and are much stronger than tanks used for storing gasoline or Diesel fuel, albeit much less so than those used for CNG. Propane can be pumped from one tank to another like any liquid, but the need to maintain pressure requires a gas-tight seal. Except for the need for a standardized, gas-tight connection, propane used as vehicle fuel can be dispensed in much the same way as gasoline or Diesel fuel. To ensure that some vapor space is always available for expansion, propane tanks used in automotive service must never be filled more than 80% full. Automatic fill limiters are incorporated in the tanks to ensure that this does not occur.

Fuel Supply and Costs

LPG is produced in the extraction of heavier liquids from natural gas, and as a byproduct in petroleum refining. Presently, LPG supply exceeds the demand in most petroleum-refining countries, so the price is low compared to other hydrocarbons. Wholesale prices for consumer-grade propane in the U.S. have ranged between $0.25 and $0.30 for several years, or about 30% less than the wholesale cost of Diesel on an energy basis. Depending on the locale, however, the additional costs of storing and transporting LPG may more than offset this advantage. Differences in road taxes, sales taxes, etc. between LPG and Diesel may also have an important effect on the economics as perceived by private consumers. Such taxation differences do not affect the social cost, however.

Because the supply of LPG is limited, and small in relation to other hydrocarbon fuels, any large-scale conversion of heavy-duty vehicles to LPG use would likely absorb the existing glut, causing prices to rise. For this reason, LPG probably makes the most sense as a special fuel for use in vehicles, such as urban buses and delivery trucks, operating in especially pollution-sensitive areas.

Capital and Maintenance Costs

The costs of producing lean-burn LPG engines based on Diesel engine designs should be no more than the costs of the existing Diesels. While LPG storage tanks are somewhat more expensive than Diesel fuel tanks, this difference would amount to no more than a few hundred dollars in a heavy-duty vehicle. For practical purposes, therefore, the capital costs of Diesel and LPG vehicles can be considered to be equivalent. To convert an existing Diesel vehicle to LPG operation would be somewhat more expensive, however. If done on a relatively large scale, the cost per vehicle would probably range from about $2,000 to $6,000, depending on vehicle size and configuration.

The maintenance costs of heavy-duty vehicles using LPG fuel should be essentially the same as those for natural gas vehicles. Extended oil change intervals and engine life would be major benefits of a switch to LPG fuel.

Current Activities

Several hundred LPG-fuelled city buses are now in use in Vienna, Austria. The engines for these buses are spark-ignition conversions of the MAN Diesel bus engine (this engine has also been adapted to methanol and natural gas). Research on heavy-duty LPG engines is also underway at TNO in the Netherlands, in New Zealand, and in Canada. LPG conversions of light and heavy-duty spark-ignition engines have been routine for some time, and several hundred thousand such vehicles are in use around the world.

6.3 Methanol

Widely promoted in the U.S. as a "clean fuel," methanol in fact has many desirable combustion and emissions characteristics, including good lean combustion characteristics and relatively high octane (both of which can lead to high efficiency), plus low flame temperature (leading to low NOx emissions) and low photochemical reactivity. One drawback of methanol as a fuel is its cost--it is highly variable, and will probably be somewhat higher than Diesel fuel. Methanol is produced in rather small volumes, and there have recently been some rather large but volatile new demands such as for MTBE production. As a result, spot prices in the last few years have varied between about $0.25 and $0.75 per gallon.

As little as one methanol plant coming on-line or off-line can markedly alter methanol spot prices, making long term planning difficult. However, a recent EPA report (EPA, 1989) has estimated that, with large-scale production, fuel methanol could be produced and landed in the U.S. at a total cost of $0.30 to $0.40 per gallon. Other estimates are generally higher. Because of the differences in energy content per gallon between Diesel and methanol fuels, an engine would consume more than 2.2 times as much methanol as Diesel fuel per mile. This must be considered when comparing future fuel prices. For example, if current methanol prices were $0.30 per gallon, methanol would be more expensive on an energy basis than Diesel fuel at the present bulk price of approximately $0.60 per gallon.

Fuel Properties

As a liquid, methanol can either be burned in an Otto-cycle engine or injected into the cylinder as in a Diesel. With a fairly high research octane number of 112, and excellent lean combustion properties, methanol is a good fuel for lean-burn Otto-cycle engines. Its lean combustion limits are similar to those of natural gas, while its low energy density results in a low flame temperature compared to hydrocarbon fuels, and thus lower NOx emissions. Methanol burns with a sootless flame and contains no heavy hydrocarbons. As a result, particulate emissions from methanol engines can be very low--consisting essentially of unburned lubricating oil.

Methanol's high octane number results in a very low cetane number, so that methanol cannot be used in a Diesel engine without some supplemental ignition source. Investigations to date have focused on the use of ignition-improving additives, spark ignition, glow-plug ignition, or dual injection with Diesel fuel. Converted heavy-duty Diesel engines using each of these approaches have been developed and demonstrated.

The low energy density of methanol means that a large amount (more than 2.2 times the mass of Diesel fuel) is required to achieve for the same power output. The high heat of vaporization of methanol, combined with the large amounts required, makes it difficult to ensure complete vaporization in Otto-cycle engines, and requires special attention to the design of intake manifolds and cold-start procedures. Current Otto-cycle engine designs using liquid methanol become nearly impossible to start below about 5° C without the use of special pilot fuels or supplemental heating techniques. Engines using Diesel-type direct liquid injection (and glow plugs) do not have this problem, and are frequently easier to start than the parent Diesels under cold conditions.

Most methanol sold in commerce is of chemical grade. For chemical purposes, methanol is required to be very low in dissolved water, and essentially free of hydrocarbons. Methanol used as motor fuel does not require the same high standards of purity, and could thus be produced and handled more cheaply than chemical-grade methanol. The admixture of substantial quantities of higher alcohols, one or two percent of hydrocarbons, and/or as much as 2% dissolved water would have little adverse effect, other than changes in volumetric energy content.

Engine Technology and Emissions

Options for methanol utilization in heavy-duty engines include both Otto-cycle and Diesel-cycle operation. As a liquid, methanol can readily be injected directly into the cylinder, in the same way as Diesel fuel in a Diesel engine. It can also be atomized, vaporized, or chemically reformed and mixed with the air charge, in the same way as gasoline in a conventional spark-ignition engine.

Otto-cycle--When burned in an Otto-cycle engine, methanol performs similarly in many respects to natural gas or LPG. The major differences are the lower flame temperature (which reduces NOx emissions by about half from those experienced with hydrocarbon fuels at the same air-fuel ratio), and the fact that liquid methanol must be vaporized and mixed thoroughly with air before it burns. One approach used by Daimler-Benz is to vaporize the methanol before mixing it with the air, using a separate vaporization system, and then burn it as a lean mixture in a Diesel engine converted to spark ignition. This results in HC and CO emissions very similar to those of similar engines using natural gas or propane (Bergmann and Busenthur, 1986). (Note that "HC" emissions for methanol engines are mostly unburned methanol, which shows less photochemical reactivity than propane, but more than natural gas.) Where methanol is mixed with the air as a liquid, somewhat higher HC and CO emissions would be expected, especially under cold start conditions. Methanol can also be used in stoichiometric, closed-loop combustion systems such as those found in light-duty vehicles. There is little information available on the performance of these systems under heavy-duty conditions, however.

Diesel injection--Recent development activities in the area of heavy-duty methanol engines have focussed on Diesel injection techniques, due to the greater fuel-efficiency possible with this approach. Although methanol can be injected into the cylinder as in a Diesel engine, the Diesel injection pump supplied with the engine would not be suitable in most cases. Since about 2.2 times as much methanol as Diesel fuel is required to supply the same amount of energy, a larger volumetric capacity is required. In addition, Diesel injection pumps are fuel-lubricated. Since methanol is a poor lubricant, a separate oil supply to the pump would be required. Other changes to the high-pressure lines, injector nozzles, and so forth are required to prevent cavitation and premature wear. All of these changes are straightforward, however, and injection pumps suitable for use with methanol have been produced for research and development purposes

Due to its poor cetane number, methanol will not self-ignite reliably in a Diesel engine; thus, some form of ignition assistance is required. Ignition approaches that have been demonstrated include spark plugs, glow plugs, dual injection with "pilot" Diesel fuel, and the use of ignition-improving additives mixed with the methanol. All of these approaches can produce thermal efficiencies as high or higher than those of a conventional Diesel with similar levels of HC and aldehyde emissions, low NOx and CO, and (except with pilot injection) virtually no particulate matter.

Of the four ignition techniques, the spark plugs and ignition-improving additives appear most attractive. Diesel pilot injection suffers from many of the drawbacks discussed above in the case of fumigation, particularly the limited potential for fuel substitution and emissions control. In addition, the need for two separate fuel injection and supply systems adds considerable complexity and expense. Glow plugs consume much more energy than spark plugs and are harder to control, and present designs have much shorter service lives. They are also slower to ignite the fuel, reducing engine efficiency somewhat. Although spark plugs require a high-voltage ignition system and major changes to the cylinder head, their advantages are considered to outweigh these drawbacks.

Perhaps the most technically attractive approach to igniting the methanol is the use of ignition-improving additives such as organic nitrates. With these additives, methanol can be used in the same way as Diesel fuel, with no need for external energy sources for ignition. This approach would also involve minimal modifications to the engine, as it would be necessary only to replace the fuel injection pump and related components. The cylinder head, pistons, and other internal engine components could be left in the same configuration as for the Diesel engines. This would allow a ready conversion back to Diesel fuel, if required, and (in an emergency) the engine could even be run on Diesel fuel in the methanol configuration.

Concerns with the ignition improver approach include the costs of the additive, and potential effects on emissions. Currently available additives have demonstrated effectiveness at concentrations of 0.5 to 5% by volume, so that even a fairly expensive additive would have a limited effect on total cost. One supplier quoted a rough cost for large quantities of a commercial additive ("Avocet") of about $1,300 per ton. Blended at a rate of 1%, this would add about $.02 per liter to the cost of the finished product. Tests have also shown no adverse effects on pollutant emissions due to the use of this additive.

Emissions--Methanol combustion does not produce soot, so particulate emissions from methanol engines are limited to a small amount of lubricating oil. Methanol's flame temperature is also lower than that for hydrocarbon fuels (at the same λ ratio), resulting in NOx emissions which are typically 50% lower. CO emissions are generally comparable to or somewhat greater than those from a Diesel engine (except for stoichiometric Otto-cycle engines, for which CO emissions may be much higher). These emissions can be controlled with a catalytic converter, however.

The major pollution problems with methanol engines come from emissions of unburned fuel and formaldehyde. Methanol (at least in moderate amounts) is relatively innocuous--it has low photochemical reactivity, and--while acutely toxic in large doses--displays no significant chronic toxicity effects. Formaldehyde, the first oxidation product of methanol, is much less benign, however. A powerful irritant and suspected carcinogen, it also displays very high photochemical reactivity. While all combustion engines produce some formaldehyde, some early-generation methanol engines exhibited greatly increased emissions compared to Diesels (Ullman and Hare, 1982). Recent progress, however, has been such that engine-out emissions are only slightly above Diesel-equivalent levels.

The potential for large increases in formaldehyde emissions with the widespread use of methanol vehicles has raised considerable concern about what would otherwise be a relatively benign fuel from an environmental standpoint. It remains to be seen if the formaldehyde increase from Diesel levels becomes in fact a major problem.

Formaldehyde emissions can be reduced through changes in combustion chamber and injection system design, and are also readily controllable through the use of catalytic converters, at least under warmed-up conditions. A significant problem with the catalytic converter approach (especially for Diesels) is that--at low temperatures--certain precious metal catalyst formulations can actually increase emissions of formaldehyde considerably. This occurs through the catalytic partial oxidation of methanol in the exhaust. If methanol emissions are high (as they tend to be during cold operation) and the catalyst temperature is low, the resulting formaldehyde emissions could present an acute problem. Efforts to resolve this problem are focussing on special low-formaldehyde catalysts, and on minimizing unburned methanol emissions. These efforts, are promising, and have demonstrated control of formaldehyde to roughly Diesel equivalent levels.

Fuel Storage and Handling

As a liquid at normal temperatures and pressures, methanol presents few special storage or handling problems other than those of materials compatibility. Methanol is corrosive to some aluminum alloys, lead, and zinc; so these materials must not be used in methanol-handling equipment. It also attacks many of the elastomeric sealing materials that are commonly used with hydrocarbons, causing them to swell and crack. The use of methanol-tolerant elastomers and other materials is required. Although pure methanol is relatively uncorrosive of carbon steel, the addition of water (as in fuel-grade methanol) increases the corrosive effect. The use of anti-corrosive additives in fuel methanol may be necessary in order to avoid excessive corrosion of storage and distribution equipment. Otherwise, methanol shares the advantage of ease of storage and handling with other liquid fuels.

Fuel Supply and Costs

Methanol can be produced from natural gas, coal, or biomass. At current and foreseeable prices, the most economical feedstock for methanol production is natural gas, especially natural gas found in remote regions where it has no ready market. The current world market for methanol is as a commodity chemical, rather than a fuel, and world methanol production capacity is limited and projected to be tight at least through the mid-90s. Any large-scale conversion of vehicles to methanol fuel would require new methanol production capacity to be built if prices were not to rise significantly.

U.S. methanol prices are commonly quoted FOB the U.S. Gulf Coast. The price of methanol on the world market has fluctuated dramatically in the last decade, from around $0.25/gallon in the early 1980's to $.60-.70 in 1988, and back to $0.25 at the present time. The lower prices reflect the effects of a glut; while the higher prices reflect a temporary shortage.

Economies of scale and the lower quality requirements for fuel methanol are expected to make its production somewhat less costly than chemical methanol. A recent EPA report (EPA, 1989), using capital and transportation cost estimates developed by Bechtel Corporation, estimates that fuel methanol could be produced for $0.25-0.35 per gallon. This study assumed that remote natural gas resources, without another market, would be available at a price of $0.50 to $1.00 per million BTU. Transportation by tanker to consumption centers in the U.S. was estimated to add another $0.05 per gallon, for a total landed cost estimated at $0.30 to $0.40 per gallon. Other estimates based on the same data place this range at $0.36-$0.41 (California Energy Commission, 1989). For comparison, the landed price of Diesel fuel (with 2.2 times as much energy per gallon) is approximately $0.60 in early 1990.

In addition to new methanol supply capacity, any large-scale use of methanol for vehicle fuel would require substantial investments in fuel storage, transportation, and dispensing facilities, which would further increase the delivered cost of the fuel. EPA estimates that long-range and local distribution from the point of entry would add $0.03 per gallon to the cost of the methanol delivered to the service station. Since 2.2 times as much methanol as Diesel would have to be delivered, this would result further increase the difference in costs. Differences in actual retail price are much harder to estimate, as they would depend on the markup demanded (which in turn would depend on the competitive situation), as well as any differences in taxation.

Capital and Maintenance Costs

In volume production, the costs of a methanol-fueled vehicle using an Otto-cycle engine would probably be about the same as those of a Diesel. For a methanol-Diesel engine, the costs would be several hundred dollars higher (or about 2 to 5%), due to the added cost of the more sophisticated fuel injection equipment and the ignition system. Retrofit costs for either system are estimated at about $2,000 to $6,000 per vehicle, depending on the vehicle type and requirements.

Maintenance costs with methanol-fueled engines could be higher than those for Diesels. Methanol combustion products are fairly corrosive, and experience with certain engine designs tested to date suggests that engine life for these designs is likely to be considerably shorter. Other designs have experienced no significant added wear. Oil change intervals may also need to be shortened to counteract the increased corrosiveness of the combustion products. Fuel injection equipment in most methanol-Diesel engines tested to date has suffered frequent blockage due to deposits, and may also wear out more quickly than in the standard engine, due to the poor lubricating qualities of methanol.

Current Activities

Much work on heavy-duty methanol engines is underway in the U.S., where methanol has been targeted for some time as the alternative fuel of choice. Nearly 100 methanol buses are in use in various demonstration fleets in the U.S. Most of these buses are equipped with Detroit Diesel two-stroke Diesel engines using compression-ignition (augmented by glow plugs at light loads). Detroit Diesel Corporation has stated publicly that it plans to offer only these engines for use in buses subject to the U.S. 1991 bus emissions standards. A significant number of MAN methanol-Diesel engines using spark-ignition are also in operation.

Daimler-Benz has demonstrated the use of methanol with ignition-improving additives in a number of engines in South Africa and elsewhere; and Cummins Engine in the U.S. is using the same approach to develop a methanol-Diesel version of its L-10 bus engine. Two such engines are currently being demonstrated as part of the MILE (Methanol in Large Engines) program in Canada. Two Caterpillar methanol-Diesel engines, using glow-plug ignition, are also being demonstrated in that program.

6.4 Ethanol

Ethanol has attracted considerable attention as a motor fuel due to the success of the Brazilian Proalcool program. Despite the technical success of this program, however, the high cost of producing ethanol (compared to hydrocarbon fuels) means that it continues to require heavy subsidization.

Fuel Properties

As the next higher of the alcohols in molecular weight, ethanol resembles methanol in most combustion and physical properties. The major difference is in the higher volumetric energy content of ethanol. Fuel grade ethanol, as produced in Brazil, is produced by distillation, and contains several volume percent of water.

Engine Technology and Emissions

Technology for ethanol utilization in heavy-duty engines is essentially the same as for methanol. Both Otto-cycle engines and ethanol-Diesel engines (using spark ignition, glow plugs, or ignition-improving additives) have been developed. Emissions from these engines are not well characterized, but are believed to be high in unburned ethanol, acetaldehyde, and other aldehydes. These could presumably be controlled with a catalytic converter (subject to the concerns regarding aldehyde production discussed above for methanol). NOx emissions are somewhat higher than for methanol, but still considerably lower than for Diesel engines. Particulate emissions, as for methanol engines, should be effectively nil.

Fuel Supply and Costs

Ethanol is produced primarily by fermentation of starch from grains or sugar from sugar cane. As a result, the production of ethanol for fuel is in direct competition with the food production in most countries. The resulting high price of ethanol (ranging from $1.00 to $1.60 per gallon in the U.S. in the last few years) has effectively ruled out its use as a motor fuel for any but very specialized applications.

The Brazilian Prooalcool program to promote the use of fuel ethanol in motor vehicles in that country has attracted worldwide attention as the most successful example of an alternative fuel implementation program extant. Despite the availability of a large and inexpensive biomass resource, however, this program still depends on massive government subsidies for its viability, and cannot be considered a success in any economic sense.

Capital and Maintenance Costs

Capital costs for ethanol-fueled heavy-duty vehicles should be essentially the same as those for methanol vehicles. Maintenance costs should be somewhat lower, however. Ethanol's combustion products are less corrosive than those of methanol, so the adverse impact on engine life and oil change frequency should be less. The lubricating qualities of ethanol are essentially the same, however, so that increased fuel injection system wear would still be expected in ethanol-Diesel engines.

Current Activities

The Proalcool program in Brazil has led to some efforts to develop and market ethanol-fueled heavy-duty vehicles. A number of heavy-duty vehicles using converted gasoline-type engines are in use in Brazil, and engine manufacturers have experimented with ethanol-Diesel engines using fuel additives and spark ignition. The drop in world oil prices, coupled with Proalcool's success in promoting ethanol use in light-duty vehicles, led the government to de-emphasize the program, however, and such development has largely stopped. Present alternative fuel development for heavy-duty engines in Brazil is focussed on compressed natural gas.

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