ENERGY AND RESOURCE CONSULTANTS, INC.

PARTICULATE CONTROL TECHNOLOGY AND PARTICULATE EMISSIONS STANDARDS FOR HEAVY-DUTY DIESEL ENGINES

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P.O. Drawer O, Boulder, CO 80306 (303) 449-5515

PARTICULATE CONTROL TECHNOLOGY AND PARTICULATE EMISSIONS STANDARDS FOR HEAVY-DUTY DIESEL ENGINES

A Report To:
The U.S. Environmental Protection Agency
Office of Policy Analysis
Washington, D.C.

Final Report
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Task 1

Christopher S. Weaver P.E., Task Manager
Craig Miller, Ph.D., Project Manager
Lisa Nelowet

Energy and Resource Consultants, Inc.
P.O. Drawer O
Boulder, Colorado 80306

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EXECUTIVE SUMMARY

INTRODUCTION

The U.S. Environmental Protection Agency has proposed stringent particulate and NO_x emissions standards for heavy-duty engines. These proposals are controversial. The major points of controversy concern levels of engine-out emissions achievable in the near and intermediate term, the effects of stringent NO_x standards on emissions and fuel consumption, and the feasibility and technical maturity of trap-oxidizers, which are devices which filter the particulate material from diesel exhaust. A major area of concern is the interrelationship between NO_x and particulate control — generally, very low NO_x emissions can be achieved only at the cost of high particulate emissions, and vice versa.

This report provides an independent assessment of these and other issues related to heavy-duty particulate control. It concludes with recommendations for feasible near-term and intermediate-term emissions standards, as well as suggestions for further research. The report is based on a thorough review of the applicable technical literature and the regulatory dockets, extensive discussions with manufacturers of heavy-duty engines and particulate control devices, and independent engineering analysis. A draft version of the report has been subjected to extensive review by the same manufacturers, as well as by other knowledgeable parties. Appendix A summarizes the reviewer's comments and the degree to which they have been incorporated into the analysis.

INDUSTRY STRUCTURE

Heavy-duty vehicles, as defined by EPA, are highway vehicles with a manufacturer's gross vehicle weight rating greater than 8,500 pounds. They range from pickup trucks and vans with GVW only a little over the minimum up to tractor-trailer rigs with a gross combined weight (tractor plus two trailers) of 150,000 pounds. They are thus a far less homogeneous group than light-duty cars and trucks. The heavy-duty vehicle manufacturing industry also has a markedly different structure from the light-duty industry — vertical integration is far less extensive, and customer choice is greater. The purchaser of a heavy truck generally specifies the make and model of the engine, transmission, rear-axle assembly, truck body, and other components, choosing from a large menu of selections compatible with a given truck chassis. A single truck model may be available with numerous different engine models from several different manufacturers. For this reason, among others, EPA regulates emissions by heavy-duty engines rather than heavy-duty vehicles.

Classes of Heavy-Duty Vehicles

The most commonly used classification scheme is that of the Motor Vehicle Manufacturers Association, which defines eight classes of trucks and buses on the basis of rated GVW. The MVMA classification is unsatisfactory for this analysis, since it lumps together highly disparate vehicles in some classes (notably the heaviest -- Class 8), while separating basically similar vehicles in the lighter classes. For this reason, the authors have adopted a scheme separating heavy-duty diesel vehicles into four classes, on the basis of technical characteristics and usage patterns as well as GVW. These classes are the following:

1. **Light-Heavy Duty Vehicles** -- This includes all heavy-duty vehicles from 8,500 up to about 14,000 pounds GVW. These are mostly large pickup trucks and vans, similar to light-duty trucks. The remainder are mostly specialized vehicles such as tow trucks and motor homes, which are built on pickup or van chassis. Diesel engines used in this class resemble those used in light-duty cars and trucks, so that light-duty emissions control technology could be adopted fairly readily.

2. **Medium-Heavy Duty Vehicles** -- This group includes all vehicles heavier than about 14,000 pounds, except for transit buses and line-haul trucks. Most medium-heavy vehicles are "straight" (single-unit) trucks, as opposed to semi-trailers. This class exhibits a very wide variety of body styles, equipment, and usage patterns, but they are primarily urban.

3. **Line-Haul Trucks** — These are very large, high-powered, very heavy trucks used primarily for inter-urban freight. Virtually all of these are semi-trailer and double-trailer combinations.

4. **Transit Buses** — These are full-sized buses used for intra-urban transit, typically in stop-and-go operation. This class does not include school buses (which resemble medium-heavy trucks) or buses for inter-urban transport (which should probably be counted in the line-haul class).

Since the draft of this report was completed, EPA has adopted very similar classifications in its recent rules defining the full useful life of heavy-duty engines and in its recent proposals for NO_x and particulate regulations.

As will be brought out below, these four classes differ markedly in technical characteristics, operating and ownership patterns, and ability to comply with emissions regulations. It is recommended that emissions standards for each class be considered separately, and on their own merits, rather than adopting one blanket standard for all heavy-duty vehicles.

Heavy-Duty Vehicle and Engine Manufacturers

The major manufacturer of light-heavy duty diesel vehicles is General Motors, which produces its own engines. Ford -- using International Harvester engines -- will probably become a major factor in the future. Major engine manufacturers in the medium-heavy, line-haul, and transit-bus classes are Cummins Engine, Caterpillar Tractor, Detroit Diesel-Allison Division of General Motors, International Harvester, and Mack Trucks. Mack Trucks, International Harvester, GMC Division of General Motors, and Ford are the major truck manufacturers; smaller firms such as PACCAR, Freightliner, and White also hold significant market shares in the line-haul class. General Motors, Flexible, and Flyer Industries produce most transit buses in the U.S., with GM supplying most of the engines. Major truck importers are Daimler-Benz (Mercedes), Fiat (IVECO), and Volvo, each of which manufactures its own engines. Imports are still a very small (but growing) portion of the heavy truck market.

EMISSIONS CONTROL TECHNOLOGIES AND FEASIBLE STANDARDS

To establish feasible emissions standards for heavy-duty engines, it is necessary to consider three things: the engine-out emissions levels that can be achieved, the feasibility and effectiveness of aftertreatment technologies, and the amount of slack or margin between achievable low-mileage emissions levels and achievable standards. These issues are discussed separately.

Engine-Out Emissions Controls

Engine-out controls are those which affect the amounts of pollutants in the exhaust as it leaves the engine, before processing by aftertreatment technologies such as catalytic converters or trap-oxidizers. The most important consideration in engine-out particulate control for diesels is the interrelationship between particulate and NO_x emissions, which is known as the NO_x/particulate tradeoff. Figure E.1 shows the general nature of this relationship. Generally, decreasing NO_x increases particulates, and vice vesa. This relationship derives from the fundamental nature of the combustion process in diesels. Thus, although there is some scope for improvement in NO_x and particulate emissions, this scope is limited. Similar fundamental tradeoffs exist between NO_x and hydrocarbon emissions, and between NO_x and fuel consumption. The later relationship has been documented in another ERC report (Weaver, 1984b).

Techniques which can be used to "trade-off" emissions along the NO_x/particulate tradeoff curve are changing the fuel-injection timing and (for very low NO_x levels) exhaust gas recirculation. Retarding injection timing to control NO_x has an adverse effect on fuel economy, as well as increasing particulate emissions. EGR (in moderation) has little effect on fuel economy, but may increase engine wear and maintenance costs.

Several techniques are available to improve on the NO_x/particulate tradeoff (i.e., shifting the entire curve inward toward the origin, rather than moving along it). Techniques which will be available in the near term are turbocharging with improved charge-air cooling, high-pressure/high-precision fuel injection systems, and incremental engine improvements. Those which will be available in the intermediate term include those already listed, plus optimal electronic control of fuel injection timing, the quantity of

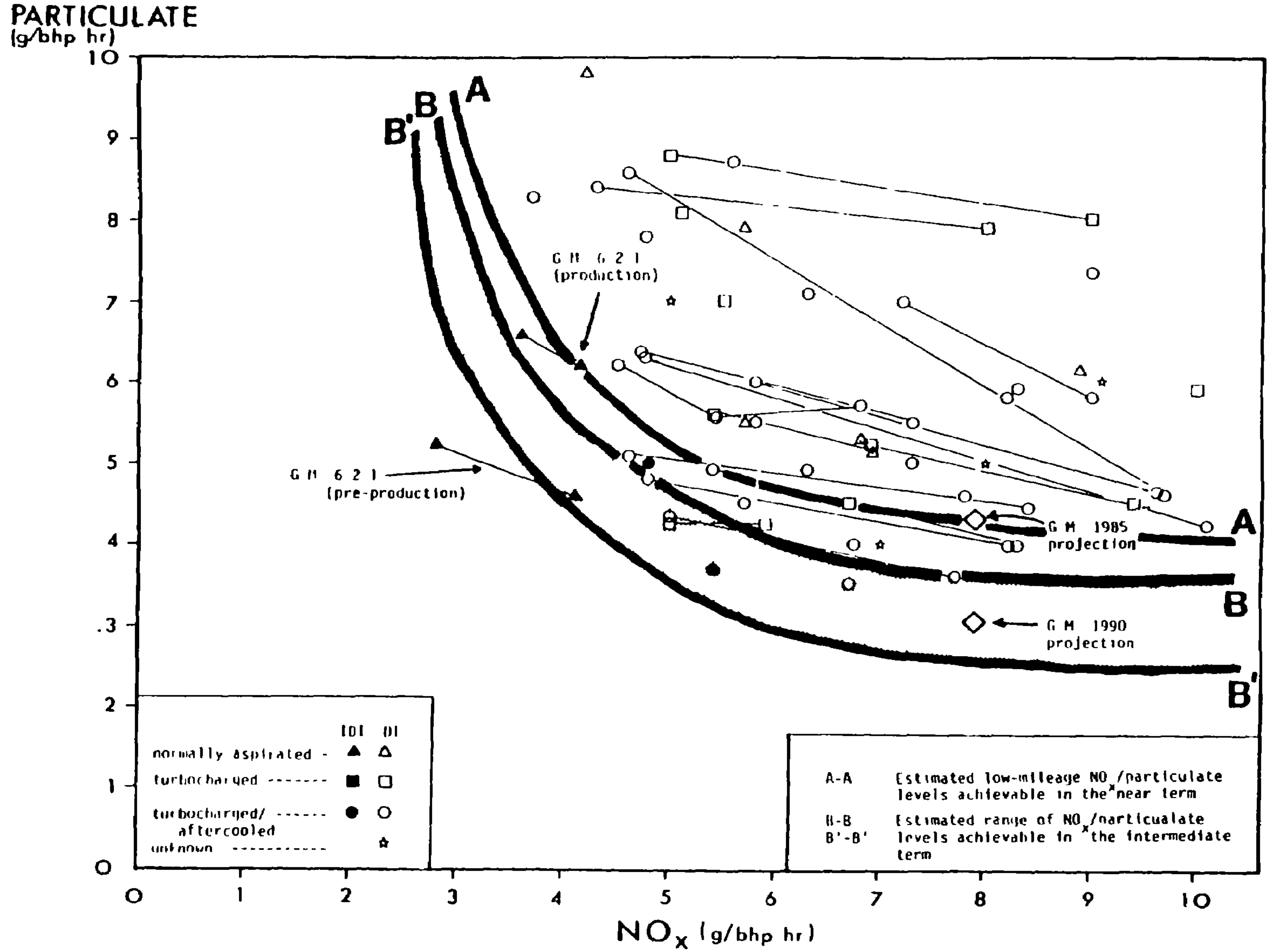

Figure E.1: Estimates of achievable average low-mileage particulate emissions vs. NO_x for near-term and intermediate-term technologies. (Note: these are not achievable emissions standards -- see text.)

fuel injected, and (at low NO_x levels) the EGR rate. All of these technologies have generally beneficial effects on fuel economy, as well as on emissions levels, and thus are likely to be adopted with or without a strict emissions standard. Without a standard, however, they would be adjusted to achieve optimal fuel economy, rather than the lowest possible emissions.

Line A-A of Figure E.1 shows the NO_x/particulate tradeoff relationship which is expected to be achievable in the near term (roughly 1987), using the techniques discussed above. Lines B-B and B'-B' of Figure E.1 show the approximate emissions levels achievable in the intermediate term (roughly 1990-1991). Figure E.1 also shows the distribution of NO_x and particulate emissions in current engines. The tradeoff curves shown in the figure are for low mileage engine-out emissions, not feasible emissions standards, and apply to direct-injection engines such as those used in the medium-heavy, line-haul, and transit bus subclasses. Small direct-injection engines are also being introduced into the light-heavy duty subclass, and the curves in Figure E.1 would apply to them as well. Light-heavy duty engines using indirect injection (presently the dominant technology in the light-heavy subclass) are inherently lower emitting, and could achieve lower levels than those shown in the near term. Emissions results for the G.M. 6.2 liter engine (a typical light-heavy indirect-injection engine) are also shown in Figure E.1

Trap-Oxidizers

Trap-oxidizers are presently the only aftertreatment technology which shows much promise for diesel emissions control. Basically, a trap-oxidizer is a durable filter (the trap) placed in the exhaust stream to catch and retain particulate material. This must be accompanied by some means of cleaning (regenerating) the filter by burning off (oxidizing) the accumulated particulate material, since otherwise the filter would clog within a few hundred miles. Regeneration and the systems for accomplishing it have presented the most important difficulties in the development of trap-oxidizer technology.

Trap-oxidizers have been developed first for light-duty diesel vehicles, in order to meet the EPA light-duty particulate standard which goes into effect in 1987 (the CARB has a similar standard going into effect in 1986). Light-duty trap-oxidizer technology is well-developed — Mercedes is now producing a trap-oxidizer equipped cars for sale in California, and several other manufacturers have reached the fleet test stage. Trap-oxidizer technology for heavy-duty vehicles is much less advanced. There are several reasons for this; the most important ones are the lesser regulatory pressure, the lesser R&D capabilities of the heavy-duty manufacturers, and the greater difficulty of the development task. As a result, heavy-duty trap-oxidizers will probably not be available before 1990 or 1991, except for light-heavy duty vehicles. These vehicles could use adaptations of light-duty trap-oxidizer technology, and could thus implement trap-oxidizers as early as 1988 if successful light-duty trap-oxidizers are introduced in 1987. The heavy-duty manufacturer which appears to have made the most progress in this area is Daimler-Benz, which has developed a very attractive heavy-duty trap-oxidizer system. Daimler states that it is confident that this system could be in production by 1990.

Four general types of trap-oxidizer systems now show promise for use on heavy-duty vehicles. Three of these were first developed for light-duty use, the other is the one developed by Daimler-Benz. These systems are described in detail in Chapter Five. At present, it is too early to state which, if any, of them will ultimately be adopted for widespread use.

Trap-oxidizer systems would be expensive: estimates of (discounted) life-cycle cost range from $550 to $715 for light-heavy vehicles, $1440 to $1540 for medium-heavy vehicles, $2409 to $2973 for transit buses, and $3462 to $4047 for line-haul trucks. A large fraction of this cost, especially in the heavier classes, is due to increased fuel consumption and the cost of maintenance and replacement traps. Users could avoid these costs by removing the trap after purchase, thus there would be a potentially serious tampering problem, especially in line-haul trucks.

Feasible Emissions Standards

Feasible emissions standards can be derived from feasible low-mileage emissions levels by considering the amount of "slack" required in the standard to account for emissions deterioration, random variation in engines, lab-to-lab variability, and the manufacturer's margin of safety. Based on manufacturer's submissions to EPA, and the authors' own analysis, the required slack is approximately 25 percent of the low-mileage level for engine-out particulates, and 10 percent for NO_x. The values assume the use of nonconformance penalties for non-compliance, as well as emissions averaging. Without these assumptions, greater margins than those listed would be required. These values also assume zero deterioration for NO_x emissions and 15 percent deterioration for particulates.

Line A'-A' on Figure E.2 shows feasible near-term emissions standards for particulates as functions of the level of the NO_x standard. This line was obtained from the low-mileage emissions curve by multiplying the NO_x coordinate of each point by 1.10 and the particulate coordinate by 1.25, corresponding to 10 percent and 25 percent slack, respectively. Figure E.3 shows a preliminary estimate of the feasible intermediate-term non-trap particulate standards, derived from the midpoint of the range shown in Figure E.1 by a similar process. Feasible trap-oxidizer based standards can be derived from the levels shown in Figure E.3 by multiplying the particulate coordinate by 0.25, corresponding to a trap efficiency of 75 percent.

Table E.1 lists feasible NO_x and particulate emissions standards and the corresponding average low-mileage emissions rates for a number of different regulatory scenarios. Achievable standards and emissions levels are shown separately for light-heavy engines and all other heavy-duty engines, since light-heavy engines would be able to comply with a stringent standard more quickly by adopting light-duty emissions control technology. All scenarios share the same initial set of regulations -- 6.0 g/BHP-hr NO_x in the near term (1987-88), accompanied by the strictest engine-out particulate standard which is estimated to be feasible by that time. The scenarios differ in the regulatory philosophy that is assumed for the intermediate term. One scenario -- the relaxed scenario -- assumes no further change from the near term. The other four scenarios assume more stringent regulations; they differ in the relative emphasis placed on NO_x and particulate emissions, and on whether or not it is considered worthwhile to require trap-oxidizers.

OTHER ISSUES

Emissions Averaging

Emissions averaging would reduce uncertainty due to statistical variations in engine emissions, and would also allow emissions from inherently higher emitting engines to be traded off against lower emitting ones, thus helping to maintain a broader product line. This would increase consumer choice and reduce the cost of compliance, and is thus desireable. However, care will be needed in designing such a regulation, in order to

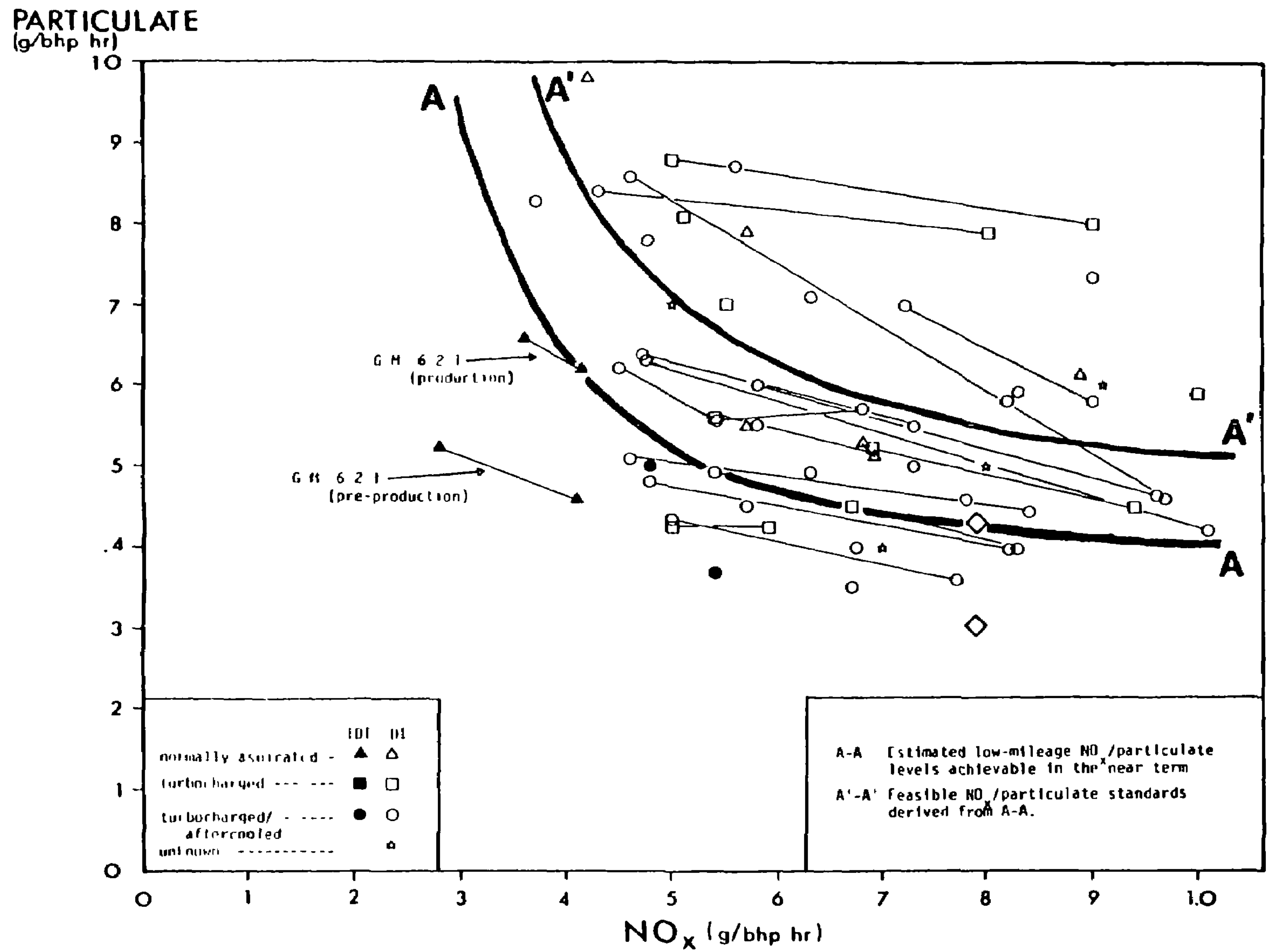

Figure E.2: Estimates of achievable near-term particulate emissions standards vs. NO_x standards for heavy-duty diesel engines.

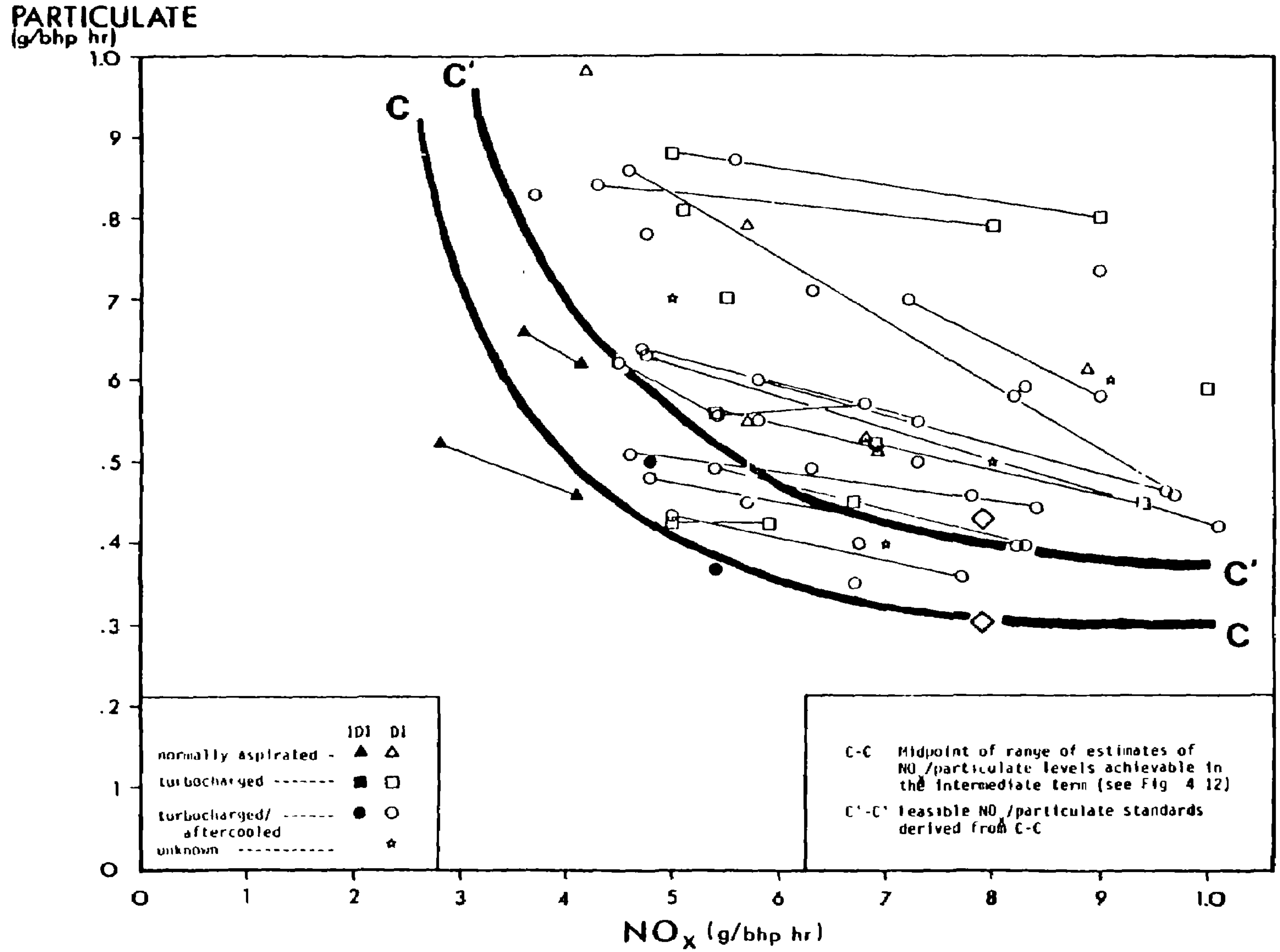

Figure E.3: Estimates of achievable intermediate-term particulate emissions standards vs. NO_x standards for heavy-duty diesel engines.

Table E.1

Numerical Standards and Low-Mileage Emissions Levels for Five Feasible Heavy-Duty Regulatory Scenarios

Scenario	Date	NO_x Standard	NO_x LMT	Particulate Standard	Particulate LMT
1. Moderate Control					
Light-Heavy	1986	6.0	5.5	0.62	0.50
All Others	1987	6.0	5.5	0.62	0.50
2. Moderate NO_x/Best Engine-Out Particulate					
Light-Heavy	1986	6.0	5.5	0.62	0.50
	1988	5.0	4.5	0.56	0.45
All Others	1987	6.0	5.5	0.62	0.50
	1990	5.0	4.5	0.56	0.45
3. Moderate NO_x/Trap Oxidizers					
Light-Heavy	1986	6.0	5.5	0.62	0.50
	1988	5.0	4.5	0.14	0.08
All Others	1987	6.0	5.5	0.62	0.50
	1990	5.0	4.5	0.14	0.08
4. Strict NO_x/No Trap-Oxidizers					
Light-heavy	1986	6.0	5.5	0.62	0.50
	1988	4.0	3.6	0.72	0.58
All Others	1987	6.0	5.5	0.62	0.50
	1990	4.0	3.6	0.72	0.58
5. Strict NO_x/Trap-Oxidizers					
Light-Heavy	1986	6.0	5.5	0.62	0.50
	1988	4.0	3.6	0.18	0.09
All Others	1987	6.0	5.5	0.62	0.50
	1990	4.0	3.6	0.18	0.09

guard against unnecessary anticompetitive effects, and to ensure that the emissions being averaged together are truly comparable. For instance, light-heavy IDI engines are inherently cleaner (on a g/BHP-hr basis) than DI engines, so that light-heavy engine manufacturers would gain a substantial competitive advantage if they were allowed to include them in averaging. Light-heavy engines also generate many times fewer BHP-hr over their useful lifetimes than do medium-heavy, line-haul, or transit bus engines, so that a simple averaging scheme which counted all of them the same would result in a net increase in emissions. Another concern stems from the difference in usage patterns between subclasses — transit buses are almost entirely urban, for instance, while line-haul trucks operate mostly in rural areas.

A simple solution to the problems of averaging would be to allow averaging only within the subclasses defined above, but this would reduce flexibility and might have adverse competitive effects. Alternatively, each engine's emissions could be weighted by its average level power and expected life, with some adjustment made for different patterns of urban vs. non-urban operation. Careful design of any averaging regulation will be regional in order to maximize the benefits to manufacturers without introducing competitive distortions, or jeopardizing air quality.

Subdivision of the Heavy-Duty Class

Heavy-duty vehicles and engines are not all alike, and these differences have important effects on the feasibility and desirability of emissions standards. As has already been remarked, light-heavy engines could readily adopt light-duty technology for trap-oxidizers and engine controls, and light-heavy IDI engines are inherently lower emitting than the DI engines used in other classes. As a result, light-heavy engines could meet a stricter standard earlier than any of the other classes. Transit-bus engines are similar to medium-heavy engines technologically, but transit buses operate in congested areas, on a cycle which produces very high emissions. Thus the benefits of emissions control for buses would be greater, and a stricter standard might be justified.

On the other hand, line-haul trucks spend comparatively little time in urban areas, while they account for nearly half of total heavy-duty fuel consumption. Thus the benefits of control would be smaller for this group, while the costs of increased fuel consumption would be very large. For this reason, EPA should consider exempting line-haul engines from any standards strict enough to have a significant effect on fuel economy. This could be done on a case-by-case basis -- EPA could issue a special permit, entitling the issuee to purchase an engine conforming to more lenient standards, upon the issuee's demonstration that the engine would be used primarily outside of urban areas. The cost of line-haul trucks is high enough and their numbers small enough that this should not pose a major administrative burden.

Diesel Fuel Quality

The major indicators of diesel fuel quality are the cetane number, aromatic content, boiling point range, and sulfur content. Cetane number and aromatic content are related -- increasing aromatic content decreases cetane, although cetane-improving additives can be added to recover this. Low cetane and high aromatic content tend to increase particulate emissions. Most of this effect appears to be due to the aromatics -- adding cetane improvers to high-aromatic fuel does not seem to improve particulates much as long as the cetane number is within the engines' design range. Due to the growing scarcity of high-quality crude, average cetane number has been decreasing, and average aromatic content increasing, over the last decade. This can be expected to lead to increased particulate emissions, as well as worsened fuel economy and performance in use. EPA should consider establishing more restrictive standards for diesel fuel aromatic content and/or cetane number.

There could be a beneficial synergism between improving cetane and reducing the sulfur content of diesel fuel. Presently, sulfur content is limited mostly by market acceptance -- too high a sulfur content leads to corrosion and excessive wear. Thus the increasing trend to high sulfur crudes has required more extensive use of desulfurization. Sulfur in diesel fuel is oxidized to SO_2, which is itself a regulated pollutant (although SO_2 emissions from motor vehicles are not regulated), as well as being a significant contributor to acid deposition. High-sulfur fuel has also been shown to increase particulate emissions significantly. Secondary particulate formation from SO_2 in the atmosphere is also a significant contributor to urban particulate levels. In addition, catalytic trap-oxidizers with precious-metal catalysts react with SO_2 to produce sulfuric acid, which can be a major problem at the high loads typical of heavy-duty service. Catalytic trap-oxidizers have numerous benefits -- they would reduce odor, HC, and CO emissions, as well as particulates, but their future is in doubt because of the sulfur problem.

The refining process used to reduce aromatic content and improve cetane also removes essentially all of the sulfur, thus offering potential double benefits. Sulfur can also be removed by hydrodesulfurization, a less severe (and thus less expensive) version of the de-aromatization process, but hydrodesulfurization has little effect on aromatics. For this reason it would be desirable to consider cetane/aromatic standards and sulfur-content standards for diesel fuel simultaneously.

CONCLUSIONS AND RECOMMENDATIONS

This report has produced a number of important conclusions and recommendations with regard to heavy-duty emissions control, regulation, and future investigation. The most important of these are listed below.

1. In establishing regulations for heavy-duty engines, EPA should consider the four major subclasses of heavy-duty vehicles separately. This does not necessarily mean that different regulations should be adopted for each subclass, only that different regulations should be considered.

2. Figure E.2 is a plot of estimated feasible engine-out particulate standards versus the NO_x standard for medium-heavy, transit bus, and line-haul engines in the near term (roughly 1987 or 1988). Because the technology involved is not radically different from what is now in use, this frontier is considered to be fairly well defined. Any emissions standards applying to that period should be chosen to fall on or above the frontier. Light-heavy duty engines are capable of complying with a similar standard by 1986.

3. Figure E.3 shows the estimated feasible engine-out particulate standard as a function of the NO_x standard for intermediate-term (1990 or 1991) application. As for Figure E.2, this figure applies to medium-heavy, line-haul and transit bus engines. Application of trap-oxidizers would reduce the feasible particulate standard by approximately 75 percent. The information in this figure is much more uncertain than that in Figure E.2, and should be clarified by additional research before being used as a basis for regulation. Light-heavy duty engines should be able to comply with a similar standard (including the use of trap-oxidizers) by 1988.

4. The continuing degradation in diesel fuel aromatic content, cetane number, and sulfur content is likely to lead to increased particulate emissions in use. EPA should consider regulations to counter this. There is a possible beneficial synergism between reduction in the sulfur content of diesel fuel and improvements in cetane and aromatics. This synergism, and possible regulations to promote it, should receive further study.

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PREFACE

This report was prepared for the U.S. Environmental Protection Agency, Office of Policy Analysis, as Task #1 of Work Order #93 under EPA contract number 68-01-6543. EPA Technical Project Manager for most of this work was Mr. Steve Steckler; due to illness, he was replaced during the later portions of the work by Mr. Willard Smith. This report was prepared by Energy and Resource Consultants, Inc. (ERC) as part of a project to determine the status and prospects for heavy-duty diesel particulate control technology, to determine feasible heavy-duty diesel particulate standards, and to evaluate the costs of meeting such standards and the air-quality benefits which would result from doing so. It describes the present status and development prospects of heavy-duty diesel particulate control technology, and discusses technically feasible particulate standards and the costs of meeting them. In addition, it deals briefly with several closely related issues: the interrelationship between NO_x and particulate emissions for diesels; the effects of changing diesel fuel quality on emissions; of the effects of subdivision of the heavy-duty diesel class; and the effects of emissions averaging.

This report is the result of an intense research effort by ERC's staff, carried out primarily during the Summer of 1983, with further research and report preparation extending through early Spring of 1984. During this period, ERC contacted every significant manufacturer or importer of heavy-duty engines in the U.S., as well as manufacturers of particulate control devices and other emissions-related technologies. A thorough review of the technical literature and of regulatory comments and submissions was also undertaken. This work was carried out primarily by Christopher Weaver of ERC, who was responsible for the engineering and technological aspects of the report. Lisa Nelowet assisted in compiling and interpreting the data, and was partly responsible for the industry characterization in Chapter 2. Dr. Craig Miller was the overall project manager.

A draft version of this report was completed in March, 1984; and was distributed to knowledgeable parties for review in May. Comments were returned by a number of reviewers, including most of the major U.S. engine manufacturers, the staffs of the California Air Resources Board and the U.S. EPA, and other parties. These comments were invaluable in pointing out numerous minor and a few major errors, as well as identifying areas which needed to be clarified in the final version. This, the final version of the report, incorporates changes made in the light of the reviewers' comments. It should be emphasized, however, that this report is by no means a consensus document. Although we have carefully reconsidered all of our conclusions in the light of the reviewers' comments, the ultimate judgement in every case has been that of the authors, and some who reviewed the report did and would doubtless still disagree. Appendix A discusses the more significant of the reviewers' comments, the authors' replies to them, and the changes, if any, made in this final report as a result.

ACKNOWLEDGEMENTS

Preparation of this report would not have been possible without the help and cooperation of many people and organizations, both in industry and in government. Special thanks are due to Rick Rykowski of EPA, John Howitt of Corning, Miles Buchman and Fred Enga of Johnson-Matthey, Tina Vujovich, and Lou Broering of Cummins, James Pasek and Charles Elder of General Motors, Dr. S.V. Yumlu and Charles Salter of Mack Trucks, Charles Hudson and J.J. Egan of International Harvester, Don Dowdall of Caterpillar, Gary Rossow and Dr. Horst Hardenburg of Daimler-Benz, and Mike Schwarz of Ford for their helpfulness in providing data and arranging discussions. A special note of appreciation is also due to Mr. W.R. Wade and Dr. S. Shahed, their staffs, and their respective employers, Ford Motor Company and Cummins Engine, for the series of superb papers on the technology of diesel particulate control they have produced.

A note of appreciation is also due to the reviewers of the draft report, who included Dr. Michael Walsh, and Mr. Tom Cackette of the CARB, as well as most of the people listed above. Needless to say, none of these people should be considered as necessarily endorsing any of our conclusions, nor are they responsible for any remaining errors; responsibility for both conclusions and errors is solely that of the authors.

The authors also wish to express their appreciation to Ms. Jana Cruz and Ms. Julie Sueker of ERC for their assistance with the graphics and report production, and to the staff of Document Control. Finally, the authors wish to express their gratitude to the EPA Technical Project Managers, Messrs. Steve Steckler and Willard Smith, for their support, and for their patience as due dates and deadlines have repeatedly slipped.

1.0 INTRODUCTION

The United States Environmental Protection Agency (EPA) has proposed very stringent standards for emissions of particulate material and oxides of nitrogen (NO_x) from heavy-duty truck engines (EPA, 1984a). These proposals have occasioned a great deal of controversy. The major points of disagreement concern the technical feasibility of meeting the proposed standards, and the maturity and reliability of the technology required to do so. The two central issues in the controversy are the feasibility and acceptability of filters (trap-oxidizers) to remove particulate material from the exhaust, and the levels of emissions reduction achievable with in-cylinder control technologies. Also controversial are the costs and benefits of meeting the proposed standards, even assuming that they are technically feasible.

Energy and Resource Consultants (ERC) has been commissioned by the EPA Office of Policy Analysis to study these issues and provide an independent assessment of the emissions control technology, feasible standards, and the costs and benefits meeting such standards. This report discusses emissions control technology, feasible standards, and the costs of meeting them. This study closely parallels an earlier study (Weaver and Miller, 1983; C. Miller et alia, 1983) of similar issues surrounding the EPA proposals for light-duty diesel particulate standards.

1.1 BACKGROUND

Due to its unmatched fuel economy and great reliability, the heavy-duty diesel engine has been the primary power source for large trucks for many years. As fuel prices have climbed in recent years, an increasing fraction of other vehicles, from medium-sized trucks to passenger automobiles, have been equipped with diesel engines as well. This dieselization trend has focused attention on the diesel engine and its contribution to air pollution.

Diesel engines emit a substantially different mix of pollutants from gasoline engines. Of the major gaseous pollutants, diesels emit only minor amounts of carbon monoxide (CO) and gaseous hydrocarbons (HC), but somewhat more oxides of nitrogen (NO_x). In addition, diesels emit substantial amounts of particulate matter, in the form of an oily black soot. Efforts to reduce either NO_x or particulate emissions are greatly complicated by the fact that most technologies which are effective in reducing one of these pollutants also tend to increase the other.

The prospect of greatly increased numbers of diesel-engined vehicles, especially in urban areas, has generated concern over the impact of diesel emissions on ambient air quality. In response to these concerns, EPA and the California Air Resources Board (CARB) have adopted regulations limiting particulate emissions from light-duty vehicles, and EPA has been studying similar proposals for heavy-duty engines for some time. Because of the relationship between diesel NO_x and particulate emissions, EPA is considering a simultaneous tightening of the heavy-duty NO_x standard as well. In addition, EPA has mandated changes in the heavy-duty engine testing procedure, with the substitution of a transient test cycle for the older 13-mode gaseous emission test.

Although tightened heavy-duty NO_x and particulate regulations were were first proposed by EPA in 1979 (EPA, 1979a; 1979b), hearings on them were not held until July, 1982. By that time, it had become clear that the standards originally proposed (4 grams per BHP-hr of NO_x and 0.25 grams per BHP-hr of particulate) could not be achieved by the proposed implementation date of 1986, and there was considerable question as to whether the NO_x standard could be achieved at all without crippling performance penalties. As a result, EPA has recently re-proposed (EPA, 1984a) significantly less stringent standards of 0.6 grams per BHP-hour particulate and 6 grams per BHP-hour NO_x to take effect in 1987, with a subsequent tightening to the levels of the original proposal in 1990. Hearings on this proposal were held in November, 1984, and as of this writing, there is yet no clear consensus as to the feasibility of the proposed 1990 standards. This report is intended to provide data and analysis to help in deciding these issues.

1.2 PURPOSE AND SCOPE OF THE REPORT

This report has three primary objectives. The first is to assess what a commercially viable heavy-duty emissions control system must include, with special attention to the differences in requirements between heavy-duty and light-duty vehicles. This includes defining the operating conditions under which it must function, the tasks it must accomplish, and the levels of efficiency, durability, and reliability required.

The second objective of the report is to characterize the present state of development of heavy-duty diesel emissions control technology, and to compare this state with the requirements for commercial viability determined in objective one. This characterization includes an analysis of technologies which could have a significant effect on NO_x and/or particulate emissions, with particular attention being paid to those technologies -- trap-oxidizers for particulates and a combination of electronic engine controls, fuel system modifications, and injection timing retardation for NO_x -- which show promise for permitting major decreases in pollutants in the reasonably near future. Another area of emphasis is the tradeoff relationship between NO_x and particulate emissions which is found in most control technologies (trap-oxidizers and charge-air cooling being the major exceptions). Work in this area has included estimation of the tradeoff curve between these two pollutants for technologies which will be available either in the near term (by 1987 or 1988) or the intermediate term (1990 - 1991).

The third objective of this report is to apply the information developed in objective two to the determination of feasible NO_x and particulate emissions standards for heavy-duty diesel engines. A range of alternative standards, corresponding to five different emissions-control scenarios are considered. These range from a requirement for what is essentially good present-day technology to the application of the most stringent controls achievable. Numerical standards corresponding to each stringency level have been defined, and the rough costs of meeting the particulate standards have been estimated. The report also considers the effects of other regulatory policies -- such as emissions averaging, subdivision of the heavy-duty vehicle class into multiple subclasses for regulatory purposes, and possible regulation of diesel fuel quality -- on the cost and feasibility of meeting the standards.

This report does not directly deal with, and makes no recommendations concerning, a number of highly controversial issues related to diesel emissions control. Excluded issues include: the suitability and cost of the EPA transient test cycle for heavy-duty engines, the issues surrounding the definition of "useful life" in heavy-duty service, the use of additive vs. multiplicative deterioration factors in determining life-cycle compliance, and the design of production compliance auditing and enforcement procedures. These issues are considered in the present report only as they affect the requirements for emissions control technologies and the numerical standards that are considered achievable.

1.3 DATA SOURCES

This report has drawn primarily on publicly available data sources, such as the publications of the Society of Automotive Engineers and other technical societies, U. S. government reports, and manufacturers' testimony at and submissions to EPA and California Air Resources Board regulatory hearings. Portions of this report have also drawn extensively on ERC's previous study of trap-oxidizer technology for light-duty vehicles. In addition, ERC personnel conducted interviews in person or by telephone with the staffs of all of the major U.S. engine manufacturers and a number of foreign ones, as well as with representatives of the major manufacturers of emissions controls. In many cases, these manufacturers have provided ERC with additional data from their own studies in the area and with test results for their engines. These, as well as the discussions and exchanges of views, have been invaluable in assisting ERC's staff to form their own judgements of technological problems and potentials.

In addition to the publicly available data, the authors have been able to draw upon a limited amount of proprietary data, provided by manufacturers on a confidential basis. In some cases, such data have played a significant role in the formation of judgements, estimates of technical feasibility, etc. Where this is possible, the general nature of such data has been described, as for instance "confidential data provided by an engine manufacturer." A bibliography, indicating the sources of significant publicly available data, is given at the end of the report.

A word on the limitations of these data sources is appropriate. The heavy-duty diesel industry is highly competitive, and technological advance is an important competitive tool. As a result, commercial secrecy is the rule rather than the exception, and many advances are not reported in the literature until well after they are developed. Thus, despite the availability of some confidential and proprietary data, the authors are painfully aware that there is doubtless much development under way with which they are not familiar. These data, had they been available, might have affected the estimates of technological feasibility contained in Chapters Four and Five. This limitation should be borne in mind in interpreting our results.

1.4 STRUCTURE OF THE REPORT

The remainder of the report following this introduction is organized in seven chapters. Chapter Two deals with the heavy-duty truck industry, with special attention to heavy-duty engine manufacturers. This chapter is intended to provide the background against which the specific requirements imposed on engines and emission controls by heavy-duty service can be discussed. The chapter describes the major types of heavy-duty vehicles, and presents a proposed classification scheme by which the highly diverse heavy-duty class can be divided into more homogeneous subclasses.

Chapter Three addresses the requirements which an emissions control system must meet in order to be considered commercially viable in heavy-duty service. These requirements are both technical and economic: an emissions control system which is technically deficient will subject its manufacturer to EPA-mandated recalls and repair programs, while one which is too expensive or which reduces fuel economy by too much will be removed or defeated in service. Chapter Three defines specific criteria by which commercial feasibility can be judged.

Chapter Four is concerned with engine-out emissions (those pollutant emissions which are produced by the engine, without consideration of exhaust treatment). This chapter begins with a discussion of what is known of the fundamentals of pollutant formation and emission in diesel engines, then proceeds to a discussion of technologies which can reduce those emissions. Both present-day emissions levels and those achievable with future technology are discussed. The development status of new emissions control technologies is briefly characterized — to the extent that it is known — and the effects of those technologies with possible near-term applicability are described. Special attention is paid to the trade-off relationship between NO_x and particulate emissions: trade-off functions for both present day technologies and possible advanced technologies are defined.

Chapter Five discusses trap-oxidizer technology, with special attention to technology for heavy-duty vehicles. Since heavy-duty trap-oxidizer technology has lagged considerably behind that for light-duty vehicles, this chapter devotes considerable space as well to light-duty technology and its implications. A general summary of technological developments in the area is given, then the special requirements and problems of trap-oxidizers for heavy duty vehicles are presented and contrasted with those typical of light-duty applications. Several potential heavy-duty trap-oxidizer systems are described, and rough estimates of the capital and operating costs of each system are given.

Chapter Six deals with diesel fuels and related issues, concentrating on the effects of changes in fuel quality on emissions. Issues addressed include the progressive deterioration in average cetane numbers, sulfur content, and other indices of diesel fuel quality, the effects of these changes on emissions levels, and possible EPA actions to reduce these effects. Other issues addressed include the effects of sulfur in diesel fuels on trap-oxidizer development, and the possible synergetic improvements in acid deposition, human exposure to SO_2 and sulfates, and reductions in diesel odor, hydrocarbon, and particulate emissions which might be made possible by reducing the fuel sulfur content.

Feasible emissions standards for heavy-duty diesel engines are discussed in Chapter Seven. This chapter includes a brief discussion of present and proposed heavy-duty regulations, then builds on the data of Chapters Four and Five to derive feasible NO_x and particulate standards corresponding to five different emissions control scenarios, ranging from requiring good present technology to requiring the most stringent control achievable, regardless of cost. The possible effects of emissions averaging and subdivision of the heavy-duty diesel class into more homogeneous subclasses are also discussed, with special attention to their implications for the cost and feasibility of compliance. This chapter concludes with recommendations for numerical standards.

Chapter Eight, the last chapter, provides a summary and restatement of the major points of the previous chapters, and lays out in condensed form the major conclusions of the study. Chapter Eight is followed by an appendix discussing the external reviewer's comments on the draft of this report, the authors' replies to those comments, and the changes, if any, made in the final version as a result. Other appendices include a bibliography of related material and a list of organizations and individuals who provided information during the study.

1.5 LIMITATIONS AND CAVEATS

No study of an area as broad, involved, and complex as heavy-duty emissions control can hope to be able to address all of the issues involved adequately, and the present study is no exception. This section describes a few of the more significant areas in which the analysis is felt to be incomplete, or where more study is felt to be required.

The limited time and funds available for this study, and the scarcity of the requisite data, have prevented a complete analysis of the effects of subdivision of the heavy-duty class and/or emissions averaging on individual manufacturers. The subdivision scheme proposed is itself rather crude; it is based on the available data and on reasonable estimates of usage patterns, vehicle production, and related information, and is intended as a "first-cut" approximation. Better classification schemes (such as by actual usage pattern) are certainly imaginable, and a more detailed study of usage and production patterns would certainly be desirable before actually implementing such a scheme. More study of issues such as useful life, average mileage before rebuild or overhaul, and the division of miles travelled between urban and rural areas for each class would also be desirable. Some of these concerns are now being addressed in research sponsored by the EPA and other interested parties (EPA, 1984b; Energy-Environmental Analysis, 1983).

The analysis of engine-out pollutant emissions (emissions as they leave the engine, before the trap-oxidizer or other external treatment) is necessarily somewhat limited in scope. Pollutant formation and destruction in the cylinder are closely linked to the overall process of diesel combustion — one of the most difficult and intractable problems in combustion science. Despite recent theoretical advances, practical design of diesel combustion systems is still largely a matter of "cut and try." A complete study of this complex and poorly understood area would require many man-years and volumes of reports, and would be well beyond the time and effort available for the present study. The analysis presented in Chapter Four is thus a somewhat superficial and primarily phenomenological aproach to a very subtle and complex area. The conclusions arrived at should be considered in that light, and treated with appropriate caution.

2.0 CLASSIFICATION OF HEAVY-DUTY ENGINES AND VEHICLES

For regulatory purposes, the EPA divides highway vehicles into two major classes: light-duty vehicles and heavy-duty vehicles. Light-duty vehicles include passenger cars and trucks with rated gross vehicle weights (GVW) less than 8,500 pounds. Trucks and buses with a rated GVW of 8,500 pounds or more are classed as heavy-duty vehicles. This report is concerned only with the latter group.

The most commonly used truck and bus classification scheme is that of the Motor-Vehicle Manufacturers' Association (MVMA), which divides vehicles into eight classes based on rated GVW. This classification is shown in Table 2.1. As this table indicates, MVMA class 2 — covering vehicles rated between 6,001 and 10,000 pounds — is further divided this class into class 2A (consisting of vehicles from 6,001 to 8,500 pounds) and 2B (containing vehicles from 8,501 pounds to 10,000 pounds) to separate vehicles classed as light and heavy-duty by the EPA.

While it is simple and widely used, the MVMA classification is unsatisfactory for this discussion. At the lighter end, MVMA classes 3 through 5 are almost unpopulated; while class 8 lumps together many different kinds of heavy trucks, some of which have very different design and usage characteristics. For the purposes of this analysis, the classification scheme shown in Table 2.2 will be used instead. This scheme divides heavy-duty vehicles into four classes: light-heavy vehicles (generally pickup trucks and vans); medium-heavy vehicles (which includes most trucks between about 10,000 and 45,000 pounds GVW); line haul trucks (generally large, powerful tractor-trailer combinations of 50,000 pounds and up); and transit buses, which are included because of their special significance as particulate emitters. The medium-heavy class can be further divided into a lighter fraction (roughly MVMA class 6) which has traditionally used gasoline engines, and a heavier fraction (MVMA class 7 and the lower portion of class 8), which has traditionally used a large fraction of diesel engines.

Table 2.1: Truck Classifications as defined by the Motor Vehicle Manufacturers Association

Class	Rated Gross Vehicle Weight (lb)
Light-Duty	
1	0 - 6,000
2A	6,001 - 8,500
Heavy-Duty	
2B	8,501 - 10,000
3	10,001 - 14,000
4	14,001 - 16,000
5	16,001 - 19,500
6	19,501 - 26,000
7	26,001 - 33,000
8	33,001 and up (to about 80,000 pounds for a truck-trailer combination, more for double-trailers)

Table 2.2: **Truck Classifications Used in This Study**

Class	Description
Light-Heavy	Heavy pickup trucks, vans, panel vans, and recreational vehicles from 8,500 to 14,000 pounds GVW
Medium-Heavy	Straight trucks and all other heavy duty vehicles above 14,000 pounds GVW except transit buses and line-haul trucks
Line-Haul Trucks	Large, heavy, very powerful trucks used for long-distance freight and similar applications. Almost all are heavy tractor-trailer and double-trailer combinations, generally of 50,000 pounds or greater GVW.
Transit Buses	Buses used for intra-urban mass transit and related applications

PARTICULATE CONTROL TECHNOLOGY AND PARTICULATE EMISSIONS STANDARDS FOR HEAVY-DUTY DIESEL ENGINES

APPROVED FOR RELEASE

***** FINAL REPORT *****

PROJECT MANAGER

12/13/84

Christopher S. Weaver, P.E. — Date

Senior Engineer

CORPORATE QUALITY CONTROL REVIEWER

12/13/84

Craig Miller, Ph.D. — Date

Principal, Engineering

Another classification scheme for heavy-duty engines, as opposed to vehicles, has been promulgated by EPA as part of its regulations concerning the definition of an engine's useful life. This scheme divides heavy-duty engines into three groups: light-heavy, with a designed useful life of 110,000 miles; medium-heavy, with a designed useful life of 185,000 miles; and heavy-heavy, with a useful life of 250,000 miles. The EPA-defined light-heavy and medium-heavy engine classes are used almost exclusively in the class of vehicles which ERC has defined as light-heavy and medium-heavy duty, respectively, but the medium-heavy class defined by ERC would also include some larger engines that EPA has defined as heavy-heavy duty. These would be the engines used in large straight trucks such as dump trucks, and in those semi-tractor vehicles which are not used in line-haul service.

It should be noted that the classifications proposed by ERC are primarily on the basis of vehicle design and function, not weight, although GVW serves as a useful criterion for separating the different classes. This is because it is the vehicle's design and function which control the patterns of its use, and thus the feasibility and cost-effectiveness of emissions standards. The medium-heavy class is intended to include those trucks which normally operate in stop-and-go driving, delivery service and so on in urban environments, while the line-haul class includes trucks used primarily for intercity freight hauling and related tasks. In the same way, light-heavy duty vehicles are distinctly difference both in form and in typical functions from either of the other classes, and transit buses, of course, have their own distinctive form and operating pattern.

Since this classification scheme was first described (Weaver, 1984a), it appears to have found favor with a number of analysts. Energy and Environmental Analysis (1983), in work for the MVMA, used a similar classification (based on the MVMA classification scheme, but with separate consideration of very heavy (i.e., line-haul)) trucks in developing estimates of the size and composition of the future heavy-duty fleet. EPA, in its recent proposals for NO_x and particulate regulations (EPA, 1984a), also proposed possible special treatment for line-haul trucks (defined as those heavier than 50,000 pounds GVW) and transit buses.

The special characteristics of each of these classes of vehicles are discussed at greater length below.

2.1 LIGHT-HEAVY DUTY VEHICLES

This class includes mainly heavy pickup trucks and vans up to about 10,000 pounds (MVMA class 2B), with a sprinkling of other types such as panel vans. Diesel-powered recreational vehicles over 8,500 pounds GVW are also included in this class, but the number of such vehicles is small. Statistically, these vehicles are usually lumped in with the more numerous light trucks in class 2A, so separate data on specific ownership and operating patterns for this group are scarce. It appears likely that almost all of these vehicles are used for commercial purposes, and that they are used primarily in urban areas. Except for being owned primarily by commercial enterprises rather than by individuals, the operating patterns in this group are probably rather similar to those of light trucks.

The technical characteristics of light-heavy duty vehicles also resemble those of light-duty trucks rather than the heavier vehicles with which they are classed for regulatory purposes. Diesel engines used in this class are the GM 6.2 liter engine and the International Harvester 6.9 liter, both of which are high-speed, indirect injection engines derived from light-duty diesel technology. However, a number of small, high-speed direct-injection diesel engines have recently been developed, and they will probably see extensive use in this class. Two manufacturers (Cummins and Isuzu) have already introduced small advanced DI engines suitable for use in light-heavy vehicles.

The production process for light-heavy vehicles also resembles that for light-duty trucks — they are mass-produced in a few standard configurations rather than in the semi-custom manner typical of medium-heavy and line-haul trucks. The major manufacturers of these vehicles are Ford, General Motors, and Chrysler, all of which also produce light-duty trucks.

2.2 MEDIUM-HEAVY DUTY VEHICLES

This class includes all of what most people think of as "heavy-duty trucks", except for the large tractor-trailer rigs. It includes all of the "straight trucks", as well as the lighter tractor-trailer combinations and some special types such as school buses. This class is characterized by a great diversity of manufacturers, sizes, body styles, and engine and powertrain options. This diversity is needed because of the widely diverse applications to which these trucks are put.

This class can be further separated into a heavier fraction in which diesel engines have been commonplace for many years, and a lighter fraction which has traditionally used gasoline engines. Engines used in the heavier fraction are typically large direct-injected medium-speed engines very similar to those used in line-haul trucks. These engines would fall into EPA's "heavy-heavy" category; they are extremely durable, efficient, and powerful, but also quite costly. Recent years have seen the introduction of a number of lines of engines which are designed to compete directly with gasoline engines in the lighter fraction of this class. These engines (which EPA classes as "medium-heavy") are typically smaller, less powerful, and less durable -- matching the lighter weight and lower lifetime mileage of the smaller trucks -- and significantly lower in cost. The technologies used, in the two classes are rather similar, however, and for many purposes the two groups of engines -- and the trucks they are sold in -- can be discussed together.

The manufacturing process for these trucks (and also for line-haul trucks) is sharply different from that for light-duty vehicles. A light-duty vehicle is sold as a package of body, chassis, engine, and drivetrain -- at most, the consumer may be able to select from two or three different standard engines or transmissions. In the larger trucks, however, the common American practice is for the purchaser to specify which engine, transmission, rear axle unit, and body he desires, choosing from a wide selection of types produced by many different manufacturers. It is for this reason that EPA regulates the pollutant emissions of heavy-duty <u>engines</u> rather than heavy-duty <u>vehicles</u>. This "mix and match" approach to truck specification greatly complicates the introduction of new emission control technologies, especially trap-oxidizers.

2.3 LINE-HAUL TRUCKS

Line-haul trucks are the largest and most powerful highway vehicles. Essentially all are large tractor-trailer and double-trailer combinations. These trucks are used primarily in intercity freight trucking. Typical lifetime mileage such a truck is in the range of 500,000 miles -- much greater than that for any other class of highway vehicles. Unlike the other classes of heavy-duty vehicles, these trucks accumulate most of their mileage outside of urban areas, a fact which has important implications for the cost-effectiveness of emissions controls.

The production process for these trucks is similar to that of the medium-heavy trucks discussed above. The purchaser normally specifies the make and model of engine, transmission, rear axle, and other major equipment to be packaged with a given cab and chassis assembly. Engines in this class are almost universally large turbocharged diesels, designed for maximum fuel economy, power output, and durability. Due to the long distances they travel and the very large loads they haul, these trucks account for a large fraction of the total heavy-duty fuel consumption. Fuel-economy is very important — the lifetime cost of even a one percent increase in fuel consumption for one of these trucks is more than $1,000.

One notable feature of this class is that many line-haul trucks are owned by individual owner-operators, rather than by commercial enterprises and governments as most smaller trucks are. Most line-haul trucks which are not owned by individuals are owned by large fleets. Both groups of owners — but especially the individuals — are highly independent and quite sensitive to their own economic interests, especially as these are affected by government regulations. Given the high cost of even a slight degradation in fuel economy, and the inevitable effects of forseeable emission control technologies in reducing fuel economy, this can be expected to pose a major enforcement problem.

2.4 TRANSIT BUSES

Transit buses, because of their numbers and the circumstances of their operation, are major contributors to urban particulate levels. In addition, their ownership and use patterns make them especially good targets for emissions control. For these reasons, they are considered here as a separate class, rather than being lumped in with medium-heavy vehicles.

The operating and ownership patterns for transit buses are almost polar opposites to those for line-haul trucks. They operate almost exclusively in urban areas, generally in the most congested portions. Furthermore, the typical transit-bus operating cycle is one of the worst conceivable from the standpoint of particulate emissions. Because of this, transit buses have been estimated to account for nearly forty percent of the total diesel particulate measured in some cities (Chock et alia, 1984).

In addition, although there is still considerable customer choice as regards engines and equipment, transit buses overall tend to be much more uniform than are, say, the medium-heavy duty trucks. At present, only one configuration — with a basically boxy body and the engine in the rear — is common, and most U.S. buses are made by a few manufacturers and equipped with one of only a few engine models. this relative homogeneity would greatly simplify the implementation of advanced control technologies.

3.0 COMMERCIAL FEASIBILITY AND HEAVY-DUTY ENGINES: REQUIREMENTS FOR EMISSIONS CONTROL TECHNOLOGIES

In order to be considered feasible for use in actual heavy-duty trucks, potential emissions control technologies and devices must be able to meet very stringent criteria for commercial feasibility. As it is used here, commercial feasibility is a much more restrictive criterion than mere technical feasibility. In order for a technique or device to be considered commercially feasible, it must not only work, it must also have characteristics such that manufacturers are willing to include it and guarantee it in or on their engines, and such that the engine's purchasers are willing to tolerate it in or on the engines that they buy. Customer acceptance is particularly important in the heavy-duty market, since—much more than the light-duty vehicle market--it is composed of sophisticated, economically motivated purchasers. Virtually all purchasers of heavy-duty vehicles are profit (or, in the case of governments, cost-effectiveness) oriented, and virtually all have extensive knowledge of and experience in the heavy-duty field. Many purchase tens of trucks or buses at a time, and can afford to carry out extensive pre-purchase comparisons. Under these circumstances, any attempt to market immature, ineffective, inefficient, overpriced or unreliable technology will result in an immediate decrease in the manufacturer's market share, and in lasting damage to the manufacturer's reputation.

A related issue which needs to be considered in assessing commercial feasibility for heavy-duty engines is the potential competition from rebuilt and reconditioned older engines. It is common practice to overhaul and rebuild heavy-duty truck engines, replacing those parts—such as cylinder liners, bearings, and injection nozzles—which are subject to significant wear or deterioration. Other parts, such as fuel pumps and engine accessories, can also be replaced as needed. By such means, a properly maintained truck engine can be kept running indefinitely.

In the past, the steady increase in the efficiency and performance of new engines, coupled with the increasing cost of maintaining an engine as it ages, have reduced the incentives to continue rebuilding an engine beyond the first one or two overhauls. Should over-stringent or premature emissions regulations result in significant degradation of new-engine performance, fuel economy, or other features, however, this situation would be reversed. The results would be increased rebuilding of present engines, a marked drop in new-engine sales, and (since older engines have higher emissions levels) a net loss in emission control from what might be attainable through less stringent regulations. Thus, in assessing commercial feasibility, it is necessary to consider not only the competition from other engine manufacturer's new models (which would, after all, be subject to the same constraints) but competition from rebuilt older models as well.

With respect to emissions control technologies, the major criteria for commercial feasibility are effectiveness, durability, reliability, and cost, and the effects of the technology on the fuel economy, performance, durability and reliability of the engine. In addition, it is necessary to consider effects on safety, maintenance requirements, tamper resistance, weight and bulk, ease or difficulty of integration into diverse styles and models of trucks, ease of manufacturing and installation, and environmental effects—the latter including both increases in unregulated pollutants and effects on other regulated emissions. The important considerations in each of these areas are discussed in the following sections.

Effectiveness

It hardly needs to be stated that any commercially feasible emissions control technology must be effective—that is, it must enable the engine on which it is installed to meet the applicable standards for pollutant emissions, with an adequate margin for variation in production and for deterioration with use. Since the numerical levels of future NO_x and particulate standards have not yet been set, no specific numerical criteria for effectiveness can be defined. The next two chapters of this report, however, will deal extensively with the relative effectiveness of potential emissions control technologies, alone and in combination with each other. Rather than define the needed effectiveness by reference to the standards, this report will, in Chapter 7, attempt to define feasible standards by reference to the attainable effectiveness of control.

Durability

Durability requirements for heavy-duty engines vary widely. Typical mileage to replacement or overhaul for light-heavy duty engines and vehicles is in the range from

100,000 to 150,000 miles. Most light-heavy engines are probably replaced (along with the rest of the vehicle) at the end of this time rather than being overhauled. In contrast, engines for medium-heavy, line-haul, and transit bus applications are normally overhauled—with replacement or refurbishing of parts subject to wear—rather than replaced. The average mileage-to-first-overhaul varies widely, depending on the specific application. A recent survey of truck owners by the Engine Manufacturers Association (EMA, 1982a) showed average mileage-to-first-overhaul of 303,000 miles for trucks used in long-haul fleet service (these would be almost entirely line-haul engines) and 221,000 miles for class 6, 7, and 8 trucks used in other fleet service (these would be predominantly medium-heavy engines). For operator-owned trucks (almost all of which are in line-haul operation), average mileage to first rebuild was 312,000 miles. The total life of the engine could be expected to be at least twice these values.

In order to be considered commercially feasible, any emissions control device which had a significant effect on the engine's performance would need to be able to last for at least the typical mileage before first overhaul, while requiring only routine maintenance and service during that period. Preferably, of course, it should be able to last the entire lifetime of the engine without requiring rebuild or replacement. This is especially true for any "add-on" emissions control devices. Since these would not add to the performance of the engine, they would be unlikely to be rebuilt or replaced voluntarily.

It is instructive to consider the acceleration smoke-limiter as an example of an add-on pollution control device which is in present use. These are commonly found on turbocharged engines, to compensate for turbocharger lag during low-speed acceleration. They limit fuel flow to the engine in order to reduce the opaque black smoke on initial acceleration which is among the most noticable aspects of truck operation in traffic. This increase in sociability yields little direct benefit to the owner, and is achieved at some cost in acceleration and driveability. An EMA study of maintenance practices (EMA, 1982a) indicates that only 53 percent of truck fleet operations routinely inspect and maintain this device, and that only 17 percent of owner operators (who are presumably less concerned about public relations) do so. A device controlling a less visible pollutant could be expected to receive even less maintenance. For this reason, it is essential that such a device should be highly durable.

In addition to the time and mileage between overhauls, it is also necessary to consider the effects of EPA in-service deterioration and warranty regulations on durability requirements for commercial feasibility. EPA issued final rules on these issues in late 1983 (EPA, 1983a). These rules require emissions compliance over the full useful life of the engine, defined as 110,000 miles or eight years for light-heavy duty engines, 185,000 miles or eight years for medium-heavies, and 290,000 miles or eight years for line-haul ("heavy-heavy") engines. These correspond closely to the actual expected life of a light-heavy duty engine, and to the expected mileage until first overhaul for the medium-heavy and line-haul groups. Engines are required to be certified for, and would be subject to recall for, the entire period. However, manufacturer's emissions warranties are only required to extend to five years/50,000 miles for light heavies and five years/ 100,000 miles for medium-heavy and line-haul engines. In addition, while emissions compliance is required over the entire period, EPA will not test for compliance any engine which has expended more than 75 percent of its expected life.

In addition to the overall useful life requirements, EPA has established minimum required maintenance intervals for a number of emissions-related components, including EGR valves, fuel injectors, and turbochargers. A commercially feasible emissions control device would need to be durable enough to meet these requirements if they were imposed.

Reliability

Reliability requirements for heavy-duty engine emissions controls will vary, depending on the nature of the control device, possible modes of failure, and the effects of failure on the engine and vehicle. In the extreme case, where a failure could destroy the engine and/or the vehicle, nearly absolute reliability would be required. Some designs of trap-oxidizers (where a regeneration failure might lead to a fire) would fall in this category, as would some designs of exhaust-gas recirculation systems. A number of California model medium-duty engines were recently destroyed when failure of the EGR system led to overloading of the lubricating oil with soot, destroying the oil's lubricating properties. Given reasonable design, however, such drastic effects should be few.

In the more common case, where failure of the emission control system would cause the engine either to run very poorly or not at all, a slightly lower level of reliability could be tolerated. Electronic engine controls and some trap-oxidizer designs would fall into this category. Failure of this type of device would cost money and time, but would not have catastrophic effects. However, frequent failures of this type would not only cost large amounts of money, they would probably lead to extensive tampering to remove the offending devices, thus negating their beneficial effects on air pollution.

A third category of devices consists of those which would have minor effects on the engine, either positive or negative, should they fail. Good reliability will be required for these devices in order for manufacturers to be able to meet in-service emissions requirements, since the devices are unlikely to be repaired if they fail. EGR systems which fail closed rather than open and transient smoke limiters would fall into this category. The infrequency of maintenance of in-service smoke limiting devices has already been discussed above.

Initial Cost

The tolerable level of increase in initial engine costs due to emission controls will vary depending on the characteristics of the service for which that engine is designed. For light-heavy and the smaller of the medium-heavy engines, the allowable increase in cost is fairly small. This is because these engines compete directly with cheaper gasoline-fueled engines, and their shorter lifetime mileage means that the owner has less opportunity to recover the increased purchase cost in the form of savings on fuel. The cost premium for a light-heavy duty diesel engine over a comparable gasoline model was approximately $2,000 in early 1984. The fuel savings over 120,000 miles (assuming 10 MPG for the gasoline version, 13 MPG for the diesel version, and both diesel and gasoline at $1.30 per gallon) is approximately $3,600, for a net (undiscounted) life-cycle savings of $1,600. Increasing the base cost of the engine by as much as $1,000 would significantly reduce these savings, and raising it by $2,000 would remove essentially all motivation to purchase a diesel.

On the other hand, it is almost impossible to imagine a cost increase which would make gasoline engines competitive with diesels in line-haul service. The increased fuel costs for such an engine, over its full 500,000 mile life, would amount to more than $50,000. The constraint on increasing costs in engines for line-haul service lies in the potential competition from rebuilt engines. Assuming no significant fuel-economy penalty for the new emissions control, the added cost of controls could probably reach $4,000 to $8,000 before new engines ceased to be competitive. This is not to say, however, that such increases would be desirable, or that they might not cause considerable economic hardship in the truck, truck engine, and trucking industries.

Effects on Fuel Economy

From the engine purchaser's standpoint, fuel economy is probably the most important characteristic of the diesel engine. This is especially true in line-haul service and in the heavier end of the medium-heavy duty class. The additional fuel cost over a vehicle's lifetime due to the one percent loss of fuel economy is of the order of $1,000 to $2,000 for a line-haul truck. Thus, the potential economic loss from even a slight fuel-economy penalty is very large. In addition, given the enormous economic incentives, it would be surprising if any emissions control device which resulted in a significant fuel economy loss—and which could be tampered with—were not to undergo extensive tampering. This potential exists with trap-oxidizers and EGR valves, and possibly with injection timing controls as well.

For light-heavy and the lighter medium-heavy engines, the constraints of fuel economy are not so binding. The major competition for these engines is with heavy-duty gasoline engines, over which they enjoy a fuel economy advantage of 25 to 35 percent (Jambekar and Johnson, 1981). These engines generally travel about 100,000 to 150,000 miles over their lifetimes, and are not usually designed to be rebuilt. The cost of a one percent loss in fuel economy over one of these engine's lifetimes is of the order of $150—much less than that for the heavier trucks. In the case of the light-heavy duty engines, the manufacturers have already decided to accept a significant fuel economy penalty--of the order of 5 to 15 percent--in return for the better performance, compatibility with gasoline-engine drivetrains, and lower emissions offered by the prechamber (indirect injection) design. Thus a fuel-economy penalty of the order of 10 percent for the lighter DI engines, and perhaps a few additional percent for IDI engines could be tolerated. It should be borne in mind, however, that these penalties--while tolerable--are by no means desirable, and that they would result in significant increased costs to the nation, both directly and in the form of political risks due to increased oil imports.

Effects on Engine Durability and Reliability

After fuel economy, the most important characteristics of the diesel engine from its purchaser's viewpoint are its durability and reliability in heavy-duty service. This is especially true of line-haul engines, and of the heavier portion of the medium-heavy class. Heavy-duty engines are quite expensive, ranging from $5,000 to $15,000 or more, and the vehicle owner expects to get his money's worth. Truck downtime due to failures, or to preventive maintenance needed to avert failures, is also very expensive, and failures can result in missed deadlines, spoiled goods, and heavy penalties as well. Thus any emissions control modifications which are perceived as significantly reducing either the expected lifetime or the overall reliability of the engine will be strongly resisted, and are likely to undergo extensive tampering and/or removal in service.

The major durability concerns associated with emissions control technologies are with EGR, which is widely perceived as increasing abrasive wear in the cylinder and increasing soot loading of the engine oil, reducing its ability to lubricate. Severe injection retardation could also harm durability by increasing exhaust gas (and thus exhaust valve) temperatures. Major reliability concerns exist with electronic engine controls, trap-oxidizers, and EGR systems.

Effects on Performance and Driveability

Performance and driveability are very important considerations for all classes of heavy-duty diesel engines, from the light-heavies to the very largest. The relatively poor performance in these areas exhibited by many diesel engines (compared to their gasoline-fueled counterparts) makes their further degradation especially problematic. As with fuel economy, durability, and reliability, any emissions control technologies leading to significant degradation in these areas can be expected to meet with widespread tampering and/or removal, or--failing that--with widespread competition from engines such as older rebuilt diesels or gasoline engines which are not burdened with such devices.

"Performance" in a heavy duty engine generally translates as "rated power". "Driveability" is a somewhat fuzzier term: "good driveability" generally means both high steady-state torque at low engine RPM and good transient acceleration characteristics (i.e., minimal turbocharger lag). Performance is a major concern throughout the heavy-duty engine market, but especially in the heavy classes, since vehicles in these classes generally have little or no power to spare. Driveability is of great concern for light-heavy and medium-heavy duty trucks, and for transit buses, since their duty cycles involve a great deal of starting, stopping, and acceleration. Engines designed for this service generally have a fairly wide speed range, and good low-speed torque characteristics. Driveability is less of a concern for line-haul trucks, since these vehicles are seldom operated in stop-and-go mode. However, there has been an increasing trend toward sacrificing driveability for fuel economy in line-haul engines, so these engines also have less driveability to give up, if that were necessary.

Both driveability and performance are closely related to the combustion system in the engine, so that any emissions control technologies affecting combustion (i.e., all engine-out technologies) would be expected to affect driveability and performance as well. Injection timing retardation (especially static retard systems), exhaust-gas recirculation, and transient smoke limiting devices all have negative effects on driveability, and the former two can also reduce maximum power. With present-day mechanical controls for these systems, the manufacturer must walk a fine line between violating emissions standards and degrading performance and driveability to an unacceptable extent. Electronic controls for the engine governor, EGR modulation, and dynamic injection timing controls are expected to improve this situation significantly--making possible both improved driveability/performance and decreased emissions.

Maintenance Requirements and Tamper Resistance

Maintenance requirements and tamper resistance are really two sides of the same coin. Almost all heavy-duty vehicles and engines are subject to planned regular maintenance at moderately frequent intervals, in order to protect the owner's investment and minimize operating costs due to failures, increased fuel consumption, etc. Any emissions-related device which is important to engine operation or efficiency can reasonably be expected to receive regular inspection and servicing as needed, as long as "as needed" is not unreasonably often. On the other hand, any emissions control device which substantially harms the vehicle's performance, fuel economy, or driveability--or which poses a real or perceived threat to its durability or reliability--can be expected to receive active "dis-maintenance", i.e. tampering and/or removal. The major concerns in this regard are for trap-oxidizers and EGR valves, both of which would degrade performance while providing no perceived benefit to the owner or operator.

Safety

Any significant safety risks due to emissions controls would, of course, be highly undesirable—the more so as many trucks are used to transport hazardous materials, and thus an accident might have very far-reaching consequences. The major concerns in this regard are with trap-oxidizers. Depending on the regeneration system used, these might present either a slight or a significant fire hazard. The most serious concern is with the burner type of regneration system, which would inevitably result in some increased risk, due to the close proximity of the fuel and fuel piping to the hot trap and exhaust system. Additive reservoirs for on-board storage of organometallic fuel additives (for a self-regenerating trap-oxidizer system) would also pose significant safety questions. Some candidate organometallic additives are quite toxic, and many are highly flammable as well.

Another, less urgent safety concern would lie in the possibility of sudden engine failure or power loss due to the failure of an emissions control device. This concern is closely tied to the questions of reliability discussed above. Perhaps the major worries in this regard would be with electronic control systems. These systems characteristically fail suddenly, unlike mechanical control systems, where steady degradation rather than sudden failure is more common. Design solutions to this problem, incorporating a "limp home" capability, have been reported in the literature, and such approaches presently seem to be favored.

Weight and Bulk, Effects on System Integration

The weight and bulk of an emissions control device are important, both because of their direct effects in reducing the payload carriable by the vehicle and because of the problems they can introduce in system integration. This problem is greatest for engine-mounted or engine-compartment-located technologies; the engine compartments of most trucks and buses today have very little room to spare. More room is generally available elsewhere on the truck or bus, but locating an emissions-control device off of the engine greatly increases the problems in system integration. This is because the engine manufacturer normally supplies only the engine itself; the rest of the truck is provided by the vehicle manufacturer. In the common case where a vehicle manufacturer offers four or five alternative engines for the same truck, he might find himself having to find room for and install four or five different off-engine control devices.

The emissions control technologies causing the greatest concern in these areas are trap-oxidizers (because of their necessarily large size), charge-air cooling (which requires either a larger radiator or a separate heat-exchanger), and electronic controls (which may need to be cab-mounted, due to the hostility of the environment in the truck's engine compartment).

Manufacturability and Installability

The ease or difficulty of producing and installing a given pollution control device, or incorporating modifications for pollution control in the engine, will clearly have a significant effect on the ultimate cost of the pollution control, as well as on the lead-time required to bring it into production.

A number of possible emissions control technologies raise significant questions of manufacturability. Perhaps the most serious questions are raised by advanced fuel-injection systems. Present-day fuel injection pumps are marvels of precision manufacture — consuming significant power and producing pressures of 500 to 1,000 atmospheres, with millisecond timing, for extremely lengthy periods in a hot, vibrating environment. Future designs will also need to incorporate provisions for dynamic timing control, fast-response electronic control of fuel quantities, and even higher pressures. The precision tooling required to manufacture such devices is extremely expensive, and must be special-ordered as much as three years in advance. This will obviously have a major effect on the production lead-time.

Environmental Effects

It need hardly be stated that the application of a control technology for one pollutant should not result in the production of other, worse emissions. The major concerns in this regard are the tradeoffs between NO_x emissions and particulates and/or gaseous hydrocarbon emissions. This report deals with those tradeoffs in considerable detail in Chapters 4 and 7. In general, the very presence of the standards minimizes the potential concerns in this area for regulated pollutants, since a standard-meeting engine will by definition not emit excessive quantities of regulated pollutants.

Among unregulated emissions, the major concerns raised by NO_x and particulate control technologies are potential increases in sulfate emissions due to the oxidation of SO_2 in catalytic trap-oxidizers. Although sulfates are measured as particulates, and thus regulated to some extent by the particulate emissions regulations, they are probably much more damaging than other diesel particulate materials. Some forms of exhaust catalysts used for HC and CO control have also been shown to increase mutagenic activity in particulates significantly (Scholl, et alia, 1982), which could conceivably be a problem. EPA regulations require that pollution control techniques for regulated pollutants should not increase emissions of specified unregulated pollutants, of which sulfate is one. If it were strictly interpreted, this provision could prevent the application of catalytic trap-oxidizers.

4.0 ENGINE-OUT EMISSIONS CONTROL FOR HEAVY-DUTY ENGINES

Pollution-control techniques for motor vehicles can generally be divided into the "engine-out" and "aftertreatment" approaches. The engine-out approach (also called "in-cylinder" control) attempts either to prevent pollutants from being formed in the first place or to increase their destruction by chemical processes inside the engine. The aftertreatment approach uses a separate processing system in the exhaust pipe to remove or destroy pollutants before they are emitted to the atmosphere.

"Engine-out" pollutant emissions are those pollutants which exist in the exhaust as it leaves the engine, before passing into the exhaust pipe and the purview of any after-treatment technologies which may be in use. At present, engine-out emissions for diesel engines are the same as tailpipe emissions, since aftertreatment technologies are not used.

A number of promising techniques for reducing engine-out NO_x or particulates are known. Unfortunately, most techniques which reduce particulate emissions increase NO_x emissions, and vice-versa, so that it is difficult to achieve a significant reduction in both NO_x and particulates by engine-out techniques alone. For this reason, trap-oxidizers (an aftertreatment technology for reducing particulate emissions) are of increasing interest for heavy-duty diesel emissions control. These would be used in conjunction with an engine-out technique to reduce NO_x, since there is presently no feasible aftertreatment technique for NO_x control in diesels.

This chapter discusses engine-out pollution control techniques — beginning with the fundamental science and proceeding to a discussion of emissions control technologies. Both technologies presently in use and the advanced technologies now under development are discussed. Finally, the potential for emissions reduction using these techniques is assessed, and rough estimates of the NO_x/particulate tradeoff relationships achievable using these technologies are developed. The next chapter contains a complementary discussion of aftertreatment technologies — specifically trap-oxidizers.

Caveat — Engine-out control techniques affect the conditions in the cylinder during combustion, and thus affect almost every other important aspect of the diesel engine. These include its efficiency, durability, drivability, maximum power, and torque curve, among other considerations. Changes in these characteristics can strongly affect the ultimate saleability of the engine, so that engine manufacturers are continually striving to improve the multiple tradeoffs between these different considerations. The truck industry is highly competitive, with technological advance a major competitive tool. In order to retain the competitive benefits of technological advance, each manufacturer shrouds its progress in these areas in secrecy, and technical data are generally either not available at all or available only on a confidential basis.

Because of the difficulty of obtaining data, the complexity of the interactions between the many different characteristics, and the limited time, funds, and manpower for this study, the discussion which follows is somewhat limited. In particular, quantitative data on the effects of many of the technologies are lacking, and estimates of the time required for introduction may be seriously in error. There is also a greater-than-desirable reliance on engineering judgment — as opposed to hard data — in estimating the effects of these technologies on emissions levels. Despite these limitations, however, the authors are reasonably confident of the ultimate conclusions as to achievable emissions levels in the near term (up to about 1988), since the effects of technologies which can be introduced in this time frame are fairly well known. Prediction of technological capabilities beyond 1989 — and especially those associated with electronic controls — is considerably less certain.

4.1 FUNDAMENTALS OF DIESEL EMISSIONS

Pollutant formation and destruction in the diesel engine are determined by the combustion process, which, in turn, is controlled by the nature of the fuel and the oxidizer, the ambient temperature and pressure, and the process of mixing between the fuel and oxidizer in the cylinder. The effects of all in-cylinder pollution control technologies can be understood (at least qualitatively) in terms of their effects on these variables. This section briefly describes the combustion process in the diesel engine, and discusses the mechanisms of NOx and particulate formation, and the effects of changes in the combustion process on these mechanisms. This discussion is necessary in order to establish a theoretical basis for the discussion of practical emission control technologies which is given in Section 4.2.

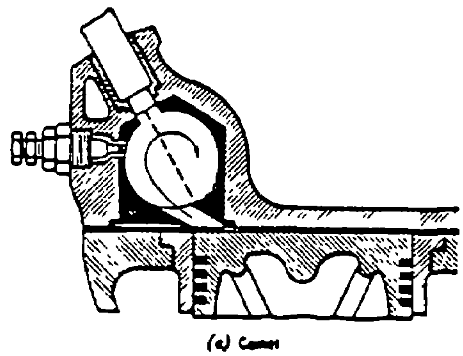
4.1.1 Combustion in the Diesel Engine

From the emissions-control standpoint, the interesting portions of the diesel cycle are the compression, fuel-injection, combustion, and power/expansion segments. In the compression process, air is taken into the cylinder and compressed by the rising piston to between about 1/15 to 1/22 of its original volume. This raises the pressure in the cylinder to about 35 - 50 atmospheres, and the temperature to abut 700 - 800 K. Near the end of the compression process, liquid fuel is injected from a nozzle into the hot compressed air in one or more high-speed jets. This fuel jet entrains some of the air in the cylinder and is heated by it, so that it evaporates rapidly. (The cylinder pressure is generally above the fuel's critical pressure, so it is not clear that "evaporate" is the right description -- no change of phase per se is possible. The process can, however, be thought of as the quasi-liquid supercritical fluid becoming more of a quasi-gas with the absorption of heat.)

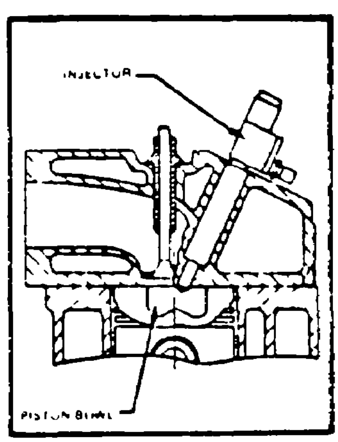
Two broad categories of diesel engines are defined on the basis of where the fuel injection takes place in the combustion chamber. In direct-injection (DI) diesel engines, there is only one combustion chamber -- the space between the top of the piston and the cylinder head (this space is mostly hollowed out of the top of the piston). Fuel is injected directly into this space, hence the term "direct" injection. In indirect-injection (IDI) engines, fuel is injected into a separate pre-combustion chamber or prechamber, which is connected to the main combustion chamber by a passage. This chamber is designed to provide very rapid air motion, resulting in rapid mixing between the fuel and the air. Figures 4.1a and 4.1b show these two arrangements.

The choice of direct or indirect injection has a profound effect on the mixing process. In IDI engines, the rapid air motion and turbulence due to expansion through the connecting passage produce rapid mixing. In the DI engine, the connecting passage is absent, and the air motion is either reduced or nearly absent (for the so-called "quiescent chamber" combustion system). This means that the fuel injection process must supply most or all of the energy required for mixing, with the result that fuel injection characteristics are far more important in DI than IDI engines.

After the beginning of fuel injection, there is a short induction time (the "ignition delay") during which some of the fuel jet mixes with the air and undergoes chemical reactions



a) indirect injection (Source: Taylor and Taylor, 1961)



b) direct injection (Source: Wade, 1980)

Figure 4.1: Diesel combustion chamber arrangments used in automotive engines.

prior to burning. Ignition occurs at the end of this induction time. The initial phase of combustion is very rapid, as the fuel which had mixed with the air during the delay period now burns as a premixed flame. After this initial "premixed burning" phase, combustion of the remainder of the fuel is limited by the rate at which fuel and air can mix. During this period, combustion takes the form of a highly turbulent diffusion flame. At least 75% of the fuel is burned in this "diffusion burning" phase (Plee and Ahmad, 1983). This phase of combustion can last 40 to 50 crank-angle degrees into the power/expansion stroke, although most combustion usually occurs between top-dead-center (TDC) and about 20 degrees afterward.

In a diffusion flame, combustion is limited by the rate at which fuel and oxidizer can mix to within combustible limits. Thus, conditions at the flame front are determined by the inherent properties of the fuel and the oxidizer -- not by how much fuel or oxidizer is present in the cylinder (these quantities do, however, affect where the flame front is located, and how long combustion continues). The limits of combustion are determined by the chemical nature of the fuel, the concentration of oxygen in the oxidizer, the specific heat of the mixture, and the starting temperature and pressure. These parameters thus determine the conditions — especially the local temperature — at the flame front.

Due to the cooling effect of expansion in gases, the starting temperature is itself a function of the pressure, which is a function of the crank-angle (as the piston moves downward, the gases expand) and the amount of the fuel which has already burned in the cylinder. Thus conditions during combustion are strongly affected by the rate of mixing in the cylinder, and by the time at which the fuel is injected. Figure 4.2 shows the pressure-crank angle traces for a number of different injection timings in a typical diesel engine.

4.1.2 Particulate Emissions

Diesel particulate material has two main components -- a solid core of soot and a covering layer of adsorbed or condensed heavy organic molecules (the "soluble organic fraction"). The relative proportions of these two components differ, depending on the engine and the operating conditions. Under most conditions, soot is the dominant component -- accounting for 50 to 90 percent of the total. The hydrocarbon content of the particulate matter tends to be greatest at low load conditions, and decreases sharply with increasing load (Bergin, 1983; Kageyama and Kinehara, 1982). Since these two com

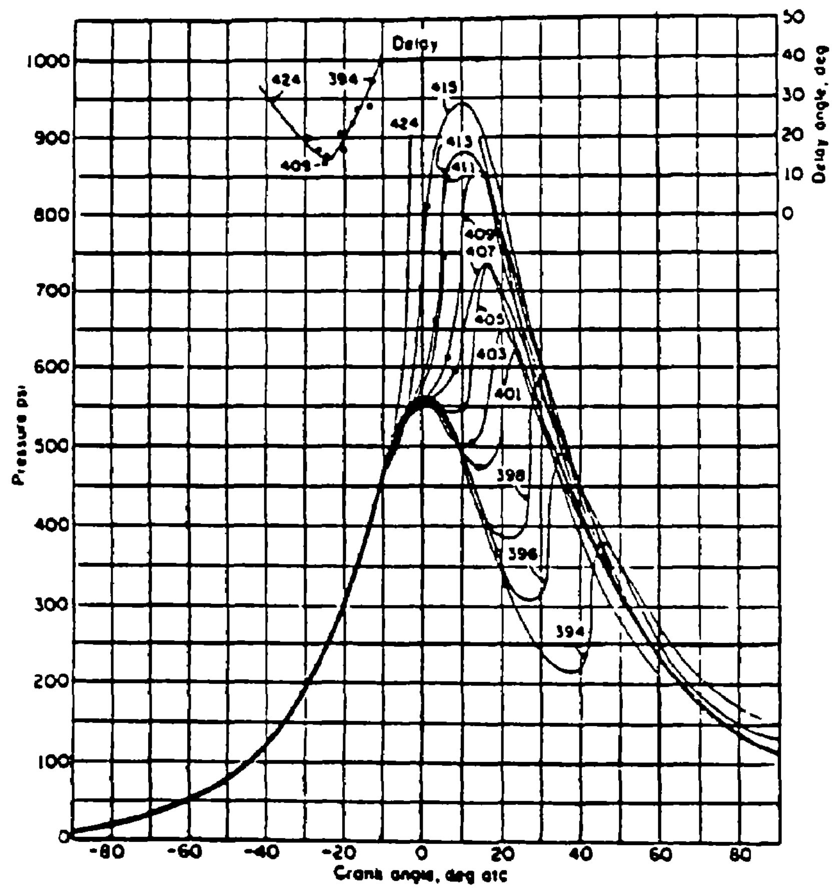


Figure 4.2: Cylinder pressure vs. crank angle for different fuel injection timings in a direct injection engine. (Source: Taylor and Taylor, 1961)

ponents are formed by somewhat different processes and are to some degree independent, they are discussed separately below.

Soot formation -- Soot consists of small spherical particles of solid carbon, about 50 to 1500 Angstroms in diameter, which are often linked together in chains and clusters to give soot its characteristic "fluffy" appearance. The size and characteristics of the soot particles depend on the conditions of combustion; soot from diesel engines is mostly made up of spheres about 100 Angstroms in diameter, which may or may not be linked into chains.

Soot forms as the result of very rapid gas-phase reactions which occur during the combustion process. The first step in hydrocarbon combustion is pyrolysis -- the breaking up of the hydrocarbon molecules into smaller, more reactive fragments when exposed to heat. If sufficient oxygen is present, these reactive fragments then oxidize rapidly to water and CO_2 -- the final products of combustion. In the absence of sufficient oxygen, however, these fragments can undergo rapid recombination and polymerization to form very large polynuclear aromatic molecules. These molecules then continue to grow by coalescence and further polymerization into soot particles. The initial stages of this process are comparable in speed to the combustion reactions themselves, so that soot can be formed as an intermediate product even in the presence of a fair amount of oxygen. Figure 4.3 shows the major stages and time-scales in the process of soot formation in the diesel.

The nature of mixing-controlled flames such as that in the diesel engine is that there is a fuel-rich mixture on one side of the flame front, an oxidizer-rich mixture on the other side, and a high temperature at the flame front itself, where the two mixtures are diffusing together. This implies that there will always be an oxygen-deficient mixture on the fuel side of the flame front, and that this mixture will be exposed to temperatures high enough to promote pyrolysis. The formation of soot is thus inherent to diffusion flames in hydrocarbons. However, the specific conditions of temperature, pressure, chemical composition of the fuel, the length of time the fuel is exposed to high temperatures, and the volume of mixture exposed can all affect the amount of soot formed, and thus the amount emitted.

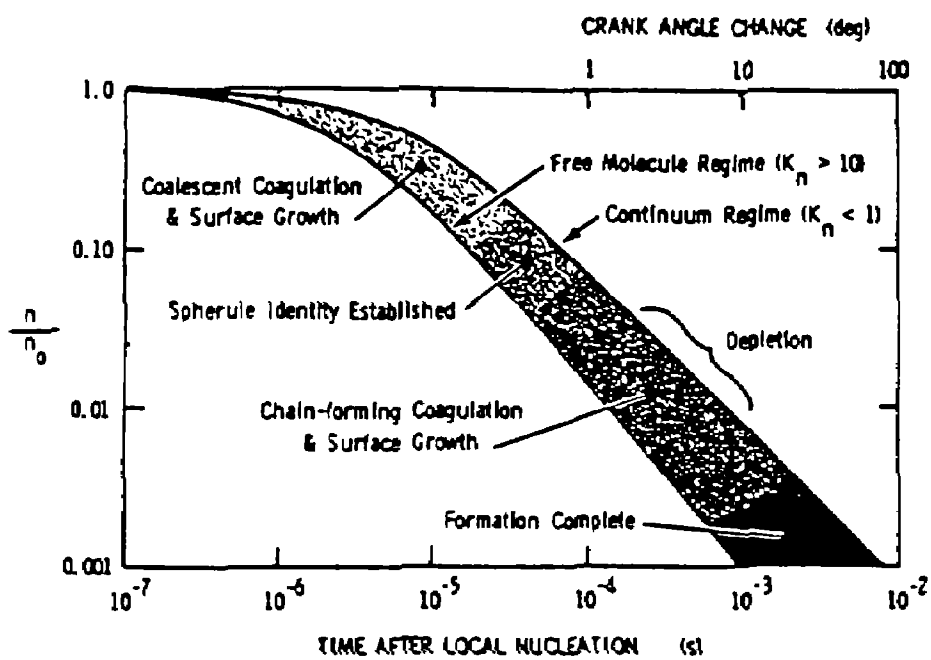


Figure 4.3: Soot nucleation and growth stages under diesel engine conditions (Source: G.W. Smith, 1981).

Because the soot-forming reactions occur very rapidly and close to the flame front, soot formation is primarily affected by changes which affect conditions at the point of combustion. Data on these effects came primarily from laboratory studies at low pressures, so their applicability to the diesel engine is not completely clear. The laboratory studies show that increasing the stoichiometric flame temperature (by increasing the oxygen concentration in the oxidizer or using a higher-energy fuel) increases soot formation, while decreasing it (such as by EGR) reduces the soot yield. There is probably a limit on this effect, however, since theoretical calculations (Amann et alia, 1980) indicate that, at chemical equilibrium, soot should not be found above a certain (pressure-dependent) temperature. This is borne out by observations in diesels (Uyehara, 1981). High pressures should also promote soot formation in theory, and increasing pressure does increase the soot yield in most laboratory systems (Wagner, 1980). Premixing the fuel with a small amount of oxygen also increases the yield, possibly due to the effect of oxygen in promoting pyrolysis.

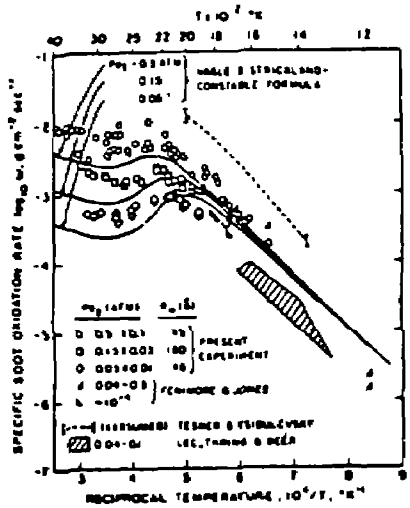
Taken together, these observations indicate that soot formation in the the diesel engine should be very rapid, and that soot yield (the fraction of carbon converted to soot) should be high. These are inherent in the diesel engine. Since the soot-formation reaction is comparable in speed to the combustion reaction, there is little that can be done to reduce the fuel's exposure to soot-forming conditions. The high pressures and high temperatures in the diesel engine will also promote soot formation. Attaining a high enough temperature to inhibit the soot formation is impossible, since a temperature gradient will always exist between the flame front and the inner core of the fuel jet.

<u>Soot oxidation</u> — Engine-out soot emissions are equal to the difference between the amount of soot formed in combustion and the amount which is subsequently oxidized. As discussed above, soot formation is very rapid, and cannot readily be reduced. Soot oxidation, on the other hand, is much slower, and much more under the designer's control. The major variables affecting the soot oxidation rate are the temperature and the partial pressure of oxygen (which can be approximated by the product of total pressure and oxygen concentration).

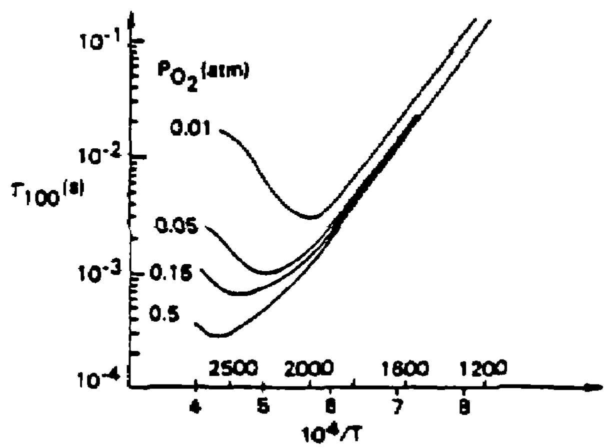
Soot is a form of pyrolytic graphite, and it has been found that correlations and kinetic data developed for larger masses of pyrolytic graphite also work well for soot. The most commonly used correlation is a semi-empirical one developed by Nagle and Strickland-Constable (Wagner, 1980; Amann et alia, 1980) Figure 4.4a shows the rate of reaction at the carbon surface predicted by this correlation as a function of temperature and oxygen partial pressure, along with some experimental data which are seen to agree rather well. Figure 4.4b shows the predicted lifetime of a 100 Angstrom soot particle under the same conditions of temperature and oxygen pressure as in Figure 4.4a. As these figures indicate, the oxidation rate increases exponentially with temperature, and nearly independently of oxygen pressure, up to some limiting value. After that limiting value is reached, the reaction is controlled by the availability of oxygen, with only minor temperature effects.

The actual process of soot oxidation is affected as much by the mixing process as by the oxidation kinetics. The initially oxygen-deficient gases containing the soot must be brought in contact with sufficient oxygen to react while remaining at a high enough temperature to promote reaction. The rate at which oxidation occurs in the flame is thus determined by the pattern of mixing, and thus — for turbulent conditions such as those in diesel combustion — by the intensity and scale of the turbulence. Theoretically, there should be an optimimal level of turbulence — with too low a level resulting in inadequate oxygen for complete reaction, and too high a level cooling the combustion products by mixing them with too much air. Under practical conditions in the diesel engine, the first consideration usually dominates — so that increasing the level of turbulence increases the amount of soot oxidized (Amann et alia, 1980).

<u>Hydrocarbons</u> — Emissions of the organic fraction of diesel particulate matter are related to emissions of gaseous unburned hydrocarbons. It is believed that the hydrocarbon coating on the particles comes from the adsorption and/or condensation of heavy hydrocarbons on the soot particles. This is borne out by recent data from Bergin (1983), who found that with a sufficiently effective filter, the soot particles could be removed from the exhaust. Heavy hydrocarbons then condensed independently to form a fine aerosol. Major factors affecting the amount of organic material in diesel particulate are the exhaust temperature (which affects hydrocarbon condensation) and the level of gaseous hydrocarbons in the exhaust.



(a) Predicted oxidation rate vs. temperature and oxygen partial presure. (Source: Appleton, 1973, cited in National Research Council, 1982)



(b) Predicted soot-particle lifetime vs. temperature and oxygen partial pressure. (Source: Wagner, 1980)

Figure 4.4: Soot oxidation rates predicted by the Nagle and Strickland-Constable theory vs. temperature and oxygen content.

Diesel engine emissions of unburned hydrocarbons appear to be derived from two major sources: (1) segments of fuel spray which are quenched and diluted below the combustion limit by rapid mixing or by contact with the cylinder walls; and (2) fuel which enters the cylinder late in the combustion process due to secondary injection, dribbling from the injecton nozzle, or vaporization of the fuel contained in the nozzle's sac volume. Hydrocarbons from this second source can be (and have been) greatly reduced by improved design of the fuel injection system. So, similarly, can some of the hydrocarbons resulting from quenching against the cylinder walls. Hydrocarbons which are quenched by mixing in the interior of the cylinder are more problematic. Reducing the mixing intensity would reduce this quenching, but would also reduce soot oxidation and increase fuel consumption.

Hydrocarbon emissions, and the hydrocarbon fraction of the particulate material, are highest at low loads and high speeds. These combine to produce intense mixing together with low temperatures in the cylinder. The hydrocarbon fraction of the particulate is correlated with the gaseous hydrocarbon emissions, although this correlation is itself a function of load (Bergin, 1983). Both gaseous hydrocarbon emissions and the dependence of particulate hydrocarbons on the gaseous hydrocarbons tend to decline with increasing load. This is presumably due to the increased temperature in the cylinder, which both promotes the oxidation of gaseous hydrocarbons and prevents their condensation onto particles.

Effects of engine variables on emissions -- The processes of soot formation and oxidation, and the oxidation of unburned hydrocarbons, are all controlled by the local temperature, pressure, and the ratio of fuel to air. However, since oxidation is a slow process, it is much more affected by the time-history of these variables thoroughout the combustion and expansion stroke. Soot formation, in contrast, is affected mostly by the values of these variables at the actual flame front during combustion. In general, high pressure promotes both soot formation and oxidation, as does high temperature. Since particulate emission represents the difference between these two processes, the effects of changes in pressure and temperature on emissions are not readily predictable.

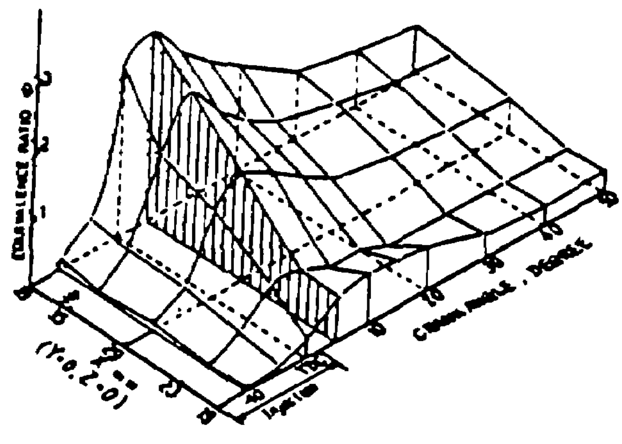
On the other hand, reducing the local fuel-air ratio in the vicinity of the flame front (as by improved mixing) should both decrease soot formation and increase oxidation, and thus could be expected to lead to an unequivocal decrease in emissions. However, more intense mixing also results in more combustion taking place near TDC, and thus at higher temperature and pressure. Intense mixing could also be expected to increase the quenching of unburned hydrocarbons. Increased mixing later in the cycle also reduces the temperature of the burned products, by diluting them with cold air. This effect may outweigh the increase in available oxygen due to mixing.

To help clarify the soot formation and oxidation process, Figure 4.5 shows three-dimensional plots of temperature, equivalence ratio, and soot concentration vs. time along a transect through the cylinder, measured with an in-cylinder sampling apparatus in a direct-injection engine. This sampling procedure necessarily involves some space and time-averaging of the results, so what is shown are volume-average properties near each sampling point. The location of the fuel jet is near the left side of the plots.

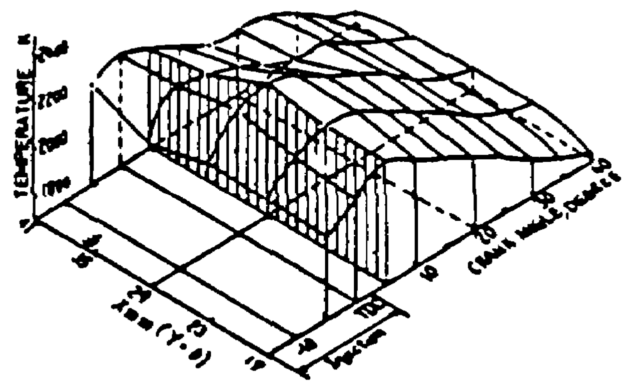
Figure 4.5 has a number of important features. Notice that the average equivalence ratio peaks sharply near the fuel jet shortly after injection, then falls off rather slowly due to large-scale mixing. The temperature distribution is much more uniform, indicating that combustion is taking place more or less evenly throughout the space. Notice also the very sharp increase in soot concentration in the area of high equivalence ratio, following the peak temperature by about 5 degrees of rotation (equivalent to 1 millisecond). This sharp increase is followed rapidly by an almost equally sharp decline, indicating that soot oxidation is very rapid at that time. Soot concentration near the end of combustion is a small fraction of the maximum value, indicating that total soot formation and oxidation over the cycle are nearly the same, and thus that a small change in either one might greatly change the emissions level.

Given all of the interacting variables in diesel combustion, it is necesary to fall back on experimental measurements to determine the effects of a given change in parameters on particulate emissions. Fortunately, a large number of such measurements is available. Some of the more important of these studies are discussed below.

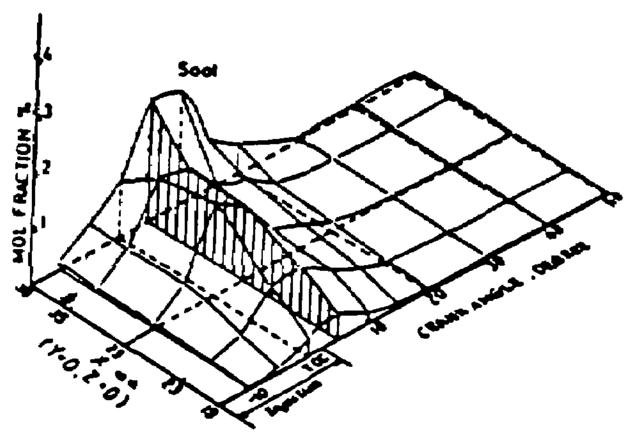
It has been found that — other things being equal — increasing turbulent intensity in the cylinder (and thus increasing the mixing rate) almost always reduces particulate emissions. Dent (1980), has reported that changes in soot emissions with turbulence can be correlated using a parameter which is related to the turbulent intensity on the very smallest scales, suggesting that the effects of small-scale mixing on the oxidation rate are predominant. The rapid drop in soot concentration in Figure 4.5, compared to the much slower drop in average equivalence ratio, also suggests that small-scale mixing of a



(a) Equivalence ratio



(b) Temperature



(c) Soot

Figure 4.5: Temperature, equivalence ratio, and soot concentration history along a transect in a direct-injection diesel engine. (Source: Aoyagi et alia, 1980)

scale too small to be resolved by the sampling probe — is dominant. A trend toward lower emissions with increasing turbulence level is also clear from extensive practical development work in diesel engines.

The effects of flame temperature on particulates have been investigated by researchers at General Motors (Plee et alia, 1980; Ahmad and Plee, 1983) and at Cummins engine (Yu and Shahed, 1981). In the GM work, the flame temperature was varied by adding oxygen or nitrogen of the engine intake air. It was found that total particulate emissions can be correlated very well with the calculated flame temperature at TDC, using the Arrhenius relation (an exponential function of temperature). This correlation is shown in Figure 4.6. The slope of this correlation line does not vary much from engine to engine, although the intercepts are different for different engines, due to variations in engine design.

The negative slope and exponential form of the correlation line in Figure 4.6 suggest that the predominant effect of temperature on particulate emission comes through increasing the rate of oxidation of the soot. This increase must outweigh the increase in soot formation due to the higher flame temperature. A possible contribution to this effect could come from the fact that changes in flame temperature were achieved by adding nitrogen or oxygen to the intake air, thus changing the oxygen partial pressure. This is also suggested by the work of Yu and Shahed (1981), who found that oxygen content, rather than flame temperature, was the more important variable in determing soot emissions.

Particulate emissions are strongly affected by engine load, especially at conditions near full load. This is widely ascribed to the effect on the overall fuel-air ratio, which increases as increasing amounts of fuel are injected. On a grams-per-kilogram of fuel basis, most engines show a rather broad minimum in particulate emissions at part load, with an increase (especially in the hydrocarbon fraction) near zero load, and a much sharper one (dominated by soot) as full load is approached. This behavior can be attributed to the competing effects of temperature and oxygen availability on the soot and hydrocarbon oxidation rate — at low loads, the low temperature attained in the cylinder dominates, while at high loads, the lack of oxygen results in little soot oxidation and thus greatly increased emissions.

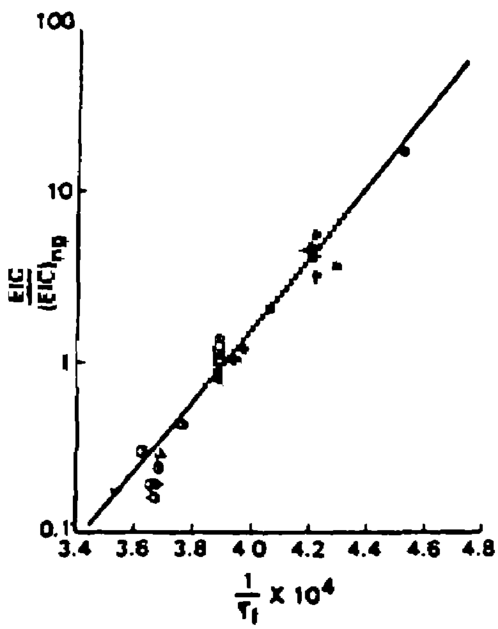


Figure 4.6: Correlation between particulate emissions index and stoichiometric adiabatic flame temperature for a number of IDI diesel engines. (Source: Plee et alia, 1980)

To sum up, it appears that the dominant process affecting diesel-engine particulate emissions is oxidation rather than formation. Changes in variables which tend to increase both soot formation and soot oxidation have a greater effect on oxidation, while those which would have opposite effects on the two processes seem to work mostly through oxidation. This is partly attributable to the fact that soot formation is a very rapid process, which takes place very close to the flame front. The conditions (and especially the concentrations) near the flame front are determined more by the basic stoichiometry of the reaction than by any variables under the control of the designer. In contrast, soot and hydrocarbon oxidation are somewhat slower processes, and are thus more affected by mixing and other variables under the designer's control. In order to minimize particulate emissions, it is necessary to maximize the degree of oxidation, by maximizing the length of time that the particulate is exposed to high temperatures and adequate oxygen.

4.1.3 Oxides of Nitrogen (NO_x) Emissions

The major constutuent of NO_x is nitrogen monoxide (NO). Most of the rest is made up of nitrogen dioxide, which is formed from NO by further oxidation. In combustion, NO itself is generally considered to be formed through two processes. "Prompt" NO is formed at the flame front, through mechanisms which are still not well understood, while "thermal" NO is formed more slowly in the hot products of lean combustion. Thermal NO is formed via the extended Zel'dovich reaction, which is given by the following mechanism.

$$O + N_2 = NO + N$$
$$N + O_2 = NO + O$$
$$N + OH = NO + H$$

The equilibrium constant for this reaction is roughly proportional to the square root of the oxygen concentration, and increases exponentially with temperature. At temperatures above about 2200 K, equilibrium shifts strongly toward NO. The reaction rate also increases dramatically at high temperatures, due to the greater dissociation of nitrogen and oxygen as well as the temperature dependence of the rate constants. Thus at high temperatures, near-equilibrium concentrations of NO can be formed. As the temperature drops, equilibrium shifts back toward oxygen and nitrogen, but the reaction rate slows as well, "freezing" the NO concentration in the exhaust gases.

In the diesel engine, most NO_x is formed in or near the flame front, during the high-pressure portions of the combustion process. This is when the flame temperature is at its maximum (Shahed et alia, 1978). The amount of NO_x formed is quite sensitive to the flame temperature at top-dead-center, following an expression of the Arrhenius (exponential) form. Figure 4.7 shows the correlation obtained by Plee and co-workers (1980) at General Motors for a number of different IDI engines. Later work (Ahmad and Plee, 1983) indicates that the same correlation also applies well to DI engines. Similar conclusions for DI engines were reached by Yu and Shahed (1981).

Mixing and injection-timing effects are very important in NO_x formation. Injection timing has an obvious effect on the amount of fuel burned near TDC, and thus on the total amount of NO_x generated. The effects of mixing seem to work primarily through the same mechanism – more rapid mixing increases the amount of fuel burned near TDC, and this effect apparently outweighs the additional cooling of the burned gases later in the cycle. Figures 4.8a and 4.8b give an idea of the magnitude of these effects. These figures show the calculated NO_x formation rates as functions of crank angle for: (a) an engine using a lower pressure injection system, and (b) one using a higher pressure system (note that high injection pressure implies high mixing rate). The NO_x formation curve is a sharp spike in either case, but a significantly sharper and higher one for the higher injection pressure, due to the fact that combustion occurs more rapidly and closer to TDC, and thus the flame temperature is higher.

To sum it up then, it appears that the conditions for maximal oxidation of nitrogen are very similar to those for maximal oxidation (and thus minimal emission) of soot and hydrocarbons. NO emissions are promoted by high flame temperatures, high mixing rates, and combustion conditions which tend to maximize the amount of fuel burned near TDC. A high overall oxygen content is also needed, but the effects of oxygen on NO formation are much less pronounced than for soot. At high loads, for instance, NO formation tends to be greater, due to the higher temperatures and pressures attained, rather than being reduced by the lower overall oxygen concentration.

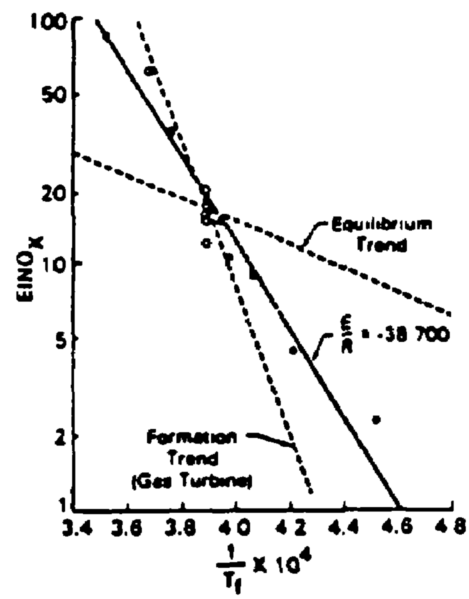
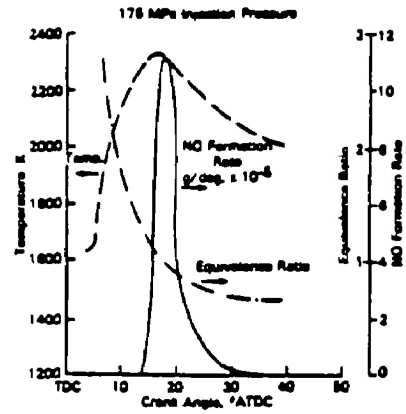
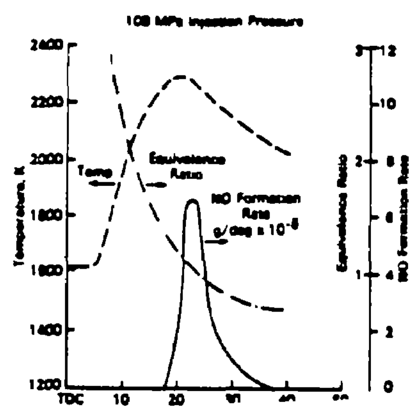


Figure 4.7: Correlation between NO_x emissions index and stoichiometric adiabatic flame temperature for diesel engines and gas turbine combustors. (Source: Plee et alia, 1980)



(a) High injection pressure



(b) Moderate injection pressure

Figure 4.8: Temperature, equivalence ration, and NO_x formation rate vs. time for different injection pressures (Source: Shahed, et alia, 1978)

4.1.4 The NO_x/Particulate Tradeoff

From the discussion above, it is clear that the NO_x/particulate tradeoff is due to very fundamental conflicts between the combustion conditions required for maximal oxidation of soot and those required for minimal oxidation of nitrogen. At some point, then, any combustion strategy which seeks to minimize soot emissions must result in increased NO_x emissions, and vice versa. However, this conflict is not absolute -- some changes in combustion conditions can be arranged so that they decrease one pollutant without drastically increasing the other. By appropriate use of such techniques, it may be possible to shift the overall NO_x/particulate tradeoff curve nearer to the origin (the point of zero NO_x and particulates).

Six different generic approaches to improving the NO_x/particulate tradeoff can be imagined. These are the following:

1. Increase engine efficiency -- pollutant emissions are directly related to the amount of fuel burned. Reducing the amount of fuel burned without changing combustion conditions (by reducing friction, for instance) will reduce emissions.

2. Take advantage of the difference in sensitivity to overall oxygen concentration between NO_x formation and particulate oxidation, by increasing the overall air/fuel ratio without increasing the oxygen concentration or temperature of the intake air. This can be accomplished by turbocharging and intercooling, and by improvements in engine "breathing".

3. Optimize combustion temperature to stay as low as possible on each of the exponential curves of pollutant emission versus flame temperature, and control other conditions in the engine to maintain this optimum temperature as closely as possible.

4. Load-dependent control of combustion variables -- brake-specific particulate emissions increase sharply at high loads (high fuel/air ratios), while brake-specific NO_x is much less affected. By changing the con-

trol strategy from one of minimizing NO_x at moderate loads to one of minimizing particulates at high loads, it would be possible to improve the overall effectiveness of control.

5. Selectively increase soot oxidation by increasing the radiant temperature in the cylinder. Soot particles are good radiation absorbers and emitters, while gases are very poor ones. Increasing the radiant temperature should decrease the cooling of soot particles by radiation without affecting NO_x.

6. Find a way to minimize soot formation. This is obviously the most desirable approach, since if the particles are never formed they need not be oxidized. Unfortunately, the only obvious way to do this is to change fuels.

Due to the stringency of the presently proposed NO_x and particulate regulations, emissions control techniques based on all of these approaches are now being developed. Since engine efficiency is already close to the best achievable, the most important short-run gains are likely to come from the second, third, and fourth approaches. However, the adiabatic engine (which combines the first and fifth techniques) may offer the potential for dramatic gains in the longer term. The sixth approach - changing fuels - has also been proposed as a solution for transit-bus emissions (Toepel et alia, 1983).

4.2 CONTROL TECHNIQUES FOR ENGINE-OUT EMISSIONS

Engine-out emissions are determined by the combustion process, which 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. As a result, the number of potential emission control techniques is very large. Table 4.1 lists the major engine-out NO_x and particulate control techniques which are presently either in use or being studied for use in heavy-duty diesel engines. As the table indicates, diesel emission control techniques can be grouped into a number of categories, such as engine modifications, charging technologies, and so forth. The remainder of this section discusses each of these categories in turn, and describes the potential, present status, and prospects for future development of each.

Table 4.1
Engine-Out Emissions Control Techniques

Technology	Status
Engine modifications	
Optimized airflow	Ongoing
Optimized cylinder pressure	Ongoing
Optimized combustion chamber	Ongoing
Optimized air swirl and spray pattern	Ongoing
Efficiency improvements	Ongoing
Fuel injection system	
Higher injection pressure/injection rate	Ongoing
Improved precision of injection	Production
Optimized injection timing	Production
Variable injection timing	Ongoing
Charging technologies	
Turbocharging	Production
Turbocharger/engine characteristic matching	Ongoing
Charge-air cooling	Ongoing
Advanced charging technologies	Development
Exhaust-gas recirculation	Ongoing (one manufacturer) Development (most manufacturers)
Electronic controls	
Open-loop injection timing control	Application
Electronic EGR modulation	Application
Electronic engine governor	Application
Integrated electronic engine control	Application
Closed-loop (feedback) control systems	Development
Indirect injection	Production
Advanced engine technologies	
Adiabatic diesel engine	Early development
Turbocompounding	Early development
Organic rankine cycle power recovery	Research
Additives and alternative fuels	
Water-in-fuel emulsions	Research
Alcohol-fuel emulsions	Research
Fumigation with water or alcohol	Research
Methanol fuel	Development

* Ongoing: In use on production engines, ongoing fine-tuning/optimization.
Production: In use on production engines, little additional potential.
Application: In the process of being adapted for production.
Development: Technical feasibility established, prototypes in development.
Research: Technical feasibility not yet established, under investigation.

4.2.1 Engine Modifications

The phrase "engine modifications" is used here to indicate changes in the design of the basic engine (the block, pistons, cylinder head, etc.), as distinct from changes in external engine equipment such as the turbocharger and fuel injection system. In general, these constitute minor improvements on designs which are already highly developed. As a result, only incremental improvements in emissions are to be expected from this source. Some truly radical engine design changes -- such as the uncooled or "adiabatic" engine -- are discussed in a separate section on "Advanced Engine Technologies" below. These more radical changes in engine design could result in correspondingly greater improvements in emissions.

Engine design involves a series of complex tradeoffs between different variables such as emissions, fuel economy, durability, manufacturing cost, and ease of service and repair. To make matters worse, engine design is as much an art as a science; the effects of individual design changes on any of these variables are only incompletely understood. This is especially true with respect to particulate emissions, for which even the theoretical understanding is not yet complete. As a result, optimization of engine design variables is a slow process, with much cut-and-try experimentation needed. Optimization for minimum emissions is also closely related to optimization for best fuel consumption, which has been going on for more than 40 years. Thus the incremental improvements in emissions through engine modifications are unlikely to be either great or rapid.

Optimized airflow and valve timing -- Optimization of the combustion air flow path to minimize pressure losses and equalize air distribution between cylinders can help to reduce particulate emissions. Equalizing the air distribution makes possible more precise control of the fuel-air ratio in the cylinder, while reducing pressure losses means that more air actually gets into the cylinder. This increases the partial pressure of oxygen in the cylinder, and thus decreases particulate emissions at any given power output. In addition, increasing the amount of air in the cylinder and equalizing its distribution can increase the maximum power obtainable from the engine.

Improvements in air flow can be accomplished by minimizing pressure losses and turbulence due to friction, by optimizing valve timing, by increasing the number of valves used in four-stroke engines from two per cylinder to four, and by optimizing the scavenging process in two-stroke engines. Air flow can also be increased by minimizing the need for turbulence and swirl in the combustion chamber, since the energy required for this must come from the incoming air. Such changes will also reduce the fuel-air mixing rate, however, so they must be offset by increases in other mixing parameters such as fuel injection pressure.

Optimized cylinder pressure and compression ratio -- The pressure in the cylinder during combustion is affected by fuel injection timing, compression ratio, intake air pressure, and engine load. In turn, this pressure affects the flame temperature during combustion, the average temperature of the gas in the cylinder, the partial pressure of oxygen, and the overall efficiency of the engine. High pressures tend to improve fuel economy, power output, and particulate emissions, but also increase NO_x. The NO_x increase is due mostly to a higher flame temperature, and can be offset by charge-air cooling and/or EGR. The maximum usable pressure is limited by the mechanical strength of the engine, and by noise and durability considerations, while the requirements for cold-starting impose a minimum value on the compression ratio. In practice, the compression ratio in a specific engine model must be carefully optimized to comply with these numerous constraints.

Optimized combustion chamber, air swirl, and spray pattern -- Together with the fuel injection system, these variables collectively determine the nature and timing of the fuel-air mixing process, and thus determine where and when combustion will take place in the cylinder. This, in turn, has major effects on both NO_x and particulate emissions. Unfortunately, the mixing process and its effects on combustion are still only partly understood, so that it is seldom clear a priori what effects a given change in any of these variables will have. Interactions between the three variables are very important -- a change in any one of them will generally require re-optimizing the other two. Air swirl also has an important and competing interaction with optimal airflow -- increasing swirl requires increasing the pressure drop, and reduces the amount of air that can be gotten into the cylinder.

Combustion chamber design is of greatest importance in indirect injection engines. In these engines, the design of the prechamber and of the connection to the main combustion chamber must combine to create rapid air motion in the prechamber, and rapid mixing between the jet from the prechamber and the charge in the main chamber. This rapid and intense mixing is primarily responsible for the very low emissions typical of these engines. The fuel spray pattern in these engines is comparatively less important, since the energy required for rapid mixing is provided almost entirely by air motion.

In direct-injection engines, the situation is somewhat different. DI engines place much more reliance on the energy of the fuel jet and less reliance on air motion than do IDI engines. The extreme form of this is the so-called "quiescent chamber" engine, in which essentially all of the mixing energy is supplied by the fuel jet. These engines use very high pressure injection systems, with as many as nine holes in the injection nozzle in order to provide better atomizing and distribution of the fuel. This type of combustion system is most commonly found in line-haul engines, due to the expense of the high-pressure injection system. An intermediate system, using moderate air swirl and moderate injection pressures is more commonly found in engines in the medium-heavy range. In these engines, combustion-chamber designs offering measurable benefits are still being developed.

In general, more rapid mixing between fuel and air is desirable, both in order to improve fuel economy and to improve the NO_x-particulate tradeoff and thus reduce pollutant emissions. As indicated in Section 4.1, both NO_x and particulates are heavily dependent on the conditions of combustion, which change continuously during the combustion cycle. More rapid mixing and combustion result in less variation in conditions, and thus make it possible to determine conditions for minimal emissions more closely. Achievable mixing rates are limited by the greater energy requirements for rapid mixing, the pressure limitations of the engine, and noise limitations — more rapid mixing produces more combustion noise.

<u>Efficiency improvements</u> — Other things being equal, any improvement in the efficiency of the engine which does not affect the combustion process will tend to decrease emissions, since less fuel needs to be burned to generate the same amount of work. Efficiency improvements due to changes in combustion would exhibit a similar effect, but this effect is normally small compared to the direct effects of combustion changes on emission levels. Some non-combustion-related efficiency improvement technologies include thermostatic control of oil temperature for optimal lubrication, use of lower-

friction lubricants, and improvements in engine design which reduce friction. Reductions in parasitic loads — such as by fluid-drive or electrically driven fans and improved design of pumps and other auxiliaries — can also generate marginal improvements in efficiency and emissions. Efficiency improvements of this sort are constantly being tested and developed, due to their importance in reducing fuel consumption. Although the effects of each individual change are generally small (changes with large results have been introduced long ago), their aggregate effect may be a significant 10-15% reduction in emissions. A study performed for the MVMA (Energy and Environmental Analysis, 1983) estimated that engine efficiency could improve by 7.3 percent between 1982 and 1987, and another 7.4 percent between 1987 and 1992.

Status and prospects — Almost without exception, the heavy-duty diesel engines now in production have been subjected to extensive optimization studies, so that they probably represent about the best that can be achieved with current technology, given other constraints such as manufacturing cost. Improvements in the area of engine modification will most likely come about as a result of re-optimization following the introduction of some other new technology (e.g. high-pressure fuel injection, charge-air cooling), or as the result of new technological developments. Improvements of this latter type are likely to involve significant increases in cost. Except for the case of re-optimization following a change in some other technology, the prospects for emissions improvements due to engine modifications do not appear to be very great.

4.2.2 Fuel-Injection Systems

The fuel injection system in a diesel engine is the system by which 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 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 which create the pressure pulses that actually send the fuel into the engine, the injection nozzles through which fuel is injected into the cylinder, and a governor and fuel-metering system, which determine how much fuel is to be injected on each stroke, and thus the power output of the engine.

Three generic types of fuel injection system are in common use. These are: (1) systems with distributor type fuel pumps, (2) systems with unitary in-line fuel pumps, and (3) systems incorporating unit injectors. Distributor-type fuel pumps have a single pumping element, which is mechanically switched to connect with fuel lines running to the injection nozzles on each cylinder. The pump generates a pressure pulse in each fuel line as it is connected to it, causing fuel to spray out of the associated nozzle into the cylinder. Because there is only one pumping element, the pump must operate at high speed (in an N-cylinder four-stroke engine, the pump must generate N/2 pulses per revolution of the crankshaft). This rapid operation and the mechanical switching process limit the injection pressure and the precision of the injection pulse that can be achieved with this kind of pump.

The in-line and unit injector systems are conceptually similar: each one incorporates a single pumping element per cylinder. In the in-line system, these pumping elements are located in a separate fuel pump, which -- as with the distributor pump -- is connected to the injection nozzle by a high-pressure fuel line. Because each pumping element operates only once every other revolution, and because all of the mechanical connections are permanent, higher injection pressures and greater precision of injection are possible. However, very high pressures can still cause problems with fuel-line cracking, and sharp pressure pulses still lose some of their definition in being transmitted through the fuel line. For this reason, some manufacturers use unit injectors, in which each cylinder has -- in effect -- its own individual fuel pump, directly connected to the injection nozzle. These can provide very high injection pressures and very sharp pulses, but the distributed location of the injectors and their close coupling to the engine can make it more difficult to control the injection timing.

Regulatory pressure on particulates, the need for acceptable performance at low NO_x levels, and increasing fuel prices are all generating significant changes in fuel-injection system design. These changes include increased precision in fuel metering and pulse generation, higher injection pressures, changes in fuel injection timing, and/or the use of variable injection timing (controlled by engine speed and/or load), and -- finally and most significantly -- development of digital electronic control systems to replace the engine governor, and for control of injection timing and rate of injection. Electronic control systems are discussed separately in Section 4.2.5; the remaining changes are discussed here.

Higher precision — There has been a general trend in the heavy-duty industry toward the use of more expensive, higher precision fuel-injection pumps and governors. Most commonly, this has involved substituting an inline fuel pump for the cheaper distributor-type pump. The benefits of this substitution are better control of the fuel injection process and the use of greater fuel-injection pressures. Improved control of the fuel injection process can reduce both emissions and fuel consumption by eliminating secondary injection (a significant source of hydrocarbon emissions) and by making possible much more precise control of injection timing. The widespread use of retarded injection timing for NO_x control has made precise control of injection timing very important, since the engine becomes more sensitive to changes in timing as timing is retarded. At very low NO_x levels, a variation of as little as 1 degree in timing can result in significant degradation in emissions and fuel economy.

Higher injection pressure — High fuel-injection pressures contribute to more rapid mixing and more precise control of the combustion process. Fuel injection requires a finite amount of time, so that the fuel injected near the end may burn under different conditions from that injected near the beginning. Increasing the injection pressure can shorten this interval, or, alternatively, can allow for finer atomization of the injected fuel. Increasing the injection rate and atomizing the fuel more finely both help to speed the fuel-air mixing process, and thus the rate of combustion. By carefully optimizing other engine settings such as the injection timing, this increased combustion rate can be made to yield a better tradeoff between fuel economy and emissions, especially NO_x.

Optimal injection timing and variable injection timing — Fuel-injection timing involves a multi-dimensional tradeoff between fuel economy, noise and engine durability, NO_x emissions, particulates, and hydrocarbons. Thus, some compromise between different objectives will always be necessary. To make matters worse, the optimal injection timing to achieve any given compromise varies as a function of the engine speed, load, and fuel cetane rating, among other variables. Because of this, a single, static setting of the injection timing -- even when carefully selected to minimize emissions over a given cycle — cannot possibly perform as well as one which is dynamically adjusted to match the current operating conditions. This is especially true when injection timing is retarded to produce low NO_x levels, since performance, particulate emissions, driveability, and fuel economy are all very sensitive to injection timing in that range.

Despite this fact, dynamically adjusted injection timing is not yet common on high-powered diesel engines. The major reason for this is the difficulty in implementing it--the fuel injection pump on a diesel engine is generally geared to the crankshaft, and absorbs several horsepower. Developing a control mechanism which is sensitive enough to adjust accurately the phase relationship between crankshaft and fuel pump, and robust enough to deal with the forces involved, is not an easy task. Because of this, *mechanically-variable injection timing control* has — with some exceptions — mostly been limited to engines with distributor-type fuel pumps. These have design features well-suited to this type of control. However, such pumps are limited to fairly low injection pressures, and the recent trend has been to higher pressures using in-line fuel pumps or unit injectors, for which dynamic timing is more difficult.

In response to regulatory pressure and the need for improved fuel-economy, dynamic timing mechanisms have been developed for some in-line fuel pumps. An outstanding example of this is the new Caterpillar fuel pump, used on the Caterpillar 3406B engine (Connor and Stapf, 1983). This mechanism uses a mechanically-actuated hydraulic servo to vary the injection timing advance in response to changes in engine speed. The system has also been designed to be used with digital electronic rather than mechanical controls, when these become available.

<u>Status and prospects</u> — Higher precision, higher pressure, and more flexible (i.e. dynamically adjustable) fuel-injection systems are among the engine manufacturers' most important tools in attempting to meet stringent NO_x and particulate standards while retaining acceptable performance, drivability, and fuel economy. For this reason, fuel injection systems have been an area of very active development, and a number of upgraded and improved injection systems have been introduced in recent years. To date, all such systems in the United States have incorporated mechanical controls. However, a number of manufacturers of fuel injection systems have recently announced the availability of digital electronic controls for use with their products and Isuzu (Wakabayashi et alia, 1984) has just introduced such a system in Japan. GM has also indicated that electronic controls will be introduced into its product line on a limited basis by 1986, and Cummins plans to introduce them on its new line of light-heavy diesels. Thus it appears certain that such systems will appear on production engines in the United States within a few years.

4.2.3 Charging Technologies

Most heavy-duty diesel engines are now turbocharged, primarily because of the increased power output turbocharging provides. Turbocharging can also increase the engine's efficiency slightly, with a consequent decrease in fuel consumption. Turbocharging increases the temperature and oxygen partial pressure in the cylinder. These tend to increase both the soot formation and the oxidation rate, but the effect of increased oxidation appears to dominate, so that the overall effect is a decrease in particulate emissions at any given power level. Finally, turbocharging reduces the incentive to operate near the engine's smoke limit in order to obtain maximum power, which also improves particulate emissions. This reduction in particulates is achieved at some cost in increased NO_x emissions, however, due to the higher temperatures and pressures reached in the cylinder. The increase in NO_x can usually be recovered by retarding the injection timing, but with some loss in the advantages of turbocharging. It can also be recovered by cooling the hot compressed air from the turbocharger before it enters the engine. This practice -- variously known as intercooling, aftercooling, and charge-air cooling -- has become extremely common.

One disadvantage of turbocharged engines is that they can exhibit very high transient particulate emissions. This is because it takes time for the turbocharger to speed up and increase the airflow in response to an increase in engine load, while the increase in fuel flow is very rapid. Thus the increased fuel flow to the engine is not, at first, matched by sufficient air, resulting in excessive particulate production and a dense black "puff" of smoke. Modern engines deal with this problem through the use of a "puff limiter" -- a device incorporated in the governor which reduces the fuel flow to the engine until the turbocharger is up to speed. These devices inevitably compromise acceleration and driveability, however.

The acceleration smoke problem can be alleviated by improving the match between the engine and the turbocharger characteristics, and by improving the design of the turbocharger itself. Current interests in this area are focussed on development of variable-inlet area turbochargers (e.g. Arvin and Osborn, 1983), incremental improvements in current fixed-area turbochargers, and on some advanced technologies which are discussed below. The incremental optimization procedures are not likely to result in any spectacular gains, but their potential for reducing transient-test particulate emissions is by no means negligible. Of equal importance is the fact that these changes can improve driveability, reducing the incentive for the driver to tamper with the puff limiter.

<u>Charge-air cooling</u> — Compressing air, as in a turbocharger, increases its temperature. Charge-air cooling is the practice of cooling the hot compressed air from the turbocharger by passing it through a heat-exchanger before allowing it to enter the engine. This has two beneficial effects: it decreases the maximum temperature reached during combustion (thus reducing NO_x emissions); and it decreases the specific volume of the air, so that a greater mass can enter the cylinder. This increases the partial pressure of oxygen in the cylinder, which usually decreases particulate emissions. In addition, charge-air cooling increases both the efficiency and the maximum power of the engine. The net result is a decrease in fuel consumption and in NO_x emissions, an increase in available power, and generally some decrease in particulate emissions as well.

Because of these advantages, charge-air cooling is rapidly becoming universal on line-haul truck engines, and it is found on many transit-bus and medium-heavy diesel engines as well. Present production charge-air coolers use the engine cooling water as a heat sink. This limits the degree of cooling possible -- the minimum temperature reachable is about 100° C. Advanced technologies which would use either a separate cooling circuit or an air-to-air heat exchanger could attain significantly lower temperatures, with a consequent decrease of up to 20 percent in NO_x emissions (Cummins, 1982).

Advanced low-temperature charge-air cooling systems would decrease fuel consumption and NO_x emissions *still more (Henriksen, 1983), but at some cost in other drawbacks.* These drawbacks would include the requirement for more heat-exchanger surface on the vehicle, with a consequent increase in bulk and drag. In addition, the greater volume of air in the heat exchanger might exacerbate the problem of turbocharger lag, and the lower exhaust temperature would reduce the attractiveness of turbocompounding. Low exhaust temperature would also make a self-regenerating trap-oxidizer system less attractive, and might rule it out altogether. There is also the possibility of over-cooling of the intake air, with a consequent sharp increase in hydrocarbon and possibly particulate emissions, and possible difficulties with cold starting. Such problems could be prevented, however, by the use of a thermostatically operated bypass valve.

<u>Advanced charging technologies</u> — A number of advanced charging technologies are under investigation. The technology which has drawn the most regulatory attention to date is the so-called "three-wheel" turbocharger or TWT (Timoney, 1983). In addition to

the traditional turbocharger's two "wheels" (the gas turbine and the compressor), the TWT incorporates a small Pelton hydraulic turbine on the same shaft. This turbine, which is driven by lubricating oil from an engine-driven pump, is used to provide additional power to the air-compressor during transient operation. This eliminates the turbocharger lag, and thus permits improved acceleration along with a decrease in particulate emissions and visible smoke. Depending on the specific engine, the reduction in particulate emissions on the certification test might be as much as 20 percent. The reduction in in-use particulate emissions would be even greater, since puff limiters are often not maintained and occasionally tampered with, and this technology would eliminate the need for a puff limiter.

The TWT is particularly attractive for use with two-stroke engines, since the presence of an independently controllable air-compressor would eliminate the two-stroke's present need for a separate blower. Eliminating the blower would reduce manufacturing cost, parasitic losses, and crowding in the engine compartment. Although the TWT has received the most attention in this regard, the same result could conceivably be accomplished by other technologies. Three possibilities in this regard are the so-called "Comprex" or gas-dynamic supercharger, an electric-motor assist for the turbocharger (controlled by a variable-speed electronic drive), and the use of an engine-driven supercharger (with turbocompounding to avoid wasting the energy now recovered by the turbocharger).

Status and prospects -- Moderate-temperature charge-air cooling (with heat rejection to the engine cooling water) is now almost universal on line-haul and other very heavy-duty engines, primarily because of the improved fuel economy and power output it makes possible. For the same reasons, an increasing number of premium medium-heavy duty engines are incorporating this technology as well. Advanced charge-air cooling systems, using either low-temperature liquid-to-air or air-to-air heat exchangers are now in the late stages of development, and can be expected to appear in production in the 1986 to 1988 time frame.

Among the advanced charging technologies, the gas-dynamic supercharger is in the most developed. Such devices have been commercially available for several years, but they have not yet been accepted by engine manufacturers and users. The TWT is still a development project at present, although the early results of this development appear very promising. The authors are not aware of any development efforts involving either superchargers or electric-motor assist for heavy-duty engines. It is still much too early to predict when or if engines incorporating any of these devices might appear in production.

4.2.4 Exhaust-Gas Recirculation

EGR is a time-proven NO_x control technique for light-duty gasoline and diesel vehicles, and it has been proven effective in heavy-duty engines (Yu and Shahed, 1981; GM, 1982a; Daimler-Benz, 1982). EGR works by recycling a portion of the exhaust gas to mix with the intake air. This dilutes the air in the cylinder with inert gases and thus increases the total amount of gas that must be heated by each unit of burning fuel. The recycled exhaust gases also have a higher heat capacity than does air. Both effects reduce the peak local temperature in the flame, and thus decrease NO_x formation. Unlike retarded injection timing, properly applied EGR should have only minor effects on performance and fuel economy at moderate loads. However, the recycled exhaust gas decreases the total amount of oxygen in the cylinder, which decreases the maximum power output of the engine. If the engine is not derated to account for this, EGR can cause it to operate above its smoke-limited power level, with a consequent enormous increase in particulate emissions.

The effects of EGR on maximum power and particulate emissions can be alleviated through the use of "modulated" EGR, in which the degree of exhaust gas recycling is changed to match the load on the engine. In this way, it is possible to obtain reasonable control of NO_x emissions at low and intermediate loads without compromising maximum power. However, the reduced flame temperature and reduced oxygen content of the charge still lead to an increase in particulate emissions, which becomes more severe as NO_x levels are reduced further by this means. EGR can be modulated either by mechanical means or by an electronic control system. The latter arrangement, which is much more flexible and effective, is discussed in the next section.

Aside from its effects on particulate emissions, EGR has a number of detrimental effects on the engine. The most important are the effects on durability, maintenance requirements, and fuel consumption.

The effect of exhaust gas recirculation on durability and maintenance requirements is due primarily to the fact that soot particles in the exhaust are recycled through the engine. These particles increase abrasive wear on the cylinder liners. They also get into the engine oil, where they absorb and neutralize some of the additives, and can also lead to abrasive wear in the other moving parts, necessitating more frequent oil changes. Soot particles can also form cakes and deposits in the air intake system and on parts such as turbochargers and blowers. These problems — especially the increased wear — are much more severe on large heavy-duty engines than in light-duty service, due to the much greater expected lifetime of the heavy-duty engine. If not successfully mitigated, they could be expected to lead both to increased economic costs and to significant tampering with the EGR valve by truck owners in an effort to protect their investment. These problems could be eliminated by the use of trap-oxidizers, with the EGR return taken from the exhaust downstream of the trap. They could probably also be alleviated to some degree by careful design, improved lube-oil additives, and more frequent oil changes. These (especially the last) would be expensive, however.

EGR is especially problematic for two-stroke engines, since the recycled soot, water, and acid gases can foul and damage the scavenging blower. On the other hand, these engines could use a form of "internal" EGR by modifying the scavenging characteristics to retain more exhaust in the cylinder between strokes. GM (the only U.S. maker of two-stroke diesels) has reported the development of a very similar system to control the cylinder temperature in a Methanol-fueled bus engine (Toepel et alia, 1984).

A number of manufacturers have reported that EGR increases fuel consumption significantly — by as much as 8 percent (Daimler-Benz, 1982). However, there is no fundamental reason to expect such an increase — at most, a slight decrease in the rate of combustion near TDC and a consequent slight (1 percent) increase in fuel consumption would be expected. One possible explanation for the reported increase is that the test engines had not been completely optimized for use with EGR. Another is that the recirculated exhaust gas is hot, thus increasing the temperature of the charge and decreasing both fuel efficiency and maximum power, in the opposite effect to that of charge-air cooling. This would also increase the flame temperature, partially offsetting the dilution effect of the exhaust gas. These problems could be overcome by cooling the recirculated gas, with a consequent increase in both fuel efficiency and NO_x control. Some manufacturers who are considering EGR appear to be planning on this approach. Design of such a cooler would not be easy, however, since it would tend to be clogged with soot, water, and oily deposits from the exhaust, and would suffer from corrosion due to the acid gases (NO_x and SO_2) in the exhaust.

Status and prospects — At present, only two heavy-duty engines use EGR to meet NO_x regulations, and only one of these (the Caterpillar 3208 for California) is in widespread use. However, a number of light-duty diesel engines (including the light-duty version of the GM 6.2 liter engine) now use EGR, and most heavy-duty engine manufacturers have experimented with it. Thus there is a well-developed technology base, and EGR could be implemented fairly readily if necessary. Because of its potential for effective NO_x control with comparatively minor effects on fuel consumption and driveability, EGR seems likely to play an important role (along with charge-air cooling, injection timing, and electronic controls) in meeting future NO_x emissions standards. However, unlike charge-air cooling and electronic controls, EGR does not produce any fuel economy or performance benefits on its own, so that it would not be adopted unless it were necessary to meet an emissions standard.

4.2.5 Electronic Controls

As the discussion above has indicated, the major problem with EGR and retarded injection timing as NO_x control techniques is the resulting increase in particulate emissions, especially at high loads. This problem can be minimized by adopting a control strategy which reduces NO_x emissions in those ranges where doing so does not greatly increase particulates, and which relaxes the NO_x controls at high loads. However, the optimal injection timing and EGR setting vary continually as functions of the engine speed, the engine load, and (especially in transient operation) the intake air pressure. Traditional hydromechanical control systems are unable to apply a sufficiently sophisticated control response at a reasonable cost, and are also subject to wear and degradation which can impair their control response over time.

Another hydromechanical control system which is subject to these problems is the engine governor — the device which is responsible for regulating the amount of fuel fed to the engine. The governor is a complex mechanical device which responds not only to the position of the accelerator pedal, but also to built-in limitations for minimum idle speed, maximum engine speed and maximum fueling rate, and cold-starting fuel flow, among others. Governors in turbocharged engines also include some form of "puff limiter" to reduce the maximum fuel flow to the engine during acceleration until the turbocharger is up to speed. Although the governor is not usually thought of as an emissions control device, it does in fact have a very important effect on emissions, especially particulates and hydrocarbons. Some recent research (Reams et alia, 1982) on light-duty diesels has indicated that the limitations of the mechanical governor (especially the problem of overshooting during acceleration) may be responsible for a significant fraction of total light-duty particulate emissions. Reams and coworkers found that an electronic governor with a fully optimized control program was able to reduce particulate emissions by 37 percent on the light-duty Federal Test Procedure, while reducing fuel consumption by three percent. Heavy-duty governors are somewhat more expensive and more precise, so the possible savings would probably be less, but they are still probably quite significant.

Because of the difficulties with present hydromechanical controls, microprocessor-based digital electronic control systems for injection timing, EGR regulation, and the engine governor are being developed by virtually all manufacturers (Voss, 1981; Day and Frank, 1982; Lucas et alia, 1983; Toepel et alia, 1983). One such system has already been introduced in Japan (Wakabayashi et alia, 1984). As they are now envisioned, these control systems will accept input from a number of sensors for accelerator pedal position, engine speed, engine load, ambient temperature, boost pressure, and other variables, and calculate optimal settings for the injection timing, fueling rate, and EGR valve position. These calculations will be based on a "map" of optimal settings stored in the microprocessor's read-only memory. In many cases, this "map" may also include externally specified limits such as road-speed governing (overriding the driver), which is desired by many fleet operators as a fuel-saving technique.

The microprocessor will then send appropriate signals to a set of electromechanical actuators to adjust the fuel injection timing, fuel metering, EGR valve setting, and so on. Ultimately, a closed-loop control system, in which the microprocessor would continuously optimize control settings based on feedback from engine sensors, will probably be adopted. A system of this type for setting injection timing has already been demonstrated in the laboratory (Pipho and Kittelson, 1983).

__Status and prospects__ — A number of fuel-injection system manufacturers have already announced the availability of digital electronic control systems for their products, although many of these have been for light-duty diesels. Because of the improvements in fuel economy and driveability of low NO_x levels that electronic controls would make possible, all heavy-duty engine manufacturers (and almost all light-duty diesel manufacturers) are now heavily engaged either in developing their own systems, or in applying the commercially available systems to their engines. The competitive importance of electronic controls is such, however, that very little information on development status or the results achieved is available. Several engine manufacturers refused to discuss testing results even confidentially.

In other work for the EPA (Weaver, 1984b), one of the authors has examined the effects of electronic controls on the relationship between NO_x and fuel economy. The conclusion of this work was that optimal electronic timing controls were most effective at moderately low NO_x levels. As Figure 4.9 shows, for most manufacturers, the electronics make little difference at high NO_x levels, where precise injection timing is less critical. The exception is manufacturer "C", in which the production (static) timing is apparently sub-optimal. As injection timing is retarded to achieve lower NO_x levels, precise timing becomes increasingly important. Under these conditions, the electronic timing controls can significantly reduce NO_x emissions with less degradation in fuel economy than static injection retardation. At very low NO_x levels (below 4 g/BPH-hr), this advantage is lost, and the fuel-economy penalties with and without electronics increase rapidly.

Both fuel economy and particulate emissions are determined by the quality and timing of the combustion process. Thus, it appears likely that improvements in particulate emissions due to electronic timing control would more or less follow the pattern in Figure 4.9 — being greatest between about 5 and 7 g/BHP-hr NO_x and dropping off on either side. Electronic governor control would improve particulate emissions still further, and should improve fuel economy slightly as well. Overall, the authors estimate that a fully developed electronic engine control system whould make it possible to achieve 5.0 g/BHP-hr NO_x at low mileage, with a small improvement in brake-specific fuel consumption over present levels, and with particulate emissions 30 to 40 percent lower than present-day engines at the same NO_x level. These estimates are based on the limited published data available (Ring, 1984; Komiyama et al, 1984; GM, 1984b), and on confidential information provided by manufacturers.

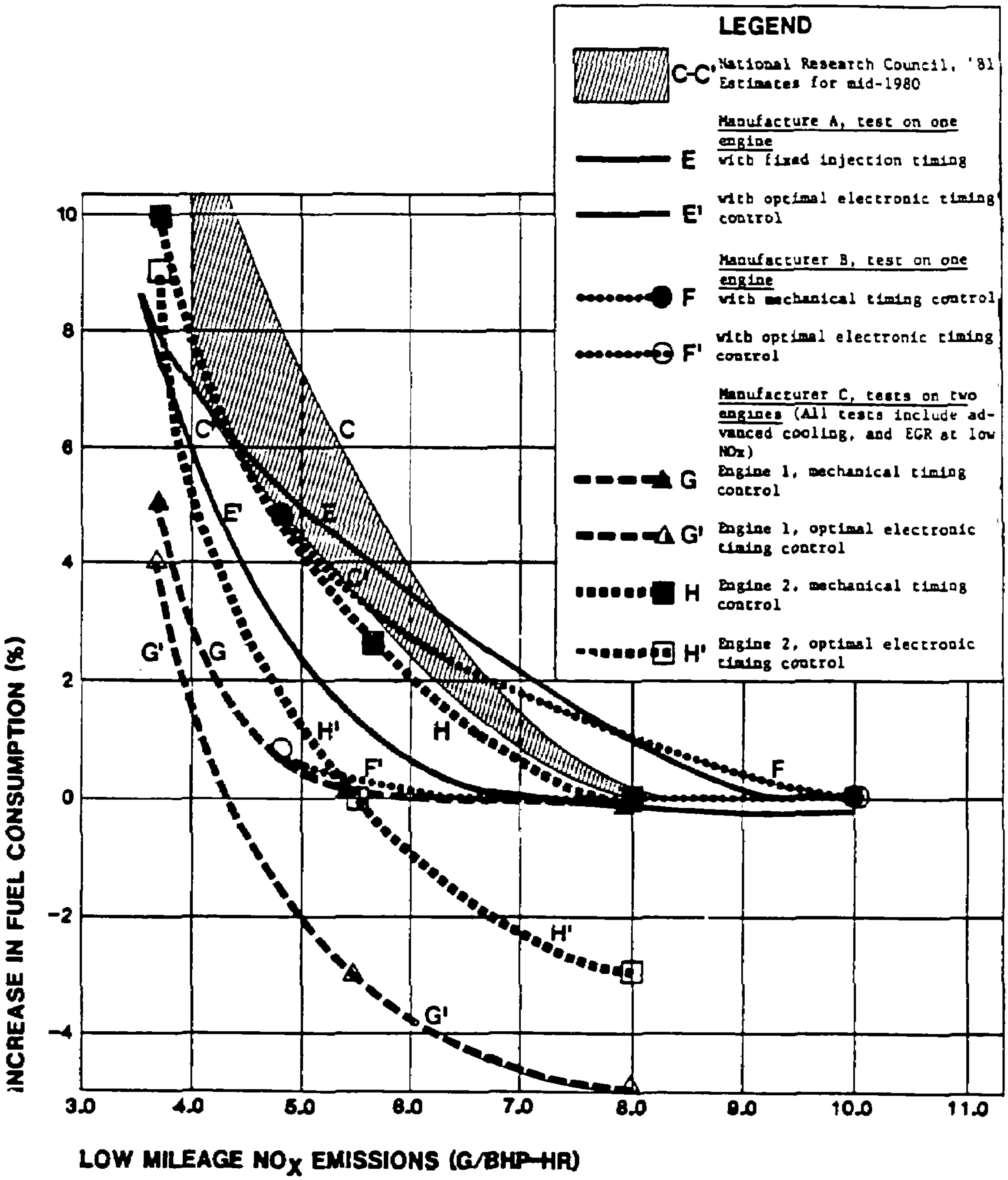


Figure 4.9: Fuel economy vs. NO_x emissions -- effects of electronic controls (Source: Weaver, 1984b)

The economic importance of these improvements, especially the improvement in fuel economy, is such that electronic engine control systems can be expected to be introduced as quickly as possible. It is expected that integrated electronic engine control systems will appear in a significant number of light-duty diesel engine models by 1985, and that some should be introduced for heavy-duty service in 1986 or 1987. By the end of the decade, virtually all heavy-duty engine families should be equipped with this technology, even in the absence of a strict NO_x limit. The presence of such a limit would, of course, tend to accelerate this trend.

4.2.6 Indirect Injection

The indirect-injection (IDI) or prechamber diesel engine is commonly used in light-duty and light-heavy duty vehicles. It differs from the direct-injection (DI) engine used in virtually all medium-heavy and larger diesel vehicles in having two combustion chambers per cylinder — the main combustion chamber above the piston, and a separate prechamber into which fuel is injected. These two arrangements have been discussed in Section 4.1.1, and the different types are shown in Figures 4.1a and b.

In the DI engine, fuel is injected directly into the main combustion chamber, which is the space between the top of the cylinder and the piston. In the IDI engine, fuel is injected into a separate prechamber where it is vaporized and partially burned. The pressure built up in the prechamber due to this burning causes the fuel air mixture to shoot out into the main chamber in a flaming, turbulent jet. This turbulence produces very rapid and complete mixing between the air and the fuel, making expensive high-pressure, high-precision injection pumps unnecessary. The rapid mixing also makes possible a greater engine speed, which is important in matching diesel engines to light-duty vehicles designed for gasoline power.

From the emissions-control viewpoint, the most important effect of indirect injection is in reducing both NO_x and particulate emissions. The delayed combustion resulting from dual combustion chambers results in low NO_x emissions, while the intense mixing and higher temperatures in the cylinder combine to reduce particulates. The overall effect is a substantial improvement in the NO_x/particulate tradeoff. The indirect-injection engine can thus be considered as an extreme case of the optimization of fuel-air mixing discussed above. By the same token, however, the potential for further improvements in

IDI engines by means of other technologies such as retarded injection timing or high-pressure fuel injection is rather slight — these technologies have most of their effect through mixing, which is already nearly optimal in the IDI engine. Other, non-mixing-related techniques such as EGR, turbocharging/aftercooling, and electronic controls would, however, be as applicable to these engines as to the direct-injection design.

The significant emissions benefits of IDI engines are attained at a significant price — a loss in fuel economy of about 8 to 12 percent from that attainable with direction injection. This loss results from the effective "injection retard" due to the dual combustion, from pressure losses due to expansion through the orifice between the prechamber and the main chamber, and from the increased heat loss to the greater area of the combustion chamber walls. This reduced efficiency has generally rendered prechamber diesels unmarketable in heavy-duty highway applications, in which fuel economy is at a premium. In addition, the increased heat rejection to the engine also requires a larger radiator area, which in some cases would make it impossible to mount a prechamber engine in existing trucks, and in any case would increase the drag and aerodynamic losses. The increased heat rejection also makes the engine run hotter, impairing its durability.

<u>Status and prospects</u> — Due to their higher speed capabilities and the fact that they do not require as expensive fuel-injection systems, IDI diesels are now the only type of engine used in light-duty or light-heavy duty service. They are likely to maintain this dominance in light-duty vehicles for the forseeable future. However, in medium-heavy and especially in line-haul service, the increased fuel consumption, increased heat rejection, and impaired durability of the IDI engine are likely to continue to rule it out. Only one manufacturer (Caterpillar) has seriously attempted to market IDI engines in these classes, and Caterpillar has stated that it plans to abandon that attempt (Caterpillar, 1982). A number of manufacturers are also introducing small high-speed DI engines into the light-heavy duty class in order to obtain the DI's lower fuel consumption there as well. In transit buses, where the willingness to pay for reduced emissions may be somewhat greater, the IDI engine could conceivably have a future. However, there does not presently appear to be any move to develop or market such an engine for this class.

4.2.7 Advanced Engine Technologies

A number of advanced heavy-duty engine technologies are now in various stages of development, and many of these — such as the stirling and the gas-turbine engine — would emit substantially less pollution than does the diesel engine. However, to date, these technologies have not been shown to be able to compete with the efficiency and durability of the diesel, and in any case, they are not themselves diesel engines, and are thus beyond the scope of this report. The three advanced diesel engine technologies which are attracting the most attention at this time are the uncooled or adiabatic diesel diesel engine, turbocompounding, and the use of an organic rankine "bottoming" cycle.

Adiabatic diesel engines — A substantial fraction of the energy consumed by a diesel engine is lost through heat transfer to the cylinder walls. With metal cylinder walls, this heat must be continuously removed in order to prevent damage to the engine — thus the need for cooling channels, water pump, radiator, and other components of the cooling system. By substituting a high-temperature ceramic for all or part of the cylinder walls, it is hoped to be able to eliminate both the heat loss and the cooling system. Eliminating the heat loss to the walls will directly increase the engine efficiency, by several percent, with a further increase due to eliminating the parasitic loads of the water pump and the radiator fan. A further increase in vehicle efficiency will be made possible by eliminating the need for the radiator, which will allow for much better aerodynamic design of the front of the truck.

Other things being equal, an increase in engine or vehicle efficiency will result in a corresponding decrease in pollutant emissions (although engine manufactorers do not receive credit for vehicle efficiency improvements under the current regulatory structure). In addition, the adiabatic engine should result in a substantial improvement in the NO_x-particulate and NO_x-hydrocarbon tradeoffs, since the higher average exhaust temperature and higher radiant temperature in the cylinder should increase HC and particulate oxidation. NO_x emissions should not be significantly increased, since the higher average temperature would have only a minor effect on the adiabatic flame temperature. The effect of increasing the radiant temperature on particulates should be especially marked, since particles — unlike gases — are highly efficient absorbers and emitters of radiation. Recent data from Cummins (Sudhaker, 1984) confirm these expectations for the NO_x/fuel consumption and NO_x/hydrocarbon tradeoffs. To date, the authors are unaware of any publicly available data on particulate emissions by adiabatic diesel engines.

<u>Turbocompounding</u> — This technique makes use of the residual energy in diesel engine exhaust to generate additional work. Diesel exhaust, especially in turbocharged engines, is emitted at temperatures and pressures well above atmospheric. Turbochargers use some of this additional energy to turn a turbine, which in turn drives the air compressor. By using a more efficient turbine, additional energy beyond that needed by the air-compressor can be generated, and used (through an appropriate linkage) to drive the wheels. Turbocompounding is most attractive when combined with the adiabatic engine, due to the greater energy content of the exhaust.

The effects of turbocompounding on emissions would be minimal -- a small decrease due to increased engine efficiency is all that could be expected. However, turbocompounding (along with the adiabatic-engine concept) would be beneficial in reducing the fuel consumption penalty due to injection timing retardation, since the turbine would then recover some of the energy invested by late combustion (Toyama et alia, 1983). On the other hand, turbocompounding might also greatly complicate other exhaust-system related emissions control technologies, especially EGR and trap-oxidizers.

<u>Organic rankine bottoming</u> — Like turbocompounding, organic rankine bottoming makes use of the residual energy in diesel exhaust to generate additional work. Unlike turbocompounding, however, the rankine engine would require a separate fluid loop and heat exchanger, with a consequent increase in size, weight, expense, and maintenance. It is doubtful whether the increased efficiency of this approach, compared to turbocompounding, would justify these increases in size and weight. If ORC bottoming is ever implemented, it will probably be in line-haul trucks, for which it can provide a decrease in fuel consumption of up to 12.5 percent (DiBella et alia, 1983). This would result in a direct decrease in NO_x and particulate emissions, of a magnitude similar to that of the decrease in fuel consumption.

<u>Status and prospects</u> — Adiabatic engines and turbocompounding are presently the subjects of intense research and development by a number of manufacturers -- primarily because of their potential for increasing fuel efficiency. Turbocompounding would use relatively well-understood technology, but its value is reduced without the adiabatic engine, so it is not clear whether turbocompound engines will appear before adiabatic

ones. Adiabatic engine development, in contrast, may require a substantial extension of the state of the art in industrial ceramics and high-temperature lubrication. Developing ceramics and ceramic bonding and fabrication techniques which can survive for hundreds of thousands of miles in a diesel engine without failing or developing excessive wear is a formidable task. The industry appears to be fairly confident that this can — eventually — be done, but it would be premature at this point to predict when (or even whether) this will occur. Given the present state of the art, and the lengthy lead times for development, it seems highly unlikely that production adiabatic diesel engines will be available before the 1990s.

Research on organic rankine bottoming cycles appears to have peaked during the late 70s, under the influence of DOE funding. While development work on this approach is continuing, it is too soon to predict when — if ever — it may be implemented in practice.

4.2.8 Additives and Alternative Fuels

Fuel additives such as barium have long been used to reduce visible smoke from diesels. The effect of barium on particulates, however, is to substitute barium sulfate particles for carbon particles, with little net effect on particulate mass emissions. For this reason, present interest in these areas is focussed on the use of alternative, cleaner fuels such as ethanol and methanol, and on the use of water and/or alcohol along with diesel fuel to affect combustion. The three most highly developed approaches in this regard are the use of water-diesel fuel and alcohol-diesel fuel emulsions, fumigation of the intake air with water, and the use of methanol as a substitute for diesel fuel in the diesel engine.

Water/diesel fuel and alcohol/diesel fuel emulsions — A number of researchers have experimented with the possibility of mixing water and/or alcohol with diesel fuel in order to reduce NO_x and particulate emissions. The primary interest in this regard has been for underground mining machinery, for which the economics of pollution control are much more favorable than they are in highway applications.

Since alcohols and water are not miscible with diesel fuel at ordinary pressures, it has been necessary to mix them in the form of an emulsion of finely divided water or alcohol droplets in the diesel fuel matrix. This emulsion can either be produced separately and substituted for diesel fuel in the fuel tank, or it can be produced on the vehicle by an emulsifier fed by separate diesel fuel and water/alcohol supplies. The former approach now seems to be preferred due to its greater simplicity. A number of workers have recently reported the results of tests using this type of fuel (Johnson and Stoffer, 1983; Callahan et alia, 1983; O'Neal et alia, 1983). The results reported in these papers were not conclusive — under steady-state conditions, use of a fuel containing a small amount of water or alcohol seems to reduce both NO_x and particulates, by as much as 20% and 50% respectively. On the other hand, transient testing using the EPA cycle showed a sharp increase in particulates with a water-in-fuel emulsion which had given good results in steady-state tests, together with increases in HC and CO emissions.

Water fumigation — Research has shown that mixing water into the intake air for a diesel engine can significantly reduce NO_x emissions (GM, 1982a). This is probably due to several effects, of which the most important are a reduction in the temperature of the intake air due to evaporative cooling, and a reduction in peak flame temperature due to dilution and the greater specific heat of water. However, the water flow rates required for significant benefits are comparable to the fuel flow rate, which would introduce major questions concerning the willingness of truck users to maintain a continuous water supply in return for no perceived benefit. Water injection also has a slight negative effect on fuel consumption, and there is concern that large water flowrates might increase engine wear. Finally, there would be a serious problem in protecting any on-board water tanks and piping from freezing during cold weather.

Methanol fuel — Methanol is a relatively inexpensive fuel which burns with a comparatively low-temperature flame and without soot. It is also readily available in reasonable quantities, and is fairly easy to produce from a wide variety of feedstocks, ranging from coal to natural gas to biomass. Because of these characteristics, it has attracted considerable attention as a possible alternative fuel for motor vehicles. Methanol-burning heavy-duty diesel engines have been developed by General Motors (Toepel et alia, 1983) and by M.A.N. A number of spark-ignited or spark-assisted diesel engines using methanol have also been developed, and there is considerable interest in applying methanol engines in service — especially in transit buses, where the reduction in visible smoke and odor would be most valuable, and the increased inconvenience of a non-standard fuel would be minimized.

Spark-ignition engines are beyond the scope of this report, and will not be discussed here. Compression-ignition methanol engines, however, are within its purview, and they have also attracted considerable attention as a possible means of reducing NO_x and particulate emissions by transit buses. Thus a brief discussion of their characteristics and prospects is in order.

The GM methanol engine is the one for which the most complete information is available. This engine is a modified version of GM's standard 6V-92TA transit coach engine. The engine is a turbocharged, aftercooled, two-stroke model designed for low-smoke operation in buses. In converting it to use methanol, GM made a number of minor changes, including alterations in the compression ratio, using a different turbocharger and blower drive ratio, addition of glow plugs, and substitution of an advanced electronically-controlled fuel injection system for the mechanical fuel injection system on the standard engine. The basic structure and design of the engine were unchanged, however, and except for the fuel injection system it was practically all made from production parts. Dynamometer tests using methanol fuel indicate that this engine has slightly lower peak power, and lower fuel consumption (measured on an energy-equivalent basis). It also had much lower particulate and NO_x levels than the corresponding diesel-fueled engine. Thirteen-mode NO_x and particulates were 0.20 and 0.17 g/BHP-hr respectively, or about a third of the levels of each pollutant emitted by a "good technology" engine burning diesel fuel.

<u>Status and prospects</u> — The prospects for fuel/water or fuel/alcohol emulsions in highway diesels are difficult to assess, because of the inconclusive nature of the testing results to date. There would be enormous practical problems in carrying out a widespread switch to a different fuel of this nature, including difficulties with fuel separation during storage, possible freezing of the water, and possible corrosion in the fuel system. The problems with water injection into the intake air would be similar -- with the additional difficulty of ensuring that a reliable supply of water is provided by the user. Because of these difficulties, neither of these approaches presently appears very promising.

The use of methanol-fueled engines — especially in transit coaches — appears to be a much more promising approach. Such engines could drastically cut particulate and NO_x emissions from transit buses. Since bus emissions result in much greater human exposure per unit of pollutant than do emissions from most other types of vehicles, this could have a disproportionate effect on increased health and welfare. Buses are also well suited to using methanol, since they have adequate spare space to carry the larger fuel tanks required, and they are virtually all supplied with fuel from a separate, central fueling facility rather than purchasing it at retail. However, all of the data concerning methanol engines are not yet in — it will be necessary to know their long-term durability and performance characteristics before a fully realistic assessment of their potential can be made.

4.3 PRESENT-DAY ENGINES AND EMISSIONS LEVELS

For discussion purposes, it is convenient to divide heavy-duty diesel engines into two groups on the basis of their technical characteristics. These groups are the light-heavy duty IDI engines on the one hand and all other heavy-duty engines on the other. The former group are small, high speed, indirect-injected designs derived from passenger car diesel technology, and bear little resemblance to the large, medium-speed, and almost entirely direct-injected designs which are used in heavier trucks. Although this latter group displays some strong internal differences of its own, these are outweighed by the underlying similarities. The new small, high speed DI engines being introduced for light-duty services bear a greater resemblance to the larger DI engines than to the IDI engines in light-heavy duty service, and are included in the former group for discussion.

4.3.1 Light-Heavy Duty IDI Engines

Light-heavy duty diesel engines are very new — until 1981 no such engines existed. At present, only three models of light-heavy duty IDI engines are manufactured for highway use. These are the International Harvester 6.9 liter engine, a similar capacity engine produced by Onan, and the General Motors 6.2 liter. The 6.2 liter engine is a modified version of GM's successful 6.2 liter light-duty truck engine. The technology for these engines is derived from passenger-car and light-truck diesels, and they closely resemble light-duty engines in their durability characteristics, performance, operating characteristics, and emissions levels. These characteristics have been designed with a view to making these engines close substitutes for gasoline engines of similar size.

The most important emissions control technology in this group is indirect injection. Although emissions control was probably not the major consideration in choosing this injection mode (other advantages such as high speed capabilities, power output, and a tolerance for lower-cost fuel injection systems were probably more important), it is nonetheless a highly effective emissions control technique. Other emissions controls used in present production versions of these engines include mechanically-variable fuel injection timing and extensive engine optimization. The close resemblance between these engines and light-duty diesels also means that light-duty emissions control techniques could be adopted very quickly. These techniques would include EGR (the light-duty version of the 6.2 liter already uses mechanically modulated EGR), electronic control of injection timing and EGR modulation, and possibly an electronic governor. Due to the comparatively low cost and limited durability of these engines, heavy-duty emissions control techniques such as turbocharging/aftercooling, turbocompounding, and adiabatic engine design would probably not be feasible.

Emissions levels -- Table 4.2 shows the 1983 model year EPA certification data for the 6.9 and 6.2 liter engines, together with some unofficial transient-test NO_x and particulate data for the 6.2. Transient test data for the 6.9 liter engine are not yet publicly available. As the table indicates, both engines are very clean -- with NO_x emissions below 4.0 g/BHP-hr and very little smoke on the EPA test. The earlier GM transient test data for the 6.2 liter engine are even more remarkable in this respect -- they are far and away the lowest measured emissions levels from heavy-duty diesel engine of which the authors are aware. Changes in the compression ratio and variations in production timing apparently increased emissions somewhat -- the later data for this engine, although still very good, are not significantly different from what the best DI diesels are now achieving. The light-duty version of the GM 6.2 liter (which differs from the heavy-duty version in having EGR) is also extremely clean. Despite the use of EGR with a mechanical control system, FTP particulate emissions for trucks using this engine are 0.35 g/mi. This would be quite respectably low for a mid-size passenger car; it is phenomenally low for a 6000 pound truck.

4.3.2 Medium-Heavy, Line-Haul, and Transit Bus Engines

Medium-heavy and line-haul engines represent more of a continuum between two extremes than they do two separate classes. Transit-bus engines fall toward the lighter end of this continuum, but with some special features of their own. At the lighter (or medium-heavy) end, engines in this group tend to be naturally aspirated, to have

Table 4.2

Light-Heavy Duty Engine Emissions Levels

	13-Mode NOx (g/BHP-hr)	Smoke Opacity (%) Accel.	Leg	Peak
EPA Certification Data (Model year 1983)[1]				
GM 6.2 liter IDI	2.8	6.3	4.9	6.7
IH 6.9 liter IDI	4.3	3.2	4.3	7.7

Transient-test data for the G.M. 62 liter IDI	NOx (g/BHP-hr)	Particulate (g/BHP-hr)
Pre-production version[2]		
Setting 1	4.1	0.46
Setting 2	2.8	0.52
Production Version[3]		
6 degrees BTC	4.16	0.66
4 degrees BTC	3.60	0.62

[1]Source: EPA, 1983a

[2]Source: General Motors, 1982a

[3]Source: General Motors, personal communication, 1984

moderate power output and limited duty cycles, and to have design lifetimes in the vicinity of 150,000 to 250,000 miles. Examples of this class include the International Harvester 9.0 liter engine and the naturally aspirated versions of the Caterpillar 3208. A step further along the continuum are the "premium" medium-heavy engines such as the International Harvester DTI 466 and the GM 8.2 liter engine. These are generally turbocharged, may have aftercooling, and tend to have better fuel efficiency and fewer duty cycle limitations. A step further yet are the engines designed to be used in heavy trucks in stop-and-go service, such as garbage trucks and dump trucks. These are turbocharged, may have aftercooling, and usually have rather steep torque curves (a rapid increase of torque with RPM) in order to improve driveability. Finally, at the other end of the continuum are the true line-haul engines, which are virtually all turbocharged and aftercooled, designed to run at rated speed and power for very long periods, and optimized for best performance and fuel economy under those conditions.

The emissions control technologies presently in use for heavy-duty engines are turbocharging, aftercooling (using the engine cooling water as the heat sink), engine modifications, and optimized or mechanically-varied injection timing control. High precision and high pressure fuel injection systems are very common in line-haul and similar heavy engines, and are coming into increasing use in the lighter groups. Mechanical puff-limiting devices are also used in turbocharged engines in order to reduce visible smoke emissions during acceleration. In addition, one California-model Caterpillar engine uses indirect injection, and another uses EGR. Neither of these latter technologies has been generally accepted for use in engines in this group, however.

<u>Emissions levels</u> — Figure 4.10 is a plot of transient-cycle NO_x emissions against transient particulate emissions for those heavy-duty engines for which these data were available. For a few engines, data were available at more than one calibration (i.e. at different points along that particular engine's NO_x/particulate tradeoff curve). Data points for these engines are shown linked by solid lines. As indicated by the symbols, almost all of the data available are for direct-injected engines, most of which are turbocharged and aftercooled. However, data for two Caterpillar prechamber engines (one of which does not appear to be offered any longer) are also shown, along with one data point for the Caterpillar engine with EGR. For comparison, the four data points for the GM 6.2 liter light-heavy duty engine have been plotted as well.

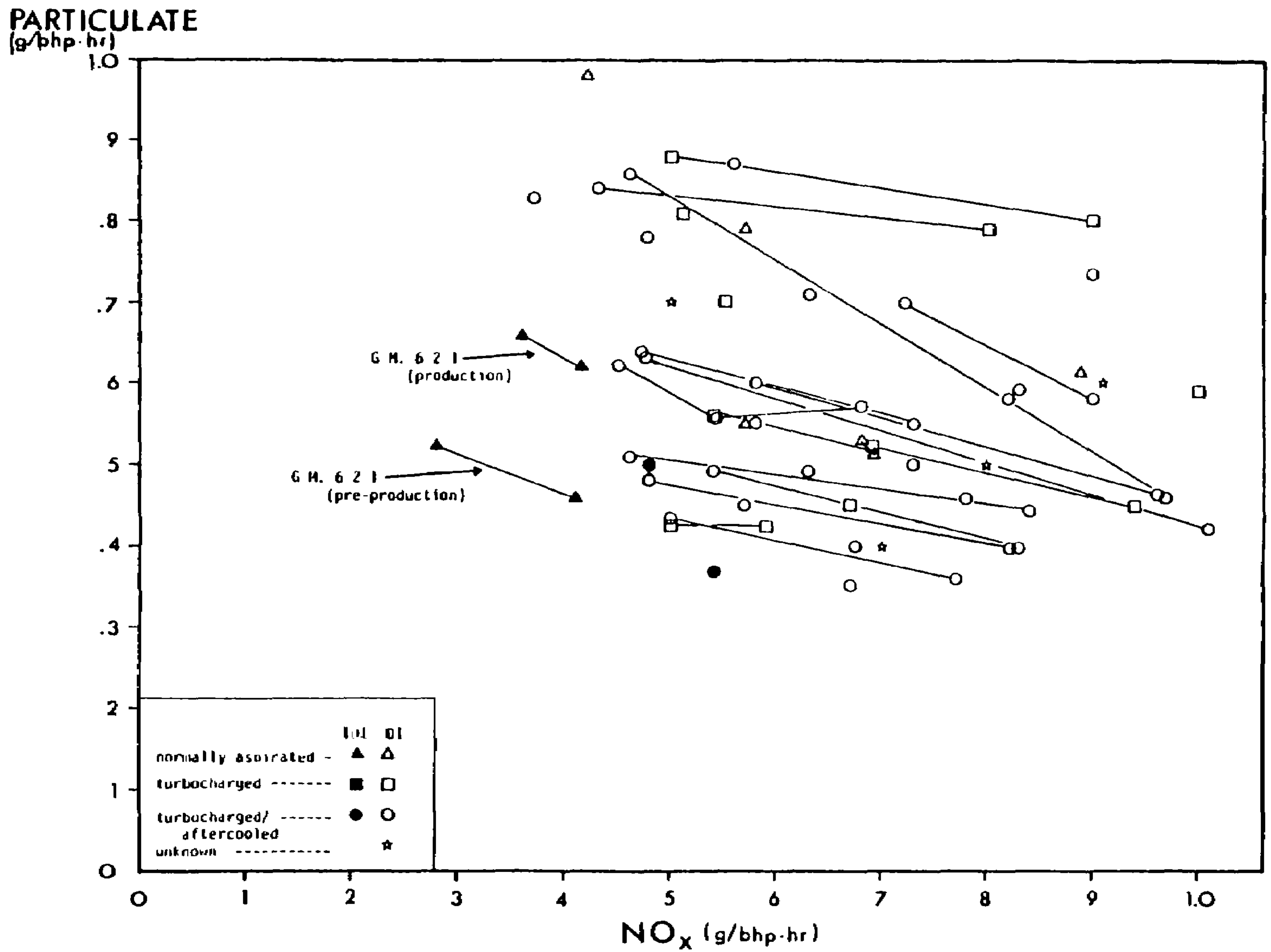


Figure 4.10: NO_x versus particulate emissions for current heavy-duty diesel engines, measured on the EPA transient test.

Several points about Figure 4.10 should be noted. The most important point is the large range in emissions performance among engines in this group. For a given NO_x emissions level, particulate emissions levels may vary by a factor of more than two. There is also little systematic variation — NO_x and particulate emissions seem to be only vaguely correlated from engine to engine, and they are not strongly correlated with either the use or non-use of aftercooling. The three naturally-aspirated DI engines, however, are all relatively high in emissions, while the three prechamber engines are among the lowest emitters. Significantly, most of the lowest emitters on the chart are turbocharged and aftercooled, but so, too, are some of the highest.

Perhaps the most important point about Figure 4.10 is the fact that three fairly distinct groups of engines are visible. Figure 4.11 outlines these groups. Group I, toward the right of the chart, contains engines using more or less standard technology from a few years ago, calibrated to meet the present Federal emissions standards. These engines are relatively low in particulates, but high in NO_x. Group II, in the upper left, consists of engines using the same level of technology but calibrated to meet California emissions standards, with lower NO_x levels but much higher particulates. Group III, contains those engines which -- either by fortunate accident or by careful design -- are able to minimize both NO_x and particulate emissions. This group includes all of the prechamber engines, a number of advanced-technology low-emission DI engines (many of which are not yet in production), and a few older direct-injection engines with exceptionally good emissions characteristics.

In some cases, the characteristics which separate the older engines in Group III from those in Group I are not completely evident, even to their designers. Probably, they include a better match between the engine and the turbocharger, more closely optimized fuel-air mixing, and possibly better design of the combustion chamber. High-quality, high-pressure, high-precision fuel injection systems are also somewhat more common in this group. However, high-pressure injection per se does not produce lower emissions -- it must be carefully matched to the combustion characteristics of the engine. It is hypothesized that this has been done more effectively in those older engines which fall into Group III.

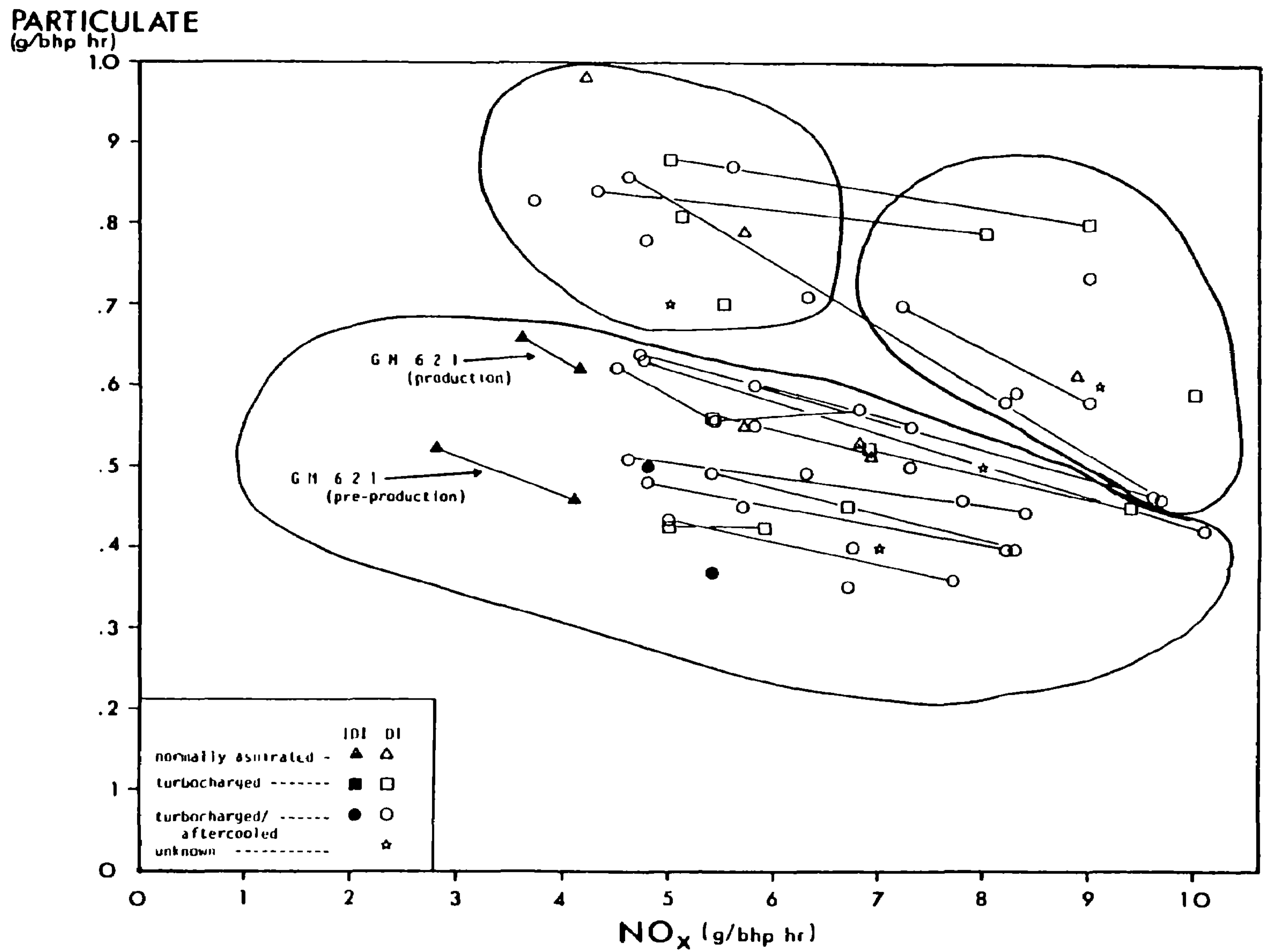


Figure 4.11: Heavy duty NO_x versus particulate emissions -- engine groupings.

4.4 ACHIEVABLE ENGINE-OUT EMISSIONS LEVELS

As discussed above, present heavy-duty engines can be divided rather naturally into two classes: light-heavy engines and all the others. It is convenient to discuss the future emissions levels achievable by these engines in the same format.

4.4.1 Light-Heavy Duty Diesel Engines

The present light-heavy IDI engines are already very low emitters, thus additional reductions cannot be expected to come easily. The major near-term improvement is likely to result from the application of electronically-controlled injection timing and possibly an electronic governor. Both of these improvements will probably be introduced as quickly as possible in order to reduce fuel consumption. Other feasible near-term control technologies such as EGR are unlikely to be introduced without regulatory pressure, due to their deleterious effects on fuel economy and cost. Any significant near-term regulatory pressure in this regard would require a special standard aimed specifically at light-heavy engines, since these engines could readily comply with any reasonable near-term standard set for the larger direct-injection diesels.

Several manufacturers, including Isuzu and Cummins, have developed small, high-speed direct-injection diesel engines for use in the light-heavy duty class. Because of their superior fuel economy, these engines are expected to claim a significant share of the market. However, DI engines generally have greater emissions than IDI engines, so that total emissions levels in this class could be expected to increase as a result. On the other hand, all of the engines being introduced are technologically quite advanced (the Cummins engines, for instance, use full electronic controls), and could thus achieve a stringent emissions standard more readily than the larger DI engines in the heavier classes. Overall, then, both the DI and IDI engines in the light-heavy class should be able to attain any emissions levels which are feasible for engines in the heavier classes, and could do so at least two years earlier.

In the longer term, only marginal improvement in emissions is to be expected in this class unless regulations are tightened significantly. Electronic governors and closed-loop control of injection timing, possibly combined with turbocharging, would probably lead to some improvements in particulate emissions, but these technologies would probably be adopted for improved fuel economy anyhow. If small, high-speed direct-injection engines are successfully introduced in the light-heavy class, the total emissions could even increase somewhat, since such engines are likely to be higher emitters than the IDI models.

4.4.2 Medium-Heavy, Line-Haul Truck, and Transit Bus Engines

Unlike the light-heavy duty engines, engines in this group are likely to be seriously constrained by proposed emissions standards. Thus, a strong and continuing effort to perfect and introduce emission control technologies is under way, and would be further accelerated by adoption of a definite standard. In the near term, a combination of improved engine/turbocharger matching, higher precision and higher pressure fuel systems, charge-air cooling, and careful recalibration and optimization will probably be able to bring all but a few engines down into the emissions range occupied by Group III (the best present-day engines) by 1987 or 1988 — which is the time frame for which standards are being discussed. Introduction of methanol-fueled engines for transit buses (and possibly other vehicles such as garbage trucks) would bring emissions for those engines down to very low levels, but it is too early to predict whether that will occur. Electronic engine controls will definitely be introduced in a few models during 1985-86, and should become fairly common by 1988. It is unlikely, however, that they could be applied across the entire product line before about 1990.

Those engines which cannot be brought into compliance by means of the technologies listed above will probably be dropped, or produced in very limited numbers under an averaging scheme. It appears certain that at least some such engines would be dropped entirely — both Caterpillar and Mack have indicated a possible need to trim their product lines in response to a strict standard.

Curve A in Figure 4.12 shows the approximate average NO_x-particulate tradeoff relationship which is estimated to be achievable by 1987, assuming vigorous application of the technologies discussed above, and assuming that definite, achievable, numerical standards for NO_x and particulates are adopted in the near future. It should be carefully noted that this curve shows the estimated average level of new-engine emissions, not the level of the numerical standard which is estimated to be achievable by 1987. Derivation of an estimated achievable standard is done in Chapter 7, and results in higher standards for NO_x and particulate emissions than are shown here as estimates of actual emissions.

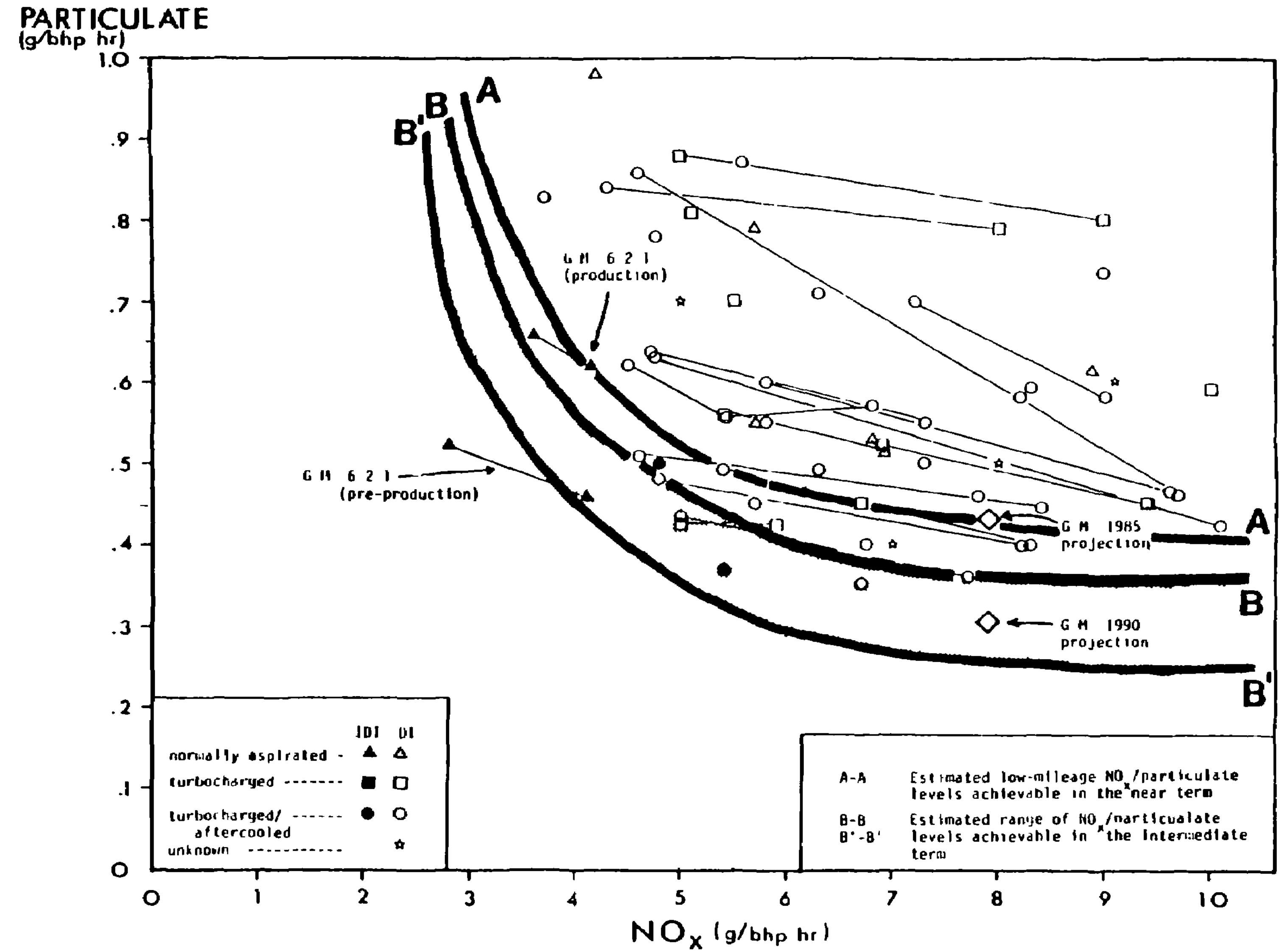


Figure 4.12: Estimates of achievable average low-mileage particulate emissions vs. NO_x for near-term and intermediate-term technologies. (Note: these are not achievable emissions standards -- see text.)

Figure 4.12 also shows two GM estimates of average engine-out emissions levels from new engines in 1985 and 1990. As can be seen, the GM 1985 estimate agrees fairly well with the authors' estimate for 1987.

In the medium term — beginning about 1988 and extending to about 1991 — it can be expected that an entire new generation of sophisticated emissions control technologies will come into production. The most important of these will be fully integrated electronic controls for injection timing, the engine governor, and (if needed) EGR modulation. Exhaust gas recirculation is expected to be widely adopted in heavy-duty engines only if a very stringent NO_x standard is imposed. Electronic controls, in contrast, would be introduced in most models quite independently of any emissions standards, due to their beneficial effect on fuel economy, performance, and driveability. Other advanced technologies which may be introduced on a few models in the 1988-1991 timeframe include the Comprex supercharger, the three-wheel turbocharger, and uncooled (or adiabatic) engines.

These technologies — especially the electronic control systems — can be expected to produce significant improvements in particulate emissions at constant NO_x, as well as better engine performance and fuel economy. The cost of a tightened engine-out particulate standard would thus be fairly small, since in most cases the emissions control equipment would already have been installed for other reasons. Alternatively, some of the benefits of improved technologies could be sacrificed to obtain lower NO_x emissions. In this case, the additional first cost attributable to the regulations would be moderately small (since, except for EGR, the emissions control equipment would already be in place), but the regulation should be charged with the full cost of lost performance, increased fuel consumption, and impaired driveability due to altering control system calibrations to minimize NO_x. These issues have been discussed at greater length elsewhere (Weaver, 1984b).

In addition to their direct effects on emissions, improved control techniques should result in lower variability and more accurate prediction — especially of particulate emissions — thus making possible a more stringent standard even in the absence of any change in average emissions.

The precise degree of improvement in emissions that can be expected and the exact shape of the NO_x-particulate tradeoff curve with these new technologies are both highly speculative — there is simply not enough information publicly available to judge. Curves B and B' in Figure 4.12 give some idea of the range that might be expected. As noted above with respect to curve A, these curves represent estimates of actual new-engine emissions levels which may be achievable — assuming vigorous application of the technologies discussed — not achievable standards. As can be seen, the GM estimate of average new-engine emissions for 1990 falls near the middle of this range.

Curves B and B' have been constructed using engine manufacturers' projections of capabilities (e.g., GM, 1984b), and limited test data provided on a confidential basis, as modified by the authors' engineering judgement. Given the general lack of hard data and reportable results, however, these curves should be understood as being little better than educated speculation, and used with appropriate caution. These curves are believed by the authors to be reasonable, but it is very easy to imagine future developments which would reveal them as either over-optimistic or over-pessimistic. Because of this, any thought of basing actual standards on these estimates would be premature. Further research to clarify the technological issues and capabilities in this area is urgently needed before final standard-setting for the 1990 timeframe takes place.

5.0 TRAP-OXIDIZER SYSTEMS FOR HEAVY- DUTY VEHICLES

Trap-oxidizers are presently the only very promising aftertreatment technology for reducing diesel particulate emissions. A trap-oxidizer system consists of one or more particulate traps (filters) which remove particulate material from the exhaust, together with a system for cleaning the traps by burning off (oxidizing) the collected particulate. Interest in trap-oxidizer technology was initially stimulated by the introduction of diesel-powered light-duty cars and trucks in the late 70's, which led EPA to propose stringent particulate emissions standards for such vehicles. In response to these standards, trap-oxidizer technology for light-duty vehicles has been developing rapidly. The first mass-produced trap-oxidizer systems were introduced on model-year 1985 Mercedes-Benz sedans sold in California, and a number of manufacturers appear to be in the late stages of development and testing for model years 1986 and 1987.

Trap-oxidizer technology for heavy-duty vehicles has undergone much less development. The reasons for this include: less regulatory pressure (no final heavy-duty particulate standard now exists), the lesser R and D capacities of many heavy-duty engine manufacturers, the depressed state of the heavy-duty vehicle and engine market between 1980 and 1983, and the greater difficulty of the development tasks for heavy-duty vehicles. The little heavy-duty trap-oxidizer development that has been done has been aimed primarily at the adaptation of light-duty trap-oxidizer concepts to heavy-duty applications.

Because of the lack of trap-oxidizer development for heavy-duty vehicles, this chapter draws extensively on the accumulated experience and testing in the light-duty field. The applicability of this experience to heavy-duty vehicles, and the problems involved in adapting light-duty technologies to heavy-duty vehicles are discussed as well. The discussion is based in large measure on the authors' previous report on light-duty trap-oxidizer technology (Weaver and Miller, 1983), and a subsequent paper by one of them (Weaver, 1983a). Up-to-date information on current developments in the field and specific data on the development of heavy-duty trap-oxidizers have also been included where applicable.

This chapter is organized into three main sections. Section 5.1 discusses the present status of trap oxidizer technology, with special attention being given to the major components of a trap-oxidizer system: the trap, the regeneration system, and the controls. Since much of the discussion in Section 5.1 concerns trap-oxidizers for light-duty applications, Section 5.2 focuses on the special considerations involved in applying trap-oxidizers to heavy-duty vehicles — either by adapting light-duty technologies or by developing new approaches suited to the special problems and opportunities of heavy-duty vehicles. These considerations include both technical and institutional barriers to trap-oxidizer deployment. Section 5.3 examines some of the more promising potential configurations for heavy-duty trap-oxidizer systems. Where Section 5.1 focuses on the technologies of the individual components, 5.3 concentrates on the systems aspects of trap-oxidizers, including the synergistic interactions between the components, and between the system and the vehicle.

5.1 TRAP-OXIDIZER TECHNOLOGY

Trap-oxidizer technology can be divided into three separate sub-areas: the traps themselves, regeneration techniques, and the controls and sensors necessary to initiate and control the regeneration process. These three areas are discussed separately in Sections 5.1.1 through 5.1.3 below. It should be borne in mind, however, that the interactions between these areas are also very important. The choice of a trap defines many of the requirements for the regeneration system, and may make possible different approaches to regeneration. Similarly, the requirements which the control system must meet are largely determined by the characteristics of the regeneration system it is controlling and the tolerance limits of the trap. These synergetic effects are discussed at greater length in Section 5.3, in which several possible combinations of trap, regeneration technique, and control system are described.

5.1.1 Diesel Particulate Traps

A great number and variety of filter materials have been investigated for use as diesel particulate filters (traps). At the present time, attention is focused on four major classes of traps: ceramic monolith filters, ceramic foam traps, ceramic-fiber based traps, and an alumina-coated catalytic wire mesh design. Each of these types of traps except the ceramic-fiber type (which was developed specifically for heavy-duty service) has seen extensive development in light-duty vehicles. This discussion will focus on the ceramic monolith, ceramic fiber, and catalyzed wire-mesh traps, since the available data indicate that ceramic foam traps have given poor results in heavy-duty service.

Ceramic monolith traps: The ceramic monolith is the most widely tested and developed type of particulate trap. Virtually every manufacturer of light-duty diesels has at least one trap-oxidizer system based on this trap under development, and it has been tested by most heavy-duty diesel manufacturers as well. The monolith has found favor because of its high trapping efficiency, temperature tolerance, demonstrated durability, and comparatively low cost. These have apparently outweighed its drawbacks — high backpressure, rapid increase of backpressure with filter loading, susceptibility to cracking due to thermal stresses and (in heavy-duty service) possible clogging due to ash retention. The monolith trap is also fairly adaptable — the porosity, cell density, and wall thickness of the ceramic monolith can be altered in order to trade off filtration efficiency for backpressure. The monolith trap is also relatively easy to coat or impregnate with either a precious metal catalyst (like the ones used in catalytic converters) or with a base metal catalyst. The use of such catalysts could make possible a simpler form of regeneration system.

Figure 5.1 is a face view of a ceramic monolith trap, of a size intended for light-duty service. Figure 5.2 shows the principle of filtration of this trap. The basic unit is a cellular ceramic monolith of the type used as a catalyst support in the catalytic converters of many gasoline-fueled automobiles. The monolith has been modified by blocking the upstream and downstream ends in alternating cells with a ceramic material. Because each cell is blocked at one end or the other, the particulate-laden exhaust gas is forced to flow through the porous cell walls. Most particulate matter is retained on the cell walls, where it builds up in a carbonaceous layer. This layer is also an effective particulate filter, which means that the trapping efficiency of these traps can actually increase as they become more heavily loaded.

Monolith traps are manufactured by extruding the square matrix of the trap in the same manner as for catalytic converter substrates. Alternate holes in this matrix are then blocked with a ceramic cement, and the whole assembly is fired. At present, the capabilities of the extrusion equipment limit the maximum trap diameter to about 6 inches -- a size suitable for light-duty but not for heavy-duty applications. Prototype heavy-duty traps of up to 12 inches diameter have been produced by cutting light-duty traps apart

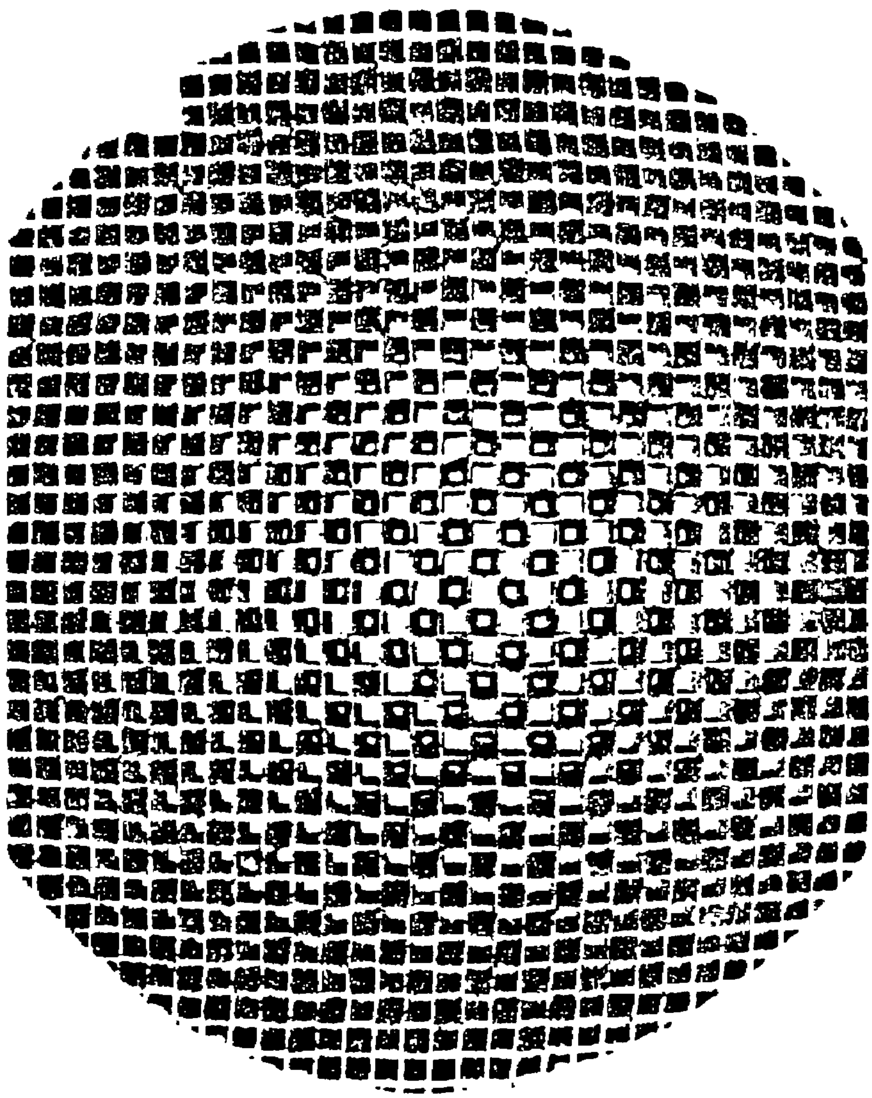


Figure 5.1: Face view of a ceramic monolith trap (courtesy of Corning Class).

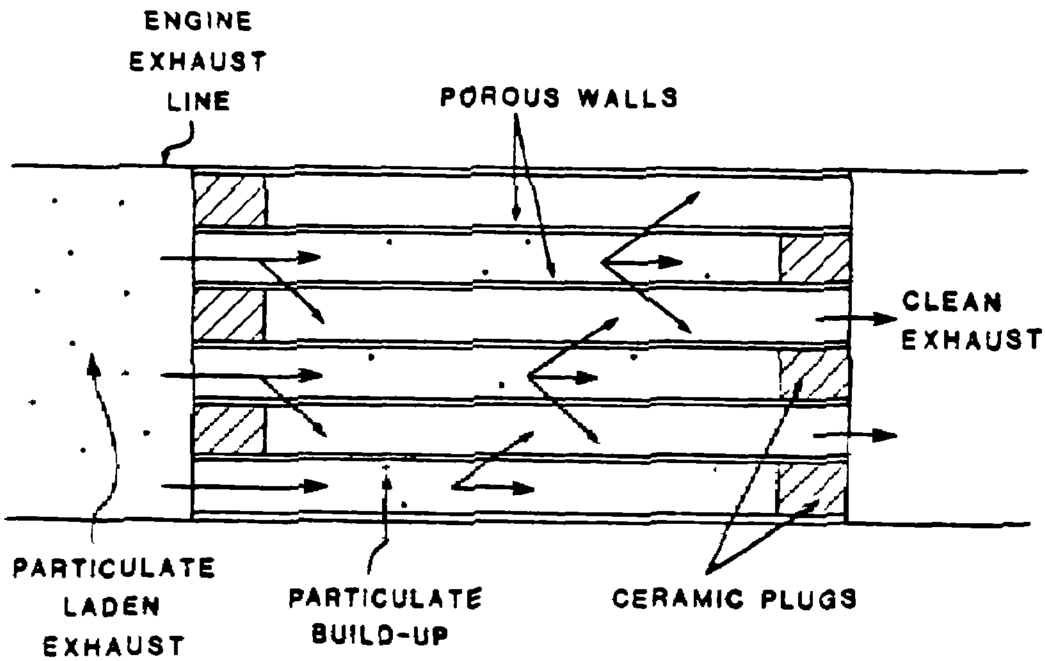


Figure 5.2: Principle of operation of the ceramic monolith trap.

into squares, gluing the squares together using a high-temperature ceramic cement, and then trimming the resulting block to shape (Howitt et alia, 1983). Corning Glass had produced approximately 50 such prototypes as of late 1983: all, apparently, for research and development on heavy-duty trap-oxidizer systems. Facilities for direct extrusion of heavy-duty sized monoliths are being developed by both Corning and NGK. Such facilities will be needed for commercial production to be feasible; the expensive handwork involved in building the prototype traps makes them too expensive for production use.

The monolith trap's major drawbacks are high backpressure, rapid increase of backpressure with filter loading, susceptibility to cracking due to thermal stress, and possibly excessive backpressure increase due to ash buildup in heavy-duty service. The high initial backpressure can be traded off against filtration efficiency, and can be reduced by increasing the size of the trap. In the same way, the backpressure rise rate can be reduced by increasing the trap size, or it can be compensated for by more frequent regeneration. The problem of cracking due to thermal stresses is much more severe — it is presently one of the the major barriers to the successful development of light-duty trap-oxidizer systems based on the ceramic monolith. Curiously, however, thermal cracking has not been reported to be a major problem in the larger heavy-duty monoliths produced to date. This may be a result of the stress relief provided by the cemented joints in the prototype units (J.H. Howitt, personal communication).

Thermal-stress cracking is caused by the interior of the trap being hotter than the exterior, and thus expanding more. This occurs during the regeneration process, when the intense heat generated by the burning particulates can raise the temperature of the trap interior above 1000^{o} C if sufficient cooling gas flow is not maintained. The differential expansion results in the exterior layers of the trap being "forced apart" (placed in tension) by the expanding interior, while the interior portions are "squashed together" in compression by the force of the exterior. The trap cracks when the tension in the outer layers exceeds the strength of the material.

Two approaches to solving the thermal cracking problem are being pursued. One is to carefully define those areas of trap operation (trap loading, gas flow rate, and gas temperature) at which cracking does not occur, and then to design the regeneration system to operate always within those areas. The second approach is to improve the structure and materials of the trap in order to reduce the probability of cracking—in effect, to expand the area of safe operation to include a wider range.

Considerable progress has been made in defining the areas of safe operation for light-duty ceramic monolith traps (Gulati, 1983; Higuchi et alia, 1983), so that it now appears to be possible to design a positive regeneration system of the burner type which will not destroy the trap through overheating and thermal stress. It is not yet clear, however, whether the trap's resistance to thermal stress is adequate for self-regenerating systems, in which the regeneration frequency and trap loading during regeneration are subject to much less control by the designer. Recent statements from knowledgeable sources in the industry, however, indicate that this is not a major problem at this time.

One area of considerable concern with ceramic monolith traps for heavy-duty applications is a possible long-term increase in backpressure due to ash buildup in the trap. Researchers at Cummins (Sachdev et alia, 1983) have reported that a significant back-pressure increase was obtained by simulating the long-term production of ash by means of a diesel-fuel burner and fuel "doped" with the ash's metallic constituents. Their results indicated that ash-loading would double the "clean-trap" backpressure after about 90,000 (simulated) kilometers. This effect, if it were actually experienced in practice, would require replacement of the trap every 100,000 km or so. Daimler-Benz (DBAG, 1984) has also indicated that its traps (which are of a different design) also suffer from ash buildup and plugging after 100,000 to 150,000 miles.

Other evidence, however, indicates that the problem may not be as severe as the Cummins study would indicate. Perhaps the most persuasive evidence to date is from an EPA-sponsored 50,000 mile (80,000 km) durability test of a ceramic trap, carried out at Southwest Research Institute. At the end of this test, the "clean trap" backpressure had increased by only about 20 percent (Urban, 1982). Furthermore, in a test involving the use of metallic fuel additives (Wade et alia, 1983), it was found that a very large amount of metalliferous ash (enough to substantially block the passages in the filter) could be accumulated without major increases in backpressure. Volkswagen (Wiedemann et alia, 1983) has reported similar results. This would seem to indicate that the much smaller amount of ash accumulated without fuel additives would have little effect. On the other hand, the use of fuel additives reduces the regeneration temperatures, which could have affected the degree of trap plugging experienced.

Another possible reason for the discrepancy between the Cummins study and other data is the difference in the conditions of combustion and ash formation, which could conceivably have led to differences in the structure or composition of the deposited ash. Sachdev et alia used a low-pressure continuous-combustion burner system. Actual vehicle combustion, however, occurs intermittently, and at very high pressures and temperatures. This could lead to different sizes and structures of ash particles. In addition, Sachdev and co-workers used a much greater rate of ash deposition with time than would be observed in a real engine, which could conceivably have affected the results. Because of the discrepancies between Sachdev and his co-worker's model and the actual diesel engine, it presently appears more reasonable to assume that the other data available (indicating lesser effects from ash accumulation) are closer to being correct. Using this assumption, a trap in heavy-duty service could be expected to last for 150,000 to 250,000 miles before needing to be cleaned or replaced. However, this is an issue which should be resolved by further research.

Ceramic fiber traps: A number of manufacturers have reported tests of ceramic-fiber based traps. These include General Motors (Ludecke and Dimick, 1983; GM, 1982a), Caterpillar (Caterpillar Tractor, 1982), and Daimler-Benz (DBAG, 1982; 1984). Caterpiller has reported experimenting with a trap utilizing "ceramic yarn", but provided no details as to configuration or results. The experiment was apparently dropped due to difficulty in developing a space-efficient support system for the yarn. GM has experimented with a ceramic fiber mat or felt supported by a perforated metal tube. An example of this type of trap is shown in Figure 5.3. GM's results with this trap have been generally discouraging — disintegration of the mat, cracking, and separation of the mat from its supports have been the major problems. Daimler-Benz also experimented with and abandoned a similar trap.

Daimler-Benz (or one of Daimler-Benz's suppliers — the submission is not clear) has also developed another, much more promising type of trap based on ceramic fibers. This trap consists of strands of woven silica-fiber yarn, cross-wound on a porous metal substrate as shown in Figure 5.4 to form cylinders which Daimler-Benz refers to as "candles". These candles are supported in a cannister, as shown in Figure 5.5, so that the exhaust gas must flow through the candle wall to escape. The silica fibers are roughened and impregnated with a heat-resistant inorganic substance to improve filtration.

Daimler-Benz has reported excellent results for this trap, including very high efficiencies (above 90%) at back-pressure levels below those of the ceramic monolith. The trap has been tested on a number of heavy-duty vehicles, and for a total of at least 200,000 kilometers, including 132,000 km on a single trap (H. Hardenburg, personal communication). The durability of the traps is fairly good. In city bus service (a fairly demanding application) the traps are reported to last between 100,000 and 150,000 miles. Failure occurs as

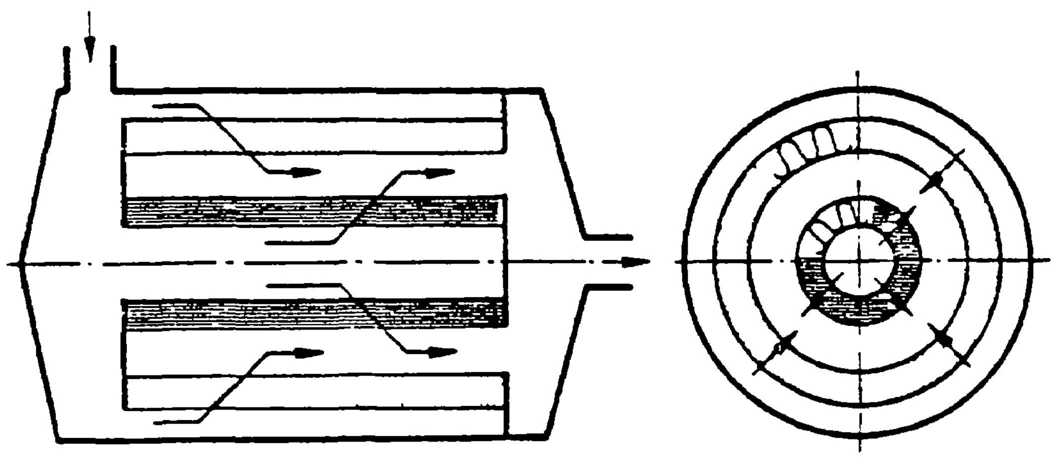


Figure 5.3: Ceramic fiber mat trap. (Source: DBAG, 1982)

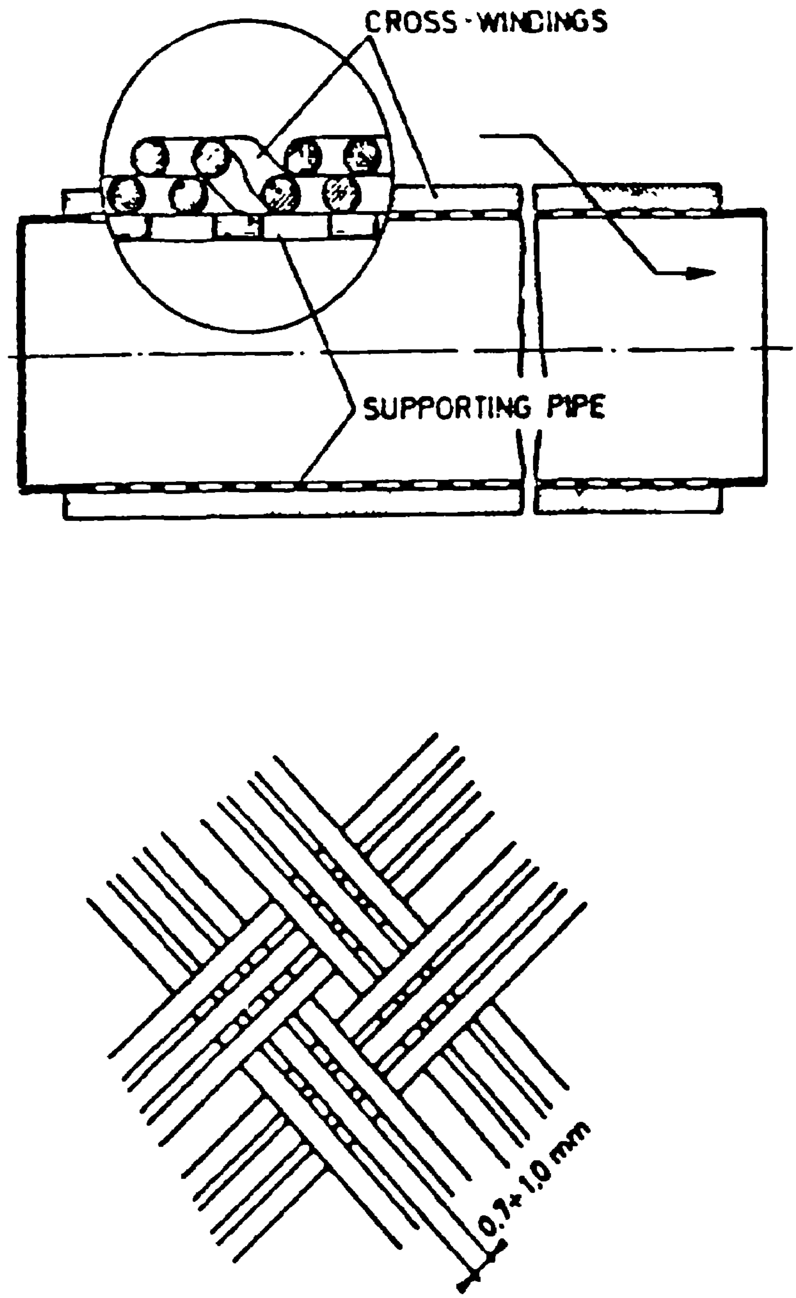


Figure 5.4: Support pipe with silicon dioxide thread windings for the Daimler-Benz silica-fiber candle trap. (Source: DBAG, 1982)

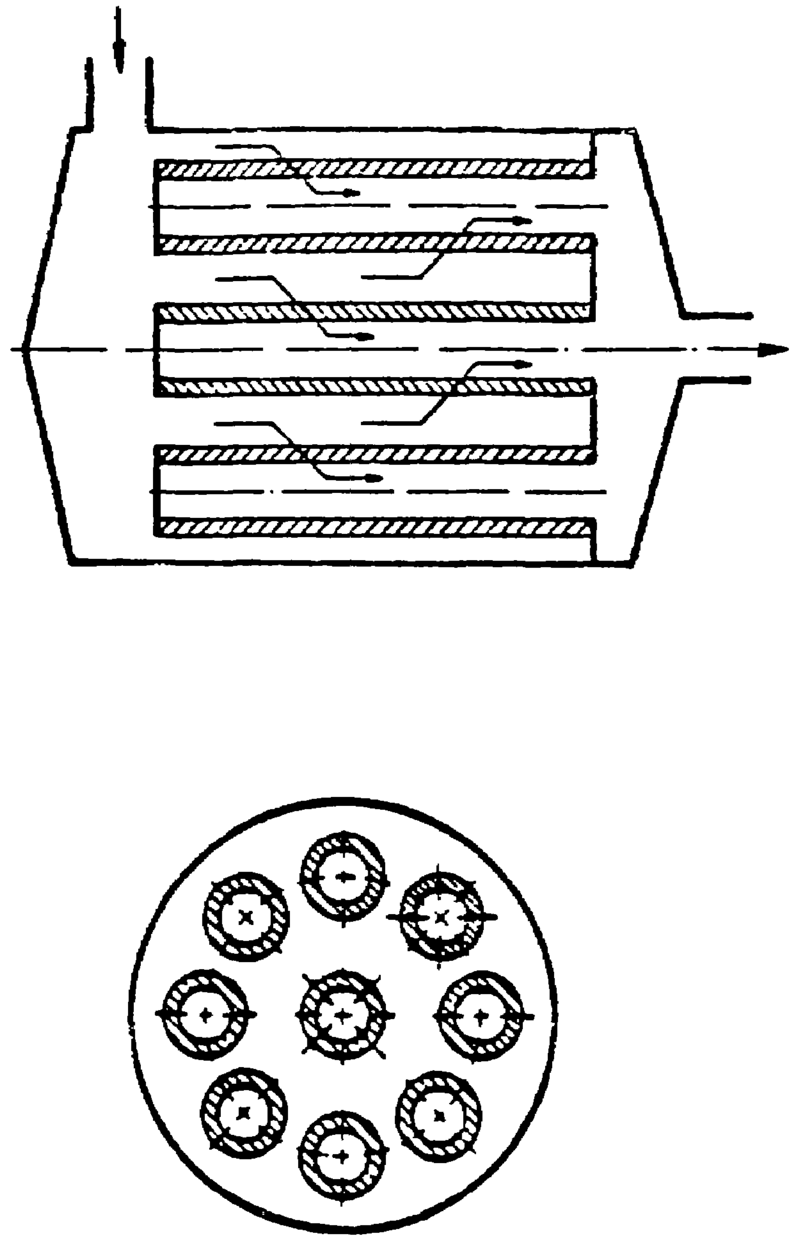


Figure 5.5: Daimler-Benz silica-fiber candle trap (Source: DBAG, 1982).

the result of the trap plugging up with non-combustible ash, resulting in unacceptable back-pressure increases (DBAG, 1984). Much of this ash is due to the sulfur content of the fuel, so that trap lifetime would be strongly affected by the use of high-sulfur or low-sulfur fuels.

With fair durability, no thermal cracking problems, very high temperature tolerance, and low back-pressure, this type of trap appears (at least on the basis of the limited data available) to be very nearly ideal. The trap is also well suited to a catalytic regeneration system developed by Daimler-Benz, which is described in Section 5.1.2 below. Its most significant drawback may be its size -- it seems likely to require significantly more space than the ceramic monolith.

Catalyzed, radial flow wire-mesh traps: This type of trap has been developed and promoted by Johnson-Matthey Incorporated; thus it is commonly referred to as the "Johnson-Matthey trap". The operation and development have been described by Enga (1982) and Buchman and Enga (1983). Its application to various off-road and heavy-duty applications is described by Budd and Enga (1984).

Figure 5.6 shows a typical trap of this type, designed for installation in place of the exhaust manifold on a light-duty engine, while Figure 5.7 shows an underfloor design. Versions intended for heavy-duty use are very similar in overall design, differing mainly in the number and length of the cylinders. The trap consists of cylindrical sections of knit stainless-steel mesh, with the density of the mesh increasing toward the center of the section. Exhaust gas flows from the periphery of the cylinder radially inward toward the hollow space in the center, from which it leaves the trap. The fact that the density of the mesh increases toward the center of the trap helps to prevent a thick layer of particles from building up around the periphery, and also helps to prevent problems with particles blowing off of the mesh with sudden increases in speed. The mesh is coated with a layer of alumina, to which a precious-metal catalyst washcoat is applied.

The precious-metal catalyst is the key to the wire-mesh trap's operation. Like a gasoline-engine catalytic converter, the catalyst oxidizes gaseous hydrocarbons and CO. In addition to reducing the emissions of these two pollutants, the oxidation of the gaseous hydrocarbons also cuts down significantly on odor emissions. The presence of the catalyst also appears to result in the oxidation of much of the hydrocarbon fraction of the particulate material. Most importantly, the catalyst reduces the light-off temperature of the particulate from about 500-600° C to about 350-400° C, reducing the amount

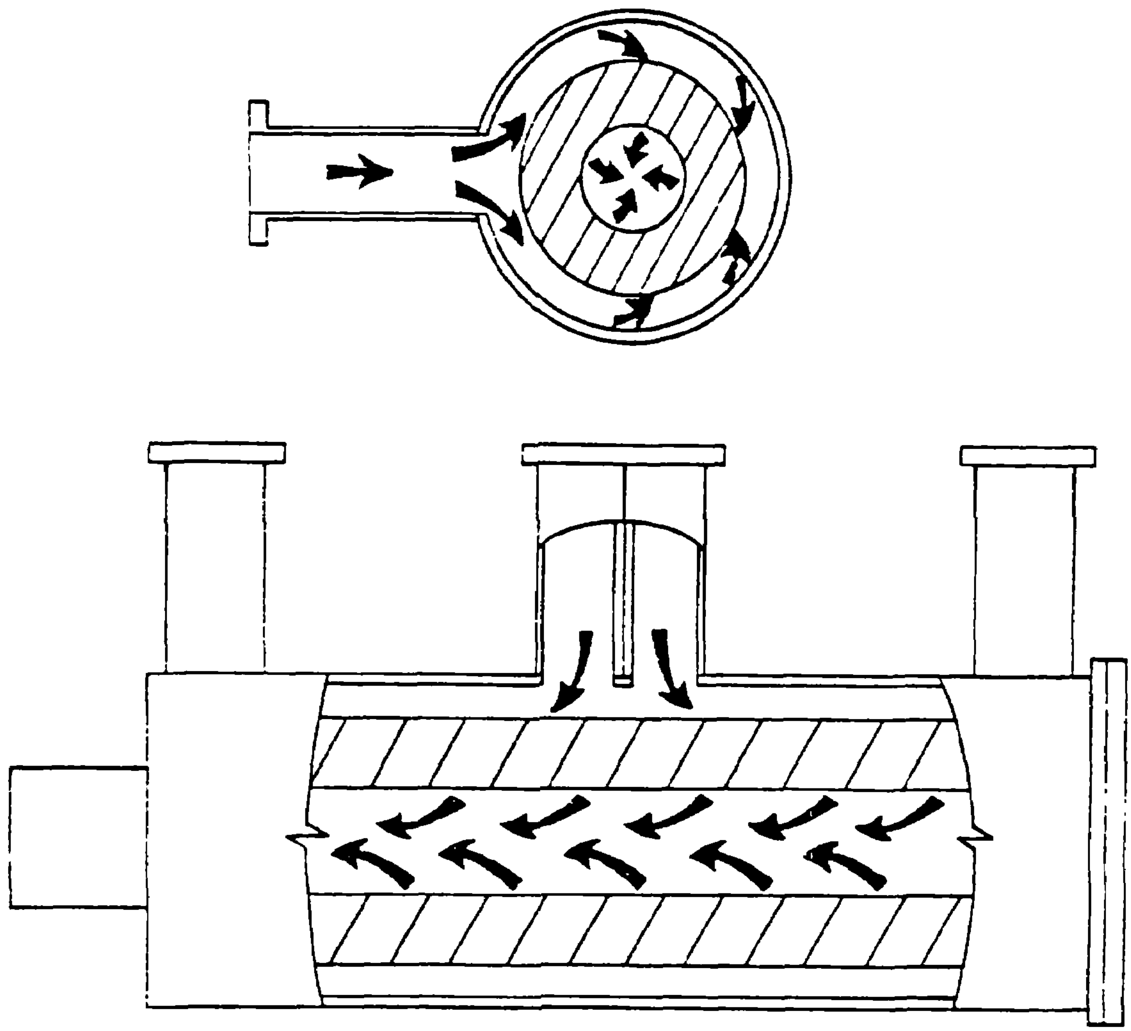


Figure 5.6: Catalytic wire-mesh trap, engine manifold location. (Source: Johnson-Matthey, Inc.)

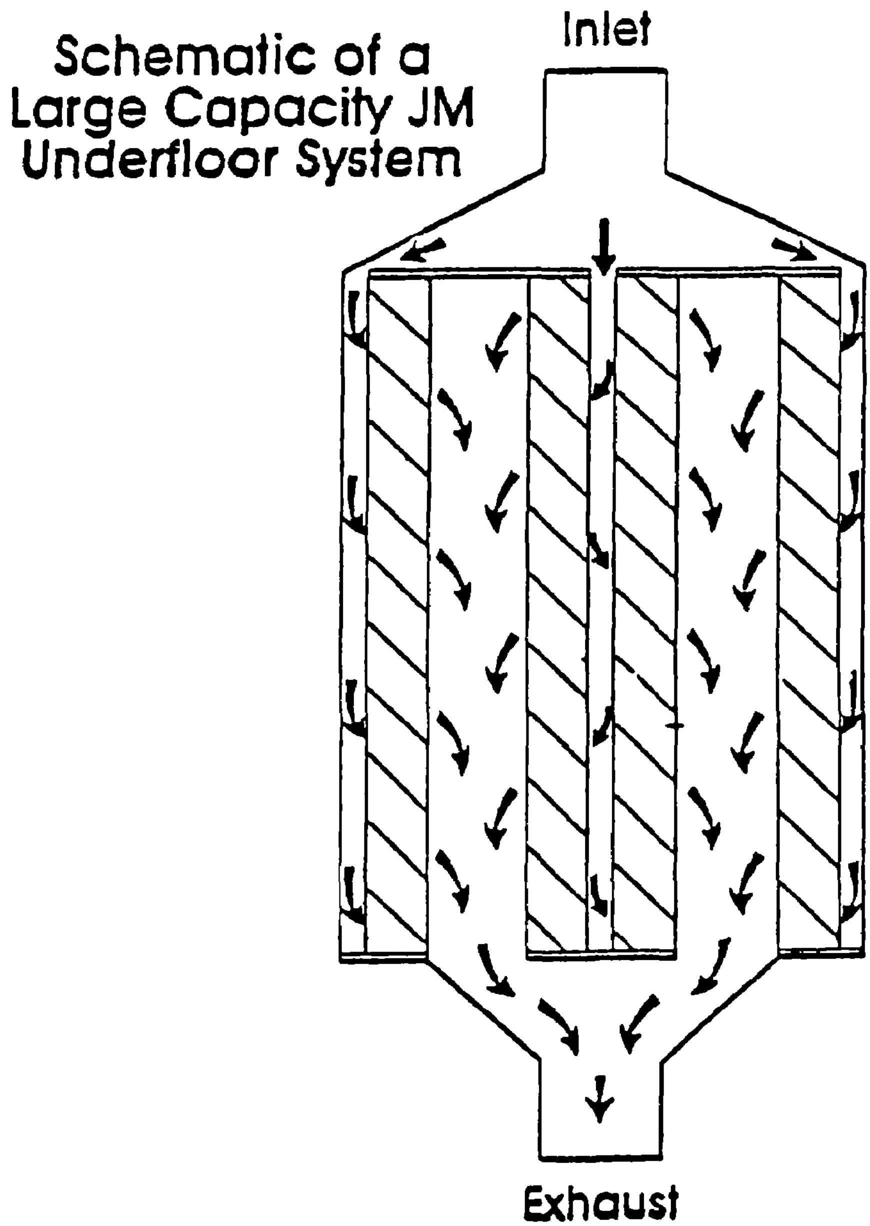


Figure 5.7: Catalytic wire-mesh trap, under-floor location. (Source: Volkswagen A G, 1981)

of energy required for regeneration. The use of the oxidation catalyst also makes possible a simplified regeneration scheme, in which the exhaust is enriched in HC and CO, which then oxidize exothermically on the catalyst, generating the heat required for regeneration. This scheme is discussed in the section on regeneration techniques.

Some of the primary advantages of this type of trap as compared to the ceramic monolith are a slightly lower initial backpressure and a slower rate of backpressure increase, which can be made slower yet by the trap's ability to self-regenerate under many driving cycles. This would be especially true in heavy-duty service, where high exhaust temperatures are more common than in light-duty vehicles. An additional advantage is that the stainless steel wire-mesh filtering material is not subject to thermal cracking, and its melting point is comparable to that of the cordierite ceramic which makes up the ceramic monolith. Because of this, the wire-mesh trap is able to tolerate a greater range of particulate loadings during regeneration. This simplifies both the regeneration process and the task of the control system.

The primary disadvantages of the wire-mesh trap are lower trapping efficiency and a tendency to increase sulfate emissions. In addition, the cost of the trap itself is higher than that of an uncatalyzed ceramic trap, although the simpler regeneration system it makes possibly may offset this. The lower trapping efficiency is probably not crippling — typical efficiencies in light-duty service are in the 50 to 70 percent range, but efficiencies as high as 80 percent have been demonstrated in light-duty service (Buchman and Enga, 1983). These efficiency levels are sufficient to meet the proposed 0.25 g/BHP-hr particulate standard.

The problem of increased sulfate emissions is, however, a major drawback. These emissions are due to the presence of the oxidation catalyst, which oxidizes some of the SO_2 normally present in diesel exhaust to SO_3. The SO_3 then combines with water to form sulfuric acid (H_2SO_4). This process also occurs naturally in the atmosphere, so the effect of the catalyst is not to increase the total environmental load of sulfate but simply to change its distribution — resulting in a greater concentration near roads and urban areas. These areas are, however, the areas in which humans are more likely to be found, so that total human exposure to sulfates is increased. Since sulfuric acid is a strong irritant as well as being highly corrosive, any significant increase in human exposure to it would be of great concern.

Johnson-Matthey has reformulated its catalyst in order to minimize sulfate conversion in light-duty service, while still attaining low regeneration temperatures. Using the reformulated catalyst, between one and five percent of the sulfur emitted under typical light-duty operating conditions is emitted as sulfate (compared to values from about .2 to .6 percent for a vehicle without a catalyst). For the higher temperatures achieved in heavy-duty operation, however, sulfate conversion is still so great as to rule out the use of this trap in its present form. The results of tests on the present catalyst formulation carried out at Michigan Technological University (Scholl et alia, 1982) indicate that at temperatures typical of high-power heavy-duty operation, from 50 to 100 percent of the sulfur in the fuel is converted to sulfate. Similar experiences are reported by Pattas et alia (1984) and by Wong and coworkers (1984). Since the sulfate is also a particulate material, this can increase the total particulates leaving the trap to several times the level seen without the trap in place. EPA transient tests conducted by several manufacturers have also indicated a several-fold increase in particulates over the engine-out emissions, with virtually all of the particulate being sulfuric acid.

Johnson-Matthey has formulated a new version of its catalyst for heavy-duty use, which it believes will reduce sulfate conversion to a much lower level (M. Buchman, personal communication). This is achieved at some cost in increased regeneration temperature, since the catalyst's efficiency at oxidizing sulfur dioxide cannot be completely separated from its efficiency at oxidizing HC and CO. Since high exhaust temperatures are more common in heavy-duty than in light-duty service, this should not present a significant problem. Preliminary laboratory tests of this formulation (Budd and Enga, 1984) appear promising, but no in-use data are available. Thus, it cannot presently be stated whether this type of trap appears workable for heavy-duty vehicles.

Johnson-Matthey is presently planning to test one of its heavy-duty traps on a Southern California Rapid Transit District bus in the near future, as part of a cooperative program with the SCRTD and the California Air Resources Board. This system will include an automatic regeneration and control system, as well as the trap itself. If successful, this program will give a good indication of the overall performance of the Johnson-Matthey trap in heavy-duty service. It will <u>not</u>, however, indicate anything about the sulfate problem, since the South Coast Air-Quality Management District — where the test will take place — is presently the only area in the U.S. which requires low-sulfur diesel fuel.

5.1.2 Regeneration Techniques

Regeneration is the process of burning off (oxidizing) the particulate material trapped on a particulate filter, thus restoring the "clean trap" filtering efficiency and backpressure. In order to oxidize the particulate completely, it is necessary to raise its temperature to the ignition point while providing a steady flow of oxygen-bearing gas to support combustion and to carry away the excess heat generated. With sufficient oxygen, and in the absence of catalysts, diesel particulate matter ignites at a temperature between about 500° and 600° C (900° to 1100° F). The actual ignition temperature is dependent on both the design of the trap and the specific operating conditions under which the particulate was collected. The required ignition temperature increases sharply at low oxygen concentrations, and decreases slightly at higher ones.

Once ignited, the particulate material will continue to burn at gas temperatures somewhat below the ignition temperature. The tolerable reduction in gas temperature below the ignition point is fairly small, however, and heavily dependent on the particulate loading of the trap and the oxygen content and flow rate of the gas. If the temperature of the gas is too low, or the flow rate is too high, too much heat is removed from the burning particulate and combustion ceases. On the other hand, if the flow rate is too low or the temperature of the gas supplied is too high, too little heat is removed from the trap, which leads to overheating and cracking or melting. In order to attain complete regeneration while minimizing the possibility of destroying the trap, it has been found best to maintain a substantial flow of gas through the trap, with the temperature of the gas at or somewhat above the ignition point.

Diesel exhaust gas normally contains adequate oxygen to support combustion, since diesels operate at low fuel-air ratios, but generally does not attain the temperatures required for ignition. Thus, regeneration does not usually occur spontaneously. In order to cause regeneration to occur, it is necessary either to raise the temperature of the collected particulates to the ignition point or to lower the ignition point of the particulates to match the available temperatures.

There are two approaches to initiating regeneration. The first approach — self-regeneration — relies on attaining the conditions required for regeneration during the normal operating cycle. Generally, this has led to attempts to reduce the ignition temperature of the particulate to within the range of normal exhaust-gas temperatures, so that regeneration will occur during normal operation. The alternative approach to initiating the regeneration process is called positive regeneration. In this approach, a decision is made to regenerate the trap at a specific point in time, and positive actions are taken to ensure that regeneration occurs. These actions may include turning on a burner, activating a throttling device, or injecting fuel or a catalyst into the exhaust stream, among others. The decision to regenerate may be made on the basis of some measure of trap loading (such as increased backpressure) or regeneration may be scheduled to occur every so many miles or engine revolutions.

The self-regeneration approach is attractive because of its potential simplicity, but it places greater demands on the trap. This is because the designer has little control over the degree of particulate loading or the gas flow rate at which regeneration will occur. Given the somewhat random nature of driving patterns, it is necessary to ensure that regeneration will occur fairly frequently on the average, in order to be certain that the trap will not be overloaded under unusual driving conditions. This is especially problematic for heavy-duty vehicles, since a much wider variety of operating patterns is found in heavy-duty service than in light-duty applications. On the other hand, self-regeneration might be a very attractive option in those heavy-duty applications (such as transit buses and garbage trucks) where the operating pattern is well known in advance.

Positive regeneration systems give the designer much more control over the regeneration conditions, and thus place fewer demands on the trap itself than self-regeneration systems. However, they require more or less elaborate systems of controls, sensors, and actuators in order to carry out the regeneration process. These add complexity and expense to the system, and may present reliability, durability, and maintenance problems as well. Despite these drawbacks, most heavy-duty engine manufacturers seem to be leaning toward positive regeneration systems for their trap-oxidizer development programs. This is in strong contrast to the situation in the light-duty field, where many of the major manufacturers have abandoned positive regeneration systems for self-regeneration.

<u>Positive regeneration techniques:</u> Most present positive regeneration systems involve raising the temperature of the particulate in order to ignite it. Some techniques for accomplishing this include: throttling the engine to increase exhaust temperature, use of a diesel oil burner or an electric heater upstream from the trap, and using the exothermic oxidation of hydrocarbons and CO on a catalyst to increase the particulate temperature. The most promising of these techniques are the diesel oil burner and the catalytic heating approaches. Daimler-Benz has also experimented with a positive regeneration technique for heavy-duty vehicles which injects catalytic metal additives into the exhaust stream to lower the particulate ignition temperature (DBAG, 1982).

The development of diesel oil burners for light-duty applications has been described in detail by Wade and co-workers (1983) at Ford Motor Company. Similar systems have also been experimented with by most manufacturers of diesel automobiles, and by several heavy-duty engine manufacturers (Cummins, 1982; Caterpillar, 1982). The advantages of the diesel oil burner include the use of a readily available energy source, a high energy release rate, and a well-understood technology base. The disadvantages include complexity, high cost, and questionable durability and reliability under the hot, sooty, and intensely oxidizing conditions found in diesel exhaust.

A trap-oxidizer system incorporating an oil burner can be arranged either so that the trap is isolated from the exhaust system during regeneration (a "bypass system) or so that exhaust continues to flow through the trap during the regeneration process (an "in-line" system). The in-line system is less complex, but entails difficult control problems due to the rapid changes that are possible in the exhaust flow-rates. Fouling of burner and ignitor surfaces by soot is also more likely in an in-line system. This method also suffers from a major disadvantage in that it must heat the entire flow of exhaust gas, which is usually much more than is required to regenerate the trap safely. With the high exhaust flow rates in heavy-duty trucks, this can waste a significant amount of energy, and it also requires a larger burner than would otherwise be necessary.

Bypass systems avoid the energy waste and control problems of the in-line systems, and permit closer control over regeneration conditions. They could be expected to suffer, however, from higher costs and possibly from lower reliability than the in-line systems, due to the additional valves, actuators, and exhaust plumbing entailed. Despite these problems, the bypass/oil burner system seems to be the one that most heavy-duty engine manufacturers are considering. Both types of systems are under active development in light-duty vehicles however, and both in-line and bypass burner systems have actually been installed and tested in light-duty service (Ford, 1982; Oser and Thoms, 1983; GM, 1981). The control technology for in-line burner systems (if it is developed at all) will probably be developed first for light-duty vehicles, and then transferred to heavy-duty applications. The only burner regeneration systems known to have undergone significant testing in heavy-duty vehicles were of the bypass type.

A second promising class of positive regeneration systems makes use of the exothermic oxidation of HC and CO to heat the exhaust and/or particulate to the light-off point. This approach is applicable only to catalyzed traps. The triggering step in this process is to greatly increase the HC and CO content of the exhaust at a time when the exhaust temperature is above the catalyst's light-off point. The excess HC and CO are then oxidized by the catalyst in the same manner as in a catalytic converter, and the heat given off by the oxidation reaction ignites the particulate. This approach has significant limitations — it will not work at low loads or at idle, for instance, because the catalyst must be fairly hot in order to function. However, it has the major advantage that it does not require as complex or expensive a control and actuation system as most other positive regeneration techniques.

Four techniques have been developed for increasing the HC and CO level in the exhaust. The first such technique is to inject fuel into a cylinder during the exhaust stroke. At this point, the exhaust gas has cooled enough to prevent the fuel from igniting, but is still hot enough to vaporize it and to crack the heavier hydrocarbons into lighter species. These hydrocarbons are then oxidized by the catalyst. A crude version of this svstem was used on the 50,000 mile durability test vehicle sponsored by Johnson-Matthey, with considerable success (Enga and Bykowski, 1982). Due to the difficulties in adapting this technique to high-pressure injection systems, it is unlikely to see much application in heavy-duty vehicles.

Three other techniques for increasing the HC and CO levels have been described by Buchman and Enga (1983). Two of these require the presence of a digital electronic control system for injection timing and/or EGR. These control systems continously optimize the parameters under their control in order to provide the best combination of emissions control and driveability. It is a relatively simple matter, given such a control system, to have it deoptimize the appropriate setting instead of optimizing it, thus greatly increasing the pollutant concentrations in the exhaust. There is some doubt as to whether EGR (and thus electronically controlled EGR) will ever see much application in heavy-duty engines, but the technique of over-retarding injection timing would certainly be applicable. Essentially every heavy-duty engine manufacturer is now engaged in development and testing of electronic injection timing controls, and they can be expected to see very wide application (due to their beneficial effects on fuel economy and performance at low NO_x levels) during the last half of this decade.

The last technique for increasing HC and CO concentrations is to throttle the air intake to one or more cylinders, thus causing incomplete combustion and increased HC and CO concentrations. Oxygen for the catalytic oxidation process is provided by the unthrottled cylinders, which continue to operate with excess air. Throttling of the entire engine would be as effective at producing HC and CO, but would not result in regeneration, since insufficient oxygen would be present in the exhaust gas to support oxidation.

Another, strikingly different, catalytic technique has been developed by Daimler-Benz for use in its heavy-duty truck and bus line (early research along these lines was also carried out by Battelle (Hillenbrand and Trayser, 1981)). This technique is to inject a catalyst containing copper and chlorine into the exhaust when a decision is made to regenerate. This catalyst lowers the light-off temperature of the collected particulate to about 200° C (DBAG, 1984). Successful regeneration requires that the exhaust temperature be at or above this value, but this temperature is low enough to be obtained under most operating conditions.

Daimler-Benz has carried out extensive bench and vehicle tests using this approach with its "candle" trap, with very encouraging results (H. Hardenburg, personal communication). In considerable on-road testing, the major problem discovered was that the ash buildup in the trap raised the trap backpressure to unacceptable levels after 100,000 to 150,000 miles of driving. At least some of these on-road tests were carried out using an automatic regeneration control system -- indicating substantial progress in that area as well. Although some design problems remain to be solved, Daimler-Benz has expressed confidence that the system can be fully developed by model-year 1990.

<u>Self-regeneration techniques</u>: Two main approaches to self-regeneration are under development. Both of these involve lowering the ignition temperature of the particulate matter; one by means of a catalytic fuel additive, and the other by means of a catalytic coating on the trap. The use of catalytic fuel additives to promote self-regeneration is the best developed self-regeneration technique. A number of light-duty manufacturers, including Ford (Wade et alia, 1983), Volkswagen (Wiedeman et alia, 1983), and General Motors (U.S. EPA, 1983b) have announced that they are investigating this approach. Both Volkswagen and GM have stated that it is presently their preferred technique for light-duty vehicles.

The additives in question are organometallic compounds containing various metallic atoms. Compounds containing lead, copper, calcium, and manganese have been used in the work reported to date, but other metals also appear to be under investigation. The most complete descriptions of the work to date are those published by Wade and co-workers at Ford Motor Company and by Wiedemann et alia, at Volkswagen. Both groups report that the use of organometallic additives reduced the ignition temperature of the particulates significantly -- to the point where regeneration conditions could be achieved reliably during the normal light-duty driving cycle. Both groups also reported successful endurance tests of light-duty vehicles using this system with a ceramic monolith trap. The Ford test lasted for 16,000 km (10,000 mi.), while two Volkswagen tests lasting 40,000 km (25,000 mi.) and 20,000 km (12,500 mi.) were reported. The last test mentioned is especially significant, since it was carried out at a steady 50 km/hr (31 MPH). That the trap was able to survive and regenerate at this low speed, without the occasional excursions to higher temperatures which are experienced during normal driving, indicates that self-regeneration can probably be relied on to occur during almost any reasonable driving cycle.

In general, since engine load factors (and thus average exhaust temperatures) tend to be higher in heavy-duty than in light-duty service, one would expect that this technique might prove especially suited to heavy-duty vehicles. On the other hand, heavy-duty vehicles may also experience long periods of very light load-factors, which could overload the trap without ever getting close to the regeneration temperature. Thus, the suitability of this type of regeneration system for all heavy-duty applications is questionable. Where the operating pattern is reliably known in advance, however, this system could be a very strong contender. Given the relative sophistication of heavy-duty vehicle drivers, it is also possible that this sytem, combined with some sort of fail-safe to warn the driver in the event of a dangerous condition, might be acceptable even where operating patterns could not be predicted.

The additive/monolith self-regeneration system presently suffers from two major potential technical problems: the tendency of the ceramic monolith traps to crack due to thermal stress, and the fact that the metallic additives tend to accumulate in the traps, eventually plugging them. The ceramic monolith's problems with thermal-stress cracking have already been mentioned. The use of self-regeneration, with the consequent poor control of the circumstances and frequency of regeneration, might be expected to exacerbate these problems. Recent statements by knowledgeable sources have indicated, however, that contrary to expectation, thermal-stress cracking has not been a significant problem in the development of self-regenerating systems based on additives. The reasons for this are unclear. They may involve the effects of the catalyst in controlling combustion rate or low trap loadings due to frequent self-regeneration in use.

In contrast, the problem of additives accumulating in the trap is a very serious one for heavy-duty applications. This problem will greatly reduce the economic attractiveness of the additive approach if it cannot be solved. One published test for which quantitative data are available was that carried out by Ford (Wade et alia, 1983). This test used a vehicle with a 2.3 liter engine and a 2 liter trap. The fuel contained 0.75 grams of metal per gallon for the first 3,500 miles, and 1.25 grams of metal per gallon for the last 6,500 miles of a 10,000 mile durability test. At the end of this test, the trap was found to have accumulated enough incombustible metal oxides and sulfates to partially block the cells on the upstream side, although trap backpressure had not increased noticeably. It seems likely that the backpressure would have begun to increase after the 10,000 mile point, however, as the remaining open space in the trap was filled up.

Current thinking favors a somewhat larger trap-volume to engine-displacement ratio, and industry sources indicate that significantly lower additive concentrations (around 0.1 to 0.3 g/gallon) are now being considered. Making allowances for these, and assuming that the Ford vehicle could have travelled another 5,000 miles before backpressure effects became so serious as to require replacing the trap, one can estimate a total mileage-to-trap-replacement in the range from 70,000 to 200,000 miles, or (in round numbers), about 100,000 miles. This is probably tolerable in light-duty vehicles, but would impose substantial additional costs in a heavy-duty truck, which could be expected to accumulate two to six times this mileage during its lifetime. Requiring the trap to be replaceable would also make it easier to tamper with, and there would certainly be a strong temptation not to replace it after the first time it filled up.

Recent publications by researchers at Corning (Montierth, 1984) and Volkswagen (Wiedemann et alia, 1984) seem to indicate that these problems may not be as severe as was once thought, however, at least for the manganese additive that Volkswagen favors. Tests indicate that the manganese tends to form a fluffy ash which could be blown out of the trap, or dissolved out by chemical means. Although both techniques would still require dismounting the trap, it would not be necessary to replace it.

In addition to these technical problems, the widespread use of organometallic additives in motor vehicles would raise some very significant environmental and safety questions. Most organometallic compounds are very toxic, and many are dangerous to handle. If the additives were to be supplied in diesel fuel, this problem would be manageable, but then many diesel vehicles without traps would be burning the fuel as well. This would result in significant emissions of metalliferous particles. The emission of large quantities of metals in particulate form could have significant environmental consequences, the more so as lead and copper are among the metals being considered. The problems of lead toxicity in the environment are well known.

The problems with metalliferous particulate emissions could be resolved by keeping the additives in a special reservoir on the vehicle rather than mixing them with the fuel--thus ensuring that only trap-equipped vehicles received the additives. This, however, would raise important safety questions, given the toxicity and flammability of many organometallic compounds. The problems of disposing of old vehicles containing such reservoirs, and of refilling the reservoirs of high-mileage vehicles could be considerable. In addition, the crash-safety of such systems would be a major concern. On the other hand, at least one additive manufacturer, and one auto manufacturer (Volkswagen) have expressed confidence that these problems can be solved, at least for light-duty vehicles.

A second approach to self-regeneration is the use of a catalyst-coated trap. The precious-metal catalyzed wire-mesh trap, for instance, is able to self-regenerate under many driving cycles, although this effect is not reliable enough to free it from the need for a positive regeneration system. The performance of precious-metal catalysts on ceramic traps, however, has been quite disappointing. For this reason, attention has turned to alternative catalysts based on a mixture of non-precious metals. Some very encouraging results from the use of base-metal catalysts on ceramic traps have recently been reported by Koberstein and co-workers (1983), working at Degussa in Germany, and by Watabe et alia (1983) at Bridgestone in Japan.

The Degussa researchers worked with catalysts on a ceramic monolith trap, while Watabe and co-workers worked with ceramic foam. The Degussa catalyst reduced the ignition temperature of the collected particulate in the trap to 380° C (a reduction of about 100° C), while the Bridgestone catalyst achieved a reduction of 120° C. These temperatures would be sufficient to give reasonable assurance of self-regeneration in heavy-duty service — the Daimler-Benz catalyst injection approach, which has been successfully tested in vehicles, gives a similar regeneration temperature.

The Bridgestone catalyst also reduced the sensitivity of the particulate ignition point to changes in oxygen concentration, which would increase the range of conditions under which it could trigger regeneration. There is also some evidence (Oser and Thoms, 1983) that the regeneration process in catalyzed traps is slower than in uncatalyzed traps. This would reduce the rate of heat generation in the trap, which in turn would reduce the problem of cracking due to thermal stresses.

At the present time, the publicly available data on this type of regeneration method are too scarce and preliminary to permit any realistic assessment of its potential. While the results reported to date are quite encouraging, they include only very preliminary tests on dynamometers, not actual on-road vehicle tests, even in light-duty vehicles. Further testing would have to include on-road tests, and would need to examine the durability of the catalyst coating, its susceptibility to poisoning by trace metals or other chemicals in the fuel, its resistance to prolonged high-temperature operation and repeated regeneration, and so forth. When such tests are carried out, and if they appear as encouraging as the initial reports would indicate, then this approach to regeneration would certainly be a very strong contender, since it would require no control system, no moving parts and no fuel additives, and would have none of the operational problems surrounding most other approaches. A catalytic-trap regeneration system would be very similar in concept and visibility to the consumer to a gasoline-engine catalytic converter — which is clearly an acceptable technology.

5.1.3 Control Systems

The requirements for a regeneration control system are heavily dependent on the specific trap and regeneration technique being used. Self-regenerating trap-oxidizer systems would — by definition — need no control system as such, although some sort of fail-safe system would be desirable in order to guard against failure of the self-regeneration process. Such a device would be highly desirable to guard against failure in positive regeneration systems as well. This fail-safe might consist of a bypass valve which would open at a specified backpressure, venting exhaust around the trap and lighting a warning light on the dashboard.

Positive regeneration systems would require some form of sensing, control, and actuation system in order to carry out the actions required for regeneration. This would also be true of "assisted" self-regenerating systems, if it proves to be impossible to develop a truly reliable self-regeneration technique. The three basic control system functions would be to determine when regeneration is necessary, to initiate the regeneration process, and to confirm that the regeneration process is complete. These would be common to all positive regeneration systems.

Other control functions would depend on the specific regeneration process used. For instance, using an oil-burner type regeneration system, it would be necessary to monitor the burner in order to ensure ignition--otherwise a failure to ignite might result in spraying raw fuel into the trap, possibly leading to a fire or subsequent uncontrolled regeneration. For other types, such as those which rely on the catalytic oxidation of HC and CO, it would be necessary to ensure that regeneration was possible at a given time, and to defer it if it were not. These systems require a certain minimum exhaust temperature for the catalytic oxidation to occur, and it would be necessary for the control system to ensure that the exhaust was at an appropriate temperature before initiating regeneration. It would also be desirable for a control system for a trap with self-regeneration potential, such as the catalyzed wire-mesh trap, to detect self-regeneration when it occurs, thus eliminating unnecessary regeneration cycles.

The development of a control system can be divided into two separate problems: the development of suitable control algorithms, and the development of a system of components which implements those algorithms. The latter problem is fairly straightforward; none of the regeneration systems described above appears to require anything beyond the present state of the art in control equipment or techniques, except possibly for some new sensor types. The former problem—that of defining the control algorithms to be used or the set of conditions which the control system must maintain—is also straightforward, but is likely to be time-consuming and costly to accomplish.

In order to define the operational requirements of a control system, it is necessary first to understand the characteristics and limits of the system to be controlled very thoroughly. Once these are known, a prototype control algorithm can be designed to maintain the controlled system within its allowable limits. This process is well advanced at the present time. A great deal is known about the performance and safe operating characteristics of the common types of traps and about the performance of the various regeneration systems. The frequent reports of trap failures in testing programs indicate that there is still something to be learned, however. Ultimately, extensive on-vehicle testing of prototypes will be necessary to ensure that the control algorithm succeeds under all possible operating conditions. From industry sources, it appears very likely that this process is going on at some light-duty manufacturers at the present time.

5.2 SPECIAL CONSIDERATIONS FOR TRAP-OXIDIZERS IN HEAVY-DUTY SERVICE

As Section 5.1 makes clear, most trap-oxidizer research and development has been directed at developing systems for light-duty vehicles. There are a number of reasons for this, of which the following are the most important.

1. Less regulatory pressure — at the present time there are no actual particulate regulations for heavy-duty engines. Many heavy-duty engine manufacturers still have lingering doubts as to whether there will ever be any such regulations, and thus are reluctant to commit resources to a major R and D program.

2. Less familiarity with regulation — stringent regulatory standards are a new experience for the heavy-duty industry, and thus the industry may be somewhat slow in responding to them. The light-duty vehicle industry has been stringently regulated since 1975.

3. Industry weakness — the last few years have been disastrous ones for the heavy-duty truck industry. International Harvester, the largest manufacturer, has been very close to bankruptcy, and Mack avoided a similar fate only by being taken over by Renault. With companies slashing overhead in order to survive, new research and development programs stood little chance of being initiated.

4. Smaller engineering and R&D staffs — The major light-duty vehicle manufacturers all have large research, development, and production engineering staffs, and relatively short product development times. This is due partly to the size of these firms (all are very large, and can afford large corporate staffs) and partly because this staff is needed to cope with the frequent model changes in light-duty automobiles. Truck and bus models change seldom, and the basic engine models change even less often. Thus, heavy-duty engine manufacturers tend to have smaller engineering staffs and longer product development lead-times than do light-duty manufacturers.

5. Responsibility for trap development is not well defined — due to the fragmented nature of the heavy-duty truck industry.

6. More difficult development task — developing a trap-oxidizer system or systems for the wide range of operating cycles and the very long lifetimes characteristic of heavy-duty service is harder than to develop one which is suitable for light-duty operation.

These conditions are likely to continue to slow heavy-duty trap-oxidizer development in the future. In particular, given the complexity of the problem, the industry's weakness, and the relative lack of regulatory impetus, there is a strong tendency on the part of the independent heavy-duty engine manufacturers to let the light-duty manufacturers solve the problem, and then to adapt their solutions. This could have important implications for competition in the industry, since two light-duty diesel manufacturers (GM and Daimler- Benz) also make heavy-duty engines, and Ford plans to enter the heavy-duty diesel market within the next few years. Ford, GM, and Daimler-Benz are among the leaders in light-duty trap-oxidizer technology, and could be expected to be able to draw on this expertise to develop heavy-duty trap-oxidizers much more quickly. Indeed, this appears to be happening already.

Light-duty trap-oxidizer development is well advanced. A previous ERC study (Weaver and Miller, 1983) concluded that it is highly probable that trap-oxidizer equipped light-duty vehicles will be in production for model year 1987, and one manufacturer (Daimler-Benz) is including trap-oxidizers on its 1985 production for California. Heavy-duty trap-oxidizer development will certainly draw on this development experience. Thus it is appropriate to consider carefully the degree to which light-duty trap-oxidizer technology is likely to be adaptable to heavy-duty use. It is especially important to consider what having light-duty trap-oxidizer systems in production by 1987 would imply about feasible development schedules for heavy-duty vehicles.

Different classes of heavy-duty vehicles differ greatly in what requirements they would impose on a trap-oxidizer system, and especially in the degree to which light-duty trap-oxidizer technology is likely to be adaptable. In addition, the industry structure and other institutional constraints to trap-oxidizer development and deployment vary greatly between different classes of vehicles. These variations have important implications for the feasible deployment schedule for trap-oxidizer technology, and even for the ultimate feasibility and cost-effectiveness of trap-oxidizers for each class of vehicle. Because of this, these issues are discussed separately for the four main subclasses of heavy-duty vehicles.

5.2.1 Light-Heavy Duty Vehicles

Light-heavy duty vehicles generally resemble the heavier end of the light-duty spectrum much more closely than they do the larger trucks with which they are grouped for regulatory purposes. The diesel engines used in this group are presently all high-speed, indirect-injection, naturally-aspirated engines derived from passenger car technology, and bear little resemblance in operational characteristics to the medium-speed, direct injection engines used in heavier trucks. A prime example is the GM 6.2 liter engine, versions of which are used in vehicles certified under the light-duty standard, as well as in light-heavy vehicles. The only other diesel engine currently in this class is the International Harvester 6.9 liter engine, which is presently certified only for heavy-duty operation. International Harvester is considering adding EGR to this engine, however, to enable it to comply with the light-duty NO_x standard as well. Isuzu and Cummins are also in the process of introducing small high-speed DI engines for this class. These engines will probably be intermediate between passenger-car IDI engines and heavy truck engines in their characteristics.

The vehicle characteristics, operating environment, lifetime mileage, driving patterns, and maintenance habits for light-heavy vehicles resemble those of light-duty vehicles more than those of the larger trucks. Lifetime mileage, for instance, averages about 110,000 miles for light-heavy vehicles. This is comparable to the 100,000 mile life typical of light-duty vehicles, but much less than the 185,000 to 500,000 mile lifetimes of the heavier trucks.

Perhaps more importantly, the manufacturers and the manufacturing process for light-heavy trucks are quite similar to those of light-duty vehicles. The vehicles in which these engines are used are also predominantly mass-produced in the manner of light-duty cars and trucks rather than in the semi-custom manner typical of medium-heavy and larger trucks. The nature and timing of the development process for these vehicles should also be similar to that of the light-duty class. It should be noted also that Ford and GM -- the major manufacturers of light-heavy trucks -- are also among the most advanced in light-duty trap-oxidizer development, so that they would have a readily available pool of expertise to draw on. At the same time, however, it should be noted that International Harvester and Cummins, the other likely light-heavy engine manufacturers are not far advanced in trap-oxidizer development, and it is the engine manufacturer who must certify the system. This might place them at a competitive disadvantage.

Given the basic similarities between the two types, and assuming that -- as ERC has predicted -- trap-oxidizer systems for light-duty vehicles are available in 1987, it would take comparatively little additional time to develop and certify trap-oxidizers for light-heavy duty engines. One, or at most two, additional years of delay would probably be justified in order to minimize the competitive disadvantage suffered by those light-heavy engine manufacturers who are not also light-duty vehicle builders, and to enable other, low-volume users of these engines such as motor-home manufacturers to integrate the trap-oxidizers into their designs.

This delay would also help to minimize the burden on engineering staffs and certification facilities by permitting the inevitable last-minute problems in trap-oxidizer application to be substantially resolved in the light-duty development process before applying them to light-heavy engines. This would decrease the added costs of trap-oxidizer development, and might result in better systems and increased public acceptance. Finally, given the comparatively small number of light-heavy duty vehicles (compared to the number of light-duty trucks sold), this delay should not have major effects on air quality.

5.2.2 Medium-Heavy Duty Trucks

This class of trucks includes all of what most people think of as "heavy-duty trucks" except for the large tractor-trailer combinations used in line-haul service. It contains a wide variety of truck types and styles, ranging from about 5 tons GVW to more than 25 tons. Most of these trucks are either single or tandem-axle straight trucks (see the truck typology given in Chapter 2), but they also include some heavy panel vans, some smaller tractor-trailer combinations, school buses, and other special types. Transit buses — which are similar to this group in size and weight — are discussed separately below.

The most distinguishing feature of this class of vehicles is its varietv. A large number of specialized body styles such as dump trucks, garbage trucks, tow trucks, electric-utility service vehicles, and others are sold as well as the more common "box" van. Often, the same basic chassis and cab will be offered with many different choices of body styles. Most trucks in this class are also available with many different choices of power-train equipment such as engine, transmission, and rear axle. In addition, many are sold with special equipment such as hydraulic lifts, garbage packers, cherry pickers, winches and snowplow blades. This equipment may be supplied either by the original manufacturer or by a third party.

Along with this bewildering array of truck types and styles goes an equally bewildering selection of operating patterns. Usage patterns include stop and go garbage collection, short haul deliveries, long-haul deliveries, extended idling while using hydraulic equipment, over-the-road trucking, and many others. This wide variety of operating patterns and truck configurations will make the development of workable trap-oxidizer systems for medium-heavy trucks a difficult and time-consuming task. Given the enormous number of applications, it would be difficult and probably uneconomical to develop a trap-oxidizer optimized for each one. At most, special systems might be developed for a few common, relatively consistent applications such as garbage packers and school buses, with the less comon applications having to rely on "generic" systems. For this reason, the generic system to be developed will need to be able to function correctly and safely under almost any conceivable duty cycle. This requirement argues strongly for a positive regeneration system, or possibly some sort of hybrid system which would include a positive regeneration capability.

Development of a generic trap-oxidizer system for medium-heavy trucks will be simplified somewhat by the fact that the majority of such trucks are built along similar lines, with similar exhaust system layouts. This means that, in most cases, the same set of changes to the engine and exhaust system will be applicable across a number of different styles and makes of truck. Offsetting this, however, is the fact that each style of truck may be offered with several different engines from different manufacturers, each of which (under the currently proposed regulatory structure) might well have its own different design of trap-oxidizer. Some attempts at industry standardization can be expected, but it can also be expected that there will inevitably be body types and/or accessory packages which will be incompatible with these standards.

Medium-heavy duty engine and vehicle manufacturers typically have smaller engineering staffs than do light-duty and light-heavy duty manufacturers, and they are less geared toward frequent model changes. Furthermore, much more extensive testing of new developments is necessary before they can be marketed, due to the long service lifetimes found in this class of trucks. For this reason, product development times are generally one or two years longer than in the light-duty industry -- it can take six years or more to bring a proven concept into production. Because of the longer delay time and the less-developed state of heavy-duty trap-oxidizer technology, it would appear wise to allow at least two or three years beyond the effective date of a light-duty trap-oxidizer standard before imposing a similar standard on these vehicles.

In addition, the smaller engineering staffs and less frequent model changes, combined with the large number of possible truck chassis, engine, body, and special equipment combinations will make it very difficult to implement trap-oxidizers across an entire product line in a single year. Thus it would be desirable to consider some sort of "phasing in" of particulate controls in order to allow time for trap-oxidizers to be engineered into all vehicle types while minimizing disruption of the market. One way to accomplish this would be by means of a sales-weighted average standard, which could be tightened each year for two or three years.

5.2.3 Line-Haul Trucks

The class of line-haul trucks includes the largest and most powerful heavy-duty trucks. These are overwhelmingly devoted to intercity freight commerce and similar activities. Almost all line-haul trucks are combination units made up of a tractor and one or two trailers. The large power requirements for this type of operation require large, powerful, usually turbocharged engines, with very high exhaust flowrates. The high exhaust flow-rates, in turn, will necessitate very large traps in order to bring the backpressure down to a reasonably low level. Low backpressure is especially important for line-haul trucks, since the increase in fuel consumption due to the trap-oxidizer is directly related to backpressure. Line haul trucks are driven for great distances and consume enormous amounts of fuel, so even small changes in fuel economy are significant. For a typical truck in this class, a one percent loss of fuel economy would increase total lifetime fuel costs by more than $1000.

The large economic effect of even small changes in efficiency could be expected to lead to widespread tampering and attempts to defeat trap-oxidizers installed in this class of trucks. This tendency would be reinforced by the well-known mechanical bent of most line-haul truck drivers, as well as by their notorious independence and sensitivity to adverse government actions. This sensitivity was dramatically demonstrated in the independent truckers' strike of a few years ago. If trap-oxidizers were to develop a reputation as being unsafe or unreliable (as seems quite possible, given their complexity and novelty) this tampering might well become nearly universal. The only obvious counter-measure to such tampering, given the fact that most of these trucks operate in interstate commerce, would be a strong Federal or Federally-coordinated inspection and maintenance program.

Given the difficulty of the tampering problem, the very large economic costs of even small changes in fuel economy for these trucks, and the fact that the great preponderance of the vehicle miles travelled by this class are in interurban rather than intraurban driving, it would make sense to consider exempting line-haul trucks from a trap-oxidizer requirement. Because these trucks spend less time in urban areas, the total effect of such an exemption on urban air quality should be small, while the economic savings would be large. Eliminating the need to develop extremely high-capacity and high-durability trap-oxidizers for these trucks would also free engineering resources to work on the easier, but still time-consuming, task of integrating trap-oxidizers into the numerous medium-heavy duty truck models, most of which are operated primarily in urban areas.

The organization of the line-haul truck industry is very similar to that of the medium-heavy duty truck industry -- indeed, many of the major manufacturers in each group are the same. Line-haul trucks are not qualitatively different from other heavy-duty trucks, they are simply larger, more powerful, and more intensively used. Thus all of the comments concerning the difficulty of developing feasible traps, the organizational and engineering manpower constraints, and other difficulties which were made above for medium-duty trucks can also be applied to this class.

If this class were not to receive a special exemption from a particulate standard, the leadtime requirements for trap-oxidizer deployment would be even longer than those of the medium-heavy class -- three or four years beyond the implementation of a light-duty trap-oxidizer standard rather than two or three. The additional year would be required to develop and test the very large traps and regeneration systems needed, and to carry out lengthy on-road durability tests. A durability test corresponding to the EPA-defined "full useful life" of a line-haul truck would need to last for 250,000 miles, and such tests take a great deal of time.

5.2.4 Transit Buses

The service locations and operating conditions of transit buses, as a group, are almost polar opposites to those of the line-haul truck class. Transit buses operate almost exclusively in urban areas, and generally in the most urbanized and congested portions of those areas. Furthermore, the typical transit-bus operating cycle is one of the worst imaginable from a particulate emissions viewpoint. Rather than profit-motivated individuals or firms, transit buses are owned and operated almost exlusively by service-oriented public or quasi-public agencies. These agencies are quite sensitive to the problem of smoke emissions and their offensiveness to the public — mitigatory measures such as derating bus engines to reduce both maximum power and smoke, use of lower-smoke diesel #1 (city-bus) fuel rather than diesel #2, and the use of smoke reducing additives such as barium are common. Thus a device such as the trap oxidizer, which could greatly reduce both smoke and particulate emissions is highly desirable from both the human exposure standpoint and that of the bus fleet owner.

Developing a feasible trap-oxidizer system for transit bus use would be considerably easier than for most applications. One major reason for this is that transit buses universally receive regular service, often on a daily basis. Similarly, they almost always operate near their base, and there is usually at least one other bus on any given route, so the consequences of a failure are not very severe. Durability and reliability requirements would not be nearly as strict as for most other types of heavy-duty vehicles. An additional advantage comes from the fact that transit buses have a rather predictable operating cycle, and one which includes a great deal of acceleration. The frequent occurrence of moderately high exhaust temperatures as a result would help to make a self-regenerating system feasible.

There are also major organizational and institutional advantages to trap-oxidizer application in this class. As remarked before, many bus operators are quite sensitive to the public offense created by their buses' smoky exhaust, and expend substantial amounts of money in reducing by such means as derating the engines, buying more expensive #1 fuel, and adding special smoke-reducing additives. Deployment of trap-oxidizers would make these steps unnecessary, with a consequent savings which would probably outweigh the cost of the trap-oxidizer. Thus, rather than being forced on unwilling consumers, trap-oxidizers might well be welcomed with joy.

A final advantage to trap-oxidizer deployment on buses is that buses, at least in congested urban areas, appear to account for a large fraction of the total ambient diesel particulate. General Motors estimates (Chock et alia, 1984) indicate that as much as 40 percent of the total diesel particulate at urban air-sampling stations is derived from buses. Since buses generally operate near the sidewalks in the most crowded areas, it seems likely that an even greater percentage of the human exposure to diesel exhaust in these areas comes from buses. Thus the cost-effectiveness of trap-oxidizers in this application would be very high — so high that it would be worthwhile investigating whether a program to retrofit existing buses with trap-oxidizers would be feasible.

Despite the attractiveness of trap-oxidizers for transit-bus applications, development of a feasible trap-oxidizer system will be by no means a trivial task. There is likely to be considerable difficulty in packaging it in the vehicle, for instance. Transit bus engines are in the rear, in an area also occupied by much else. Unless the trap-oxidizer could be successfully substituted for an existing component such as the muffler, it would be necessary to redesign the back end of the bus.

For this reason, as well as the general problems in developing trap-oxidizer standards for heavy-duty vehicles, it would probably be best to delay the application of a hard-and-fast particulate regulation for buses to take effect at the same time as the one for medium-heavy trucks — about two or three years after a light-duty trap-oxidizer standard goes into effect. However, it would also be very desirable to take steps (perhaps in concert with the Urban Mass Transit Administration, which supplies Federal funds to purchase buses) to try to get at least a few trap-oxidizers deployed in service earlier. In addition to the direct benefit of reduced particulate emissions, these units would also provide engineering experience with the systems, and would help to familiarize the public and truck purchasers with their use.

5.3 POSSIBLE TRAP-OXIDIZER SYSTEM CONFIGURATIONS FOR HEAVY-DUTY VEHICLES

The commercial feasibility of a proposed trap-oxidizer system cannot be assessed by considering the individual components in isolation. Synergetic effects are important: the nature of the trap determines the types of regeneration systems which may be feasible, and the nature of the regeneration system has important consequences for the durability and performance of the trap. Similarly, the trap and regeneration system jointly determine what control system is necessary. The interactions between all three components affect the durability, safety, reliability, initial and operating costs, and other characteristics of the overall system. Thus, in order to determine the feasibility of a given trap-oxidizer system, it is necessary to examine the system in its entirety.

This section discusses the four types of trap-oxidizer systems which presently appear most promising for heavy-duty vehicles. These systems are the following:

- Ceramic monolith trap with bypass oil-burner regeneration.
- Ceramic monolith trap using self-regeneration, either by means of fuel additives or a base-metal catalyzed trap.
- Catalyzed wire-mesh trap with regeneration by HC and CO enrichment of the exhaust.
- Silica-fiber "candle" trap with catalytic regeneration using CuCl.

Each type of system is described, and its important characteristics — including effectiveness, durability, reliability, and cost — are discussed. The estimated "sticker price" and life-cycle cost to the vehicle owner of each system in each of the four major classes of heavy-duty vehicles are also given. Finally, the overall state of development and the potential for commercial feasibility of each type of system are assessed.

5.3.1 Bypass/Burner System With Ceramic Monolith Trap

System Description: A bypass/burner trap-oxidizer system would consist of one or more ceramic monolith traps and one or possibly more diesel-oil burners, along with suitable valves and plumbing to bypass the trap(s) during regeneration and a fairly sophisticated system of controls, sensors, and actuators. In order to eliminate the extra complexity and cost of additional valves, sensors, and burners, most systems of this type could be expected to use a single trap. However, due to limitations on the maximum trap size, the largest trucks would need at least two traps, and possibly more, in order to provide sufficient trapping area and to keep the pressure drop through the trap to a minimum. A conceptual diagram of a one-trap system of the by-pass/burner type is shown in Figure 5.8. The system shown would be appropriate for a light-heavy vehicle, and for the majority of the medium-heavy class.

Effectiveness: The ceramic monolith trap is an extremely efficient filter — depending on the exact material used, its efficiency can be above 90 percent. It is most efficient at capturing soot — much of the organic fraction of the particulate passes through it, as does much of the mutagenic activity (Scholl et alia, 1982; McDonald, 1983). These effects have been discussed in Section 5.1.1. This type of trap would enable manufactur

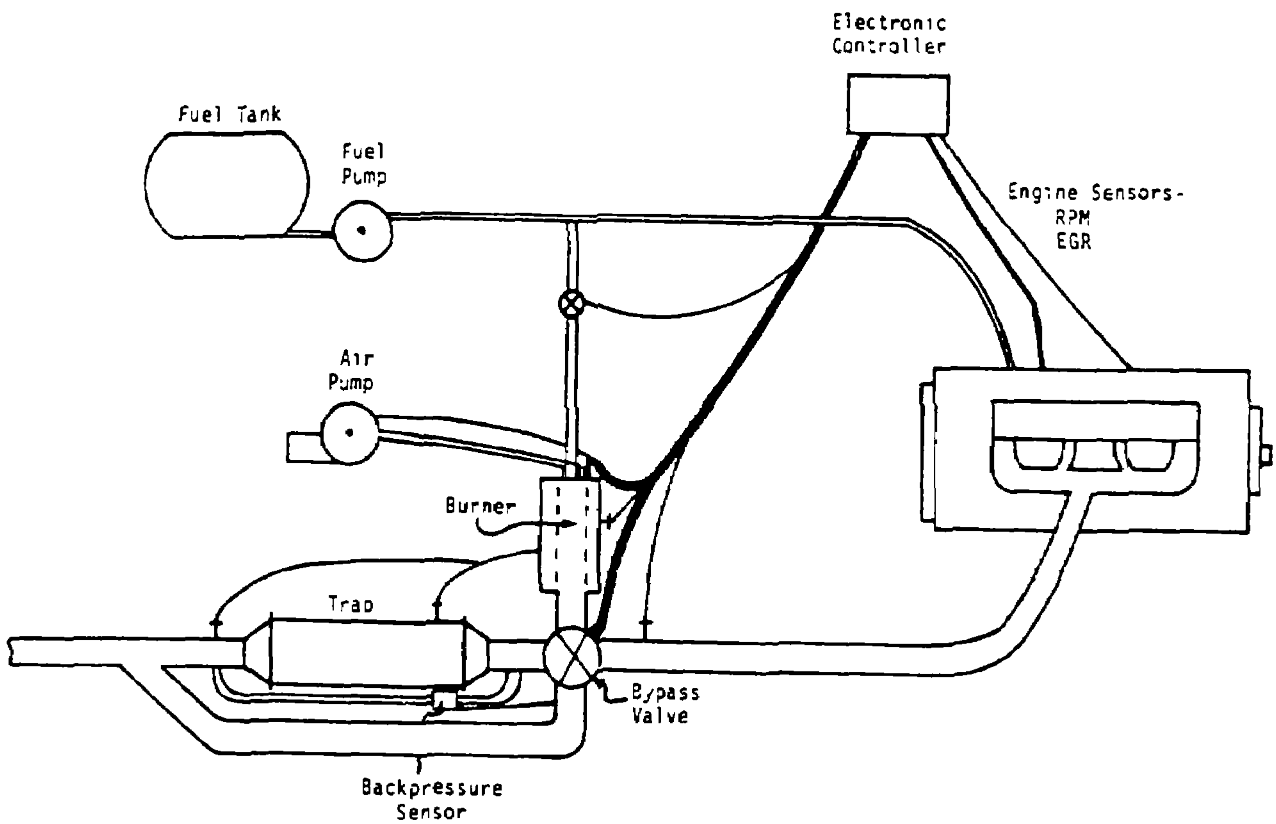


Figure 5.8: System diagram — ceramic monolith/burner trap-oxidizer system.

ers to meet a very strict standard for total mass emissions of particulates, and would effectively reduce both the total mass of particulates in the air and the degradation in visibility due to diesel particulate matter. Reductions in human exposure to particulate-borne organics and especially to particulate-carried mutagens would be much less. The effects on other pollutants would be minor, except for a possible reduction in odor.

Durability and reliability: These two areas could be expected to present significant problems for this type of system, especially in the medium-heavy and line-haul truck classes. The major problems would probably be with the complicated regeneration control system and with the burner — the trap itself is quite durable unless subjected to high temperatures during regeneration. The regeneration control system would contain a great deal of complicated electronics, which would need to survive for very long period in the hostile operating environment of an on-the-road truck. Similarly, the burner and associated valves and actuators would need to survive for very long periods in the hot, sooty, intensely oxidizing environment of the diesel exhaust with minimal service. Although some inspection and service requirements would probably be tolerable, any such requirements greatly increase both the risk of tampering with the system and the risk of system failure (since, inevitably, some systems will not be serviced).

There is also some disagreement over the potential reliability of the bypass/burner system, even assuming that the regeneration system is working properly. On the basis of published data, it presently appears probable that a system of this type for light-duty vehicles can be designed so that (when it is functioning properly) it reliably regenerates without cracking or melting the trap. The range of tolerances is fairly narrow, however. In a larger trap, other things being equal, one would expect a greater thermal stress level, and thus a greater tendency to crack. It is not yet completely clear that a system of this type, using a truck-sized trap, can be designed to regenerate reliably without damage to the trap.

Performance and fuel economy effects: The use of any type of trap-oxidizer system will result in some slight harm to a truck's fuel economy and performance, since power is required to force the exhaust gases through the trap. In addition, the presence of a trap can affect turbocharger performance — resulting in significant performance and fuel-economy losses unless the turbocharger is carefully matched to the altered system. The effect of the bypass-burner/monolith system on fuel economy would be somewhat greater than that of the other systems discussed, due to the additional use of fuel in the burner.

The magnitude of the loss in performance and fuel economy is difficult to estimate, since the total effects are small compared to test-to-test and engine-to-engine variability. The magnitude of the effects is also dependent on how well the turbocharger characteristics are matched to those of the trap/engine combination. Most tests of this concept indicate fuel-economy losses ranging from unmeasurably small to a few percent, and one would expect performance losses to be of similar magnitude. The effect on performance would probably not be perceptible, and is thus of little importance, but the increased fuel consumption would add significantly to the life-cycle cost of the system, especially in the heavier trucks. This increase is estimated to be about 3.0 percent in transit buses, 2.5 percent in light-heavy and medium-heavy trucks, and 2.0 percent in line-haul trucks. These figures reflect the fact that a proportionally larger trap (resulting in a lower pressure drop and less frequent regeneration) would be cost effective in the line-haul trucks.

<u>Estimated Cost:</u> Table 5.1 shows the authors' estimates of the increases in purchase price and operating and maintenance costs for each of the four major classes of heavy-duty vehicles which would result from a bypass/burner trap-oxidizer system. The estimated initial cost increase was calculated from the estimated costs of the trap, container, and other components and the estimated assembly labor requirements using the method developed by Fronk (1984) for EPA. This method, in turn, was based on earlier work by Lindgren (1977) and by EPA. All of these approaches were originally designed for, and are based on data for, light-duty vehicle manufacturers. They have thus had to be adapted somewhat to be applicable to the heavy-duty industry.

This report uses the following equation (adapted from Fronk) for the increase in a vehicle's selling price that results from the addition of an emissions control device (such as a trap-oxidizer) provided by an outside supplier.

$$RPE = ((SP + AL + AO)\,MM + RD + TE)\,DM)$$

Table 5.1
Estimated Cost of Ownership For A Monolith/Burner System

	Light-Heavy	Medium-Heavy	Line-Haul	Transit-Bus
INITIAL COST TO MANUFACTURER				
Trap	$ 72.00	$120.00	$ 240.00	$150.00
Container and Piping	50.00	60.00	120.00	60.00
Regeneration and Control system	170.00	180.00	220.00	180.00
Modifications to Vehicle	$20.00	$40.00	$80.00	$100.00
TOTAL COST TO MANUFACTURER	$312.00	$400.00	$660.00	$490.00
Assembly Labor (hours)	2.00	3.00	5.00	4.00
Cost @ $20/hour	$40.00	$60.00	$100.00	$80.00
Assembly overhead @ 40%	$16.00	$24.00	$40.00	$32.00
TOTAL COST TO MANUFACTURER	$368.00	$484.00	$800.00	$602.00
Manufacturer's Markup @ 20%	$73.60	$96.80	$160.00	$120.40
Estimated Tooling Cost Per Unit	5.00	50.00	50.00	100.00
Estimated R&D Cost Per Unit	15.00	150.00	150.00	300.00
INCREASE IN DEALER COST	$461.60	$780.80	$1160.00	$1122.40
Dealer's Markup @ 8%	36.93	62.46	92.80	89.79
INITIAL COST TO CONSUMER	$498.53	$843.26	$1252.80	$1212.19
OPERATING COSTS				
Vehicle Lifetime (Miles)	120,000	250,000	500,000	250,000
Vehicle Lifetime (Years)	8	8	8	8
Maintenance Costs				
Per 100,000 Miles	$70.00	$70.00	$100.00	$70.00
Discounted Lifetime	$56.02	$116.70	$333.43	$116.70
Fuel Consumption				
Base Fuel Economy (MPG)	16.20	8.81	6.44	6.00
- Reduction Due to Trap	2.5%	2.5%	2.0%	3.9%
Cost of Fuel ($/Gallon)	$1.30	$1.30	$1.30	$1.30
Discounted Lifetime Cost	$160.54	$615.02	$1346.16	$1083.66
Trap Replacement Cost				
Trap Lifetime (Miles)	150,000	250,000	250,000	150,000
Trap Replacements Needed	0	0	1	1
Cost of Replacement	$300.00	$416.00	$776.00	$476.00
Discounted Replacement Cost	$ 0.00	$ 0.00	$ 530.02	$295.56
TOTAL OPERATING COSTS	$216.56	$731.72	$2209.61	$1495.92
TOTAL LIFECYCLE COSTS	$715.09	$1574.98	$3462.41	$2708.11

Where

SP	is the price charged by the supplier to the manufacturer
AL	is the direct cost of assembly labor for mounting the device in the vehicle
AO	is the manufacturer's assembly overhead cost per unit
MM	is the manufacturer's markup percentage
RD	is the manufacturer's research and development cost, per unit
TE	is the manufacturer's tooling cost, per unit
DM	is the dealer's markup percentage

In Table 5.1, the supplier price is estimated separately for each of the major components of the trap-oxidizer system. These estimates are based on data obtained from suppliers and vehicle manufacturers, comparison with prices of similar components which are now in use (e.g. catalytic converters), and a great deal of engineering judgment. The prices shown for traps represent a very large decrease from present price levels — currently, large heavy-duty ceramic monolith traps sell for $500 to $1,000. However, these prices reflect small volume prototype production, and appear to include a substantial premium for the supplier's R&D. The prices shown are ERC's estimates of prices in mass production.

The labor required to assemble and install a trap-oxidizer system was estimated by ERC on the basis of engineering judgment and the apparent difficulty of the mounting process (thus, more labor is required to mount a trap-oxidizer in the confined space of a bus than is required for a truck). The cost of assembly labor was taken as $20 per hour. Assembly overhead for light-duty manufacturers was estimated at 40 percent of direct labor costs by Fronk; for want of a better estimate, that figure is used here as well.

Research and development and tooling costs shown for each category are primarily guesswork — since no one presently has a fully developed trap-oxidizer system for heavy-duty vehicles, no one really knows what the development will cost. EPA (1984b) has estimated the cost of trap-oxidizer research and development as $2.5 million per manufacturer, plus $208,000 per engine line. These costs are far too low, however, considering that General Motors claims to have spent more than $64 million on trap-oxidizer development already, and that GM has not yet reached the most expensive stages of development: fleet testing, adaptation to production, durability assurance, and certification testing. ERC has (somewhat arbitrarily) estimated the total cost R&D cost per manufacturer for the bypass/burner system at $30 million in the medium-heavy and heavy-heavy classes. Tooling expenses were estimated (arbitrarily) at $10 million.

Assuming that the typical heavy-duty manufacturer produces 40,000 units per year, and that the tooling and R&D costs are recovered at 20 percent per year, this gives an R&D cost per unit of $150, with a further $50 for tooling costs. These costs were arbitrarily doubled for transit buses, reflecting their very small production volume (about 2,500 units per year, in total). For light-heavy duty trucks, these costs were arbitrarily reduced by a factor of 10, reflecting the much larger volume and the relative ease of adaptation of light-duty trap-oxidizer technology to the light-heavy class.

The manufacturer's markup term (MM) accounts for both the manufacturer's corporate overhead and for corporate profits. Fronk, using financial data from the years 1979-1983, estimates this factor as 1.11 (11 percent markup) for light-duty vehicle manufacturers. In the case of heavy-duty manufacturers, however, there are often not one but two corporate markups to consider — that of the engine maker and that of the vehicle assembler (light-duty manufacturers generally fill both roles). The duplication of corporate staffs should result in a higher markup, as should the smaller size and lower volume (and thus lower economies of scale) of heavy-duty manufacturers. In addition, the years 1979-1983 are generally regarded as having been disastrously unprofitable ones for both light and heavy-duty manufacturers. Thus, profit margins estimated from data in these years would be expected to be too low. Taking all of these factors into account, the authors consider that a markup factor of 20 percent is probably more representative than Fronk's value of 11 percent. This value is the one used in Table 5.1.

The dealer's markup term (DM) was estimated by Fronk as being 1.05 for passenger cars, and 1.06 for trucks. Again, this value was based on data for 1979-1983, and is thus probably too low to represent the long-term average. There are also major differences between light-duty vehicles sales and sales of heavy-duty trucks — generally, truck dealer's technical expertise must be much greater, and their carrying costs are probably also more. For this reason, the authors regard a dealer's markup of eight percent as probably more appropriate than the six percent estimated for light-duty trucks.

Inserting the values shown into the equation and calculating through results in the estimated increased cost to the purchaser shown in Table 5.1. Considering the uncertainties inherent in estimating cost for a system which has not even been designed yet, these values should be taken as only very rough and approximate. They are also probably somewhat conservative (that is, they may underestimate the actual cost). One area where costs may have been underestimated is in provisions for warranty and recall. An allowance for warranty and recall costs is supposed to be included in the manufacturer's markup, but the serious reliability questions surrounding trap-oxidizers in general, and especially the bypass/burner system, make it questionable whether this allowance is sufficient.

In addition to the initial cost of the system, there would also be significant operating and maintenance expenses. These expenses and the assumptions going into them are shown in Table 5.1. The vehicle lifetimes and lifetime mileages shown are considered to be reasonably representative of vehicles in each class, although of course individual vehicles would vary. Maintenance cost per 100,000 miles was estimated using engineering judgment, and taking into account the mechanical complexity of the system. This cost was then spread over the life of the truck, and discounted to the year of purchase at a 10 percent (real) rate.

Typical fuel-economy values for each class of truck are those estimated for 1992 by Energy and Environmental Analysis (1983), except for transit buses, for which the estimate was done by the authors. These represent substantial improvements over present-day values, and could probably not be achieved in the face of a 4.0 gram NO_x standard. The increase in fuel consumption due to the trap-oxidizer was estimated by the authors, and may be somewhat optimistic. A two to 2.5 percent penalty is probably about the best that can be achieved with a reasonable-size trap, considering that the burner regeneration process also consumes fuel, while a penalty in the three to four percent range would not be at all surprising. The penalty for buses is estimated to be somewhat greater, due to the limited space in which to put a trap. The discounted lifetime fuel cost of the system is calculated by dividing the average mileage per year by the MPG rating, and multiplying by the fuel-economy penalty to give the average cost per year. This is then discounted (at 10 percent) to the year of purchase to give the discounted lifecycle cost.

The trap replacement frequencies shown have been estimated by the authors, using somewhat optimistic estimates of trap plugging rates and average lifetime. As the table indicates, only line-haul trucks and transit-buses are expected to require trap replacements with this system. The cost of a trap replacement was estimated as parts and labor, with the parts cost taken as supplier's price for the trap, marked up 100 percent to reflect the premium charged in the aftermarket. The labor cost of the trap replacement was estimated at two labor hours, at a cost of $28 per hour, and the total was discounted to the year of purchase at 10 percent per year.

As Table 5.1 indicates, trap-oxidizers would be fairly expensive, especially in heavy-duty vehicles. The reader is cautioned that these estimates are very crude, however, and are based on a technology which is still undergoing development. They should be treated with appropriate caution. In performing these estimates, the authors have tended to err on the side of optimism — thus the actual costs would probably not be less than those shown, but might well be significantly more if unforseen problems occur during development.

Safety and Environmental Effects: Deleterious environmental effects from this type of system should be minimal. Some minor increases in emissions of gaseous pollutants would be generated by the burner and the regeneration process. In addition, the fact that the trap is more effective at removing soot than condensable hydrocarbons can result in the formation of very fine particles of condensed hydrocarbon (MacDonald, 1983). The net effect on condensable hydrocarbons is a reduction however.

In the area of safety, on the other hand, some very serious questions exist. The presence of a diesel fuel burner, with its associated fuel lines, ignition source, etc. in the exhaust system would clearly increase the chance of fire, as would the regeneration process in the trap itself. This risk could probably be reduced to insignificance by careful design, at least in the majority of applications. However, the acceptability of this (or perhaps any) type of trap-oxidizer system for trucks hauling flammable or explosive products is very questionable.

Other Considerations: The complexity of this type of system, and the presence of the oil burners — which could lead to drastic consequences in case of failure — would probably tend to encourage tampering and interference in order to minimize the inconvenience and perceived hazard of the system. Such tampering could be relatively simple — the trap-oxidizer could simply be bypassed entirely by jamming the bypass valve open. This problem would possibly be most serious in the larger trucks, and especially those owned by individual truckers rather than by organizations.

Development Status: Until about 1982, the bypass/burner system was perceived as the most promising type of trap-oxidizer system for light-duty vehicles, due primarily to the fact that it allows complete control of the regeneration process and uses comparatively well-understood technology. Since that time, a greater appreciation of the serious cost and reliability problems associated with this type of system and technological progress (notably in additive self-regeneration) have caused most light-duty vehicle manufacturers to turn away from it. Nonetheless, many heavy-duty manufacturers (including Caterpillar and Cummins) still seem to regard this as the leading system. However, those manufacturers favoring this system appear to have done very little work in developing it. The converse is also true -- those manufacturers which have devoted significant effort to developing these types of systems now favor other approaches. At present, the monolith/burner system appears to be in limbo, awaiting the success or failure of attempts to develop more attractive systems.

Overall Assessment: The ceramic monolith/burner system is quite unattractive from both the manufacturer's and the user's viewpoint, due to its complexity and questionable reliability. However, the basic trapping arrangement should last for a reasonably long time, unlike the other systems discussed below in which the trap can become plugged more quickly. For this reason, this type of system might be attractive in very high-mileage applications such as line-haul trucks and city buses, which otherwise would require more frequent replacement of the trap. Significantly, those heavy-duty manufacturers who are most interested in this system are those whose primary markets are in large, high-mileage trucks. Even in these applications, however, this system's competitive advantge is not clear-cut.

5.3.2 Ceramic Monolith Trap/Self Regeneration

System Description: A self-regenerating trap-oxidizer system based on the ceramic monolith trap would most likely be based on the use of catalytic fuel additives. A possible alternative approach would be to have the trap itself impregnated with a base-metal catalyst, but there is too little publicly available information on the performance of such traps to realistically assess their potential. For this reason, only the fuel-additive based system is discussed here.

A self-regenerating system based on catalytic fuel additives would consist of one or more ceramic monolith traps and some system for getting the additives into the fuel. As with the bypass-burner/monolith system, use of a single trap would be desirable in order to minimize complexity and cost, but would probably not be possible for the largest trucks, due to the size limitations of the trap. In addition to the trap and the additive supply, some simple sensors to detect trap overheating and some sort of fail-safe bypass in case of regeneration failure would probably also be required.

Two systems for providing the needed fuel additives have been proposed. These are: (1) to keep the additives in an on-board reservoir, from which they are metered into the fuel as required; and (2) to provide the additives in the fuel as it is pumped into the tank, either by mixing additives into all diesel fuel, creating a special "catalytic" grade of diesel fuel, or by some sort of at-the-pump mixing. Neither option is fully satisfactory, for reasons discussed below. Figure 5.9 diagrams a one-trap system based on option one; a similar system using the second option could be obtained by deleting the reservoir and the metering pump in the diagram.

<u>Effectiveness</u>: The ceramic monolith trap used in this system would be identical to the one used in the bypass-burner/monolith system described above. Thus, most of the comments on the trap's effectiveness are also the same. This trap is extremely efficient at capturing soot, but less so in capturing particulate hydrocarbons and in reducing the mutagenic activity of the exhaust. It would thus allow meeting a very strict standard for total mass emissions of particulates, and would effectively reduce both the total mass of particulates in the air and degradation in visibility due to particulates. Reductions in human exposure to particulate-borne organics and especially to particulate-carried mutagens would be much less. The effects on other pollutants would be minor, except for a possible reduction in odor due to the surface-catalytic metals in the additives. This increase should be very slight, however, since almost all of the catalytic metal is retained in the trap (at least for the tests reported to date). If catalytic additives were

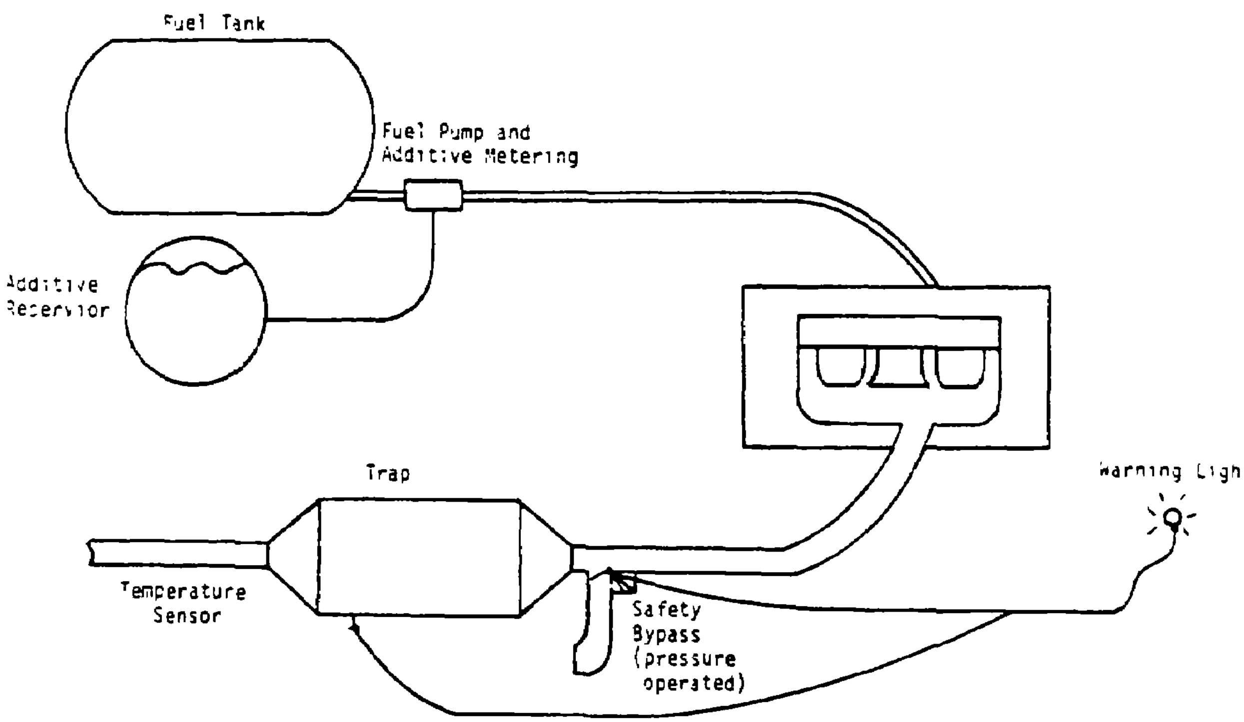


Figure 5.9: System diagram — ceramic monolith trap-oxidizer with fuel-additive self regeneration.

to be mixed into all diesel fuel, there could be a significant increase in metal emissions, since the catalyst-containing fuel would then be used by many vehicles without traps.

Durability and Reliability: Although no tests of this type of regeneration system with heavy-duty vehicles have been reported, the results reported for light-duty vehicles indicate that reliability should not be much of a problem. The additive self-regeneration system appears to work quite reliably, even under adverse circumstances such as constant low-speed driving. Since heavy-duty engines are, in general, more heavily loaded than those of light-duty cars, their average exhaust temperatures are higher. This should make self-regeneration even more reliable in these vehicles.

The durability of these systems remains somewhat problematic, however. The ceramic monolith trap retains essentially all of the catalytic metal provided in the fuel in the form of oxides and sulfates. Over time, these compounds accumulate, and they will eventually build up to the point where they block the trap. From the currently available data it is estimated that the traps would need to be cleaned or replaced at intervals between 70,000 and 200,000 miles. Thus, one trap might well last the lifetime of a light-heavy duty vehicle, but the heavier and higher mileage trucks might well require three or four sets of replacements during their lives. The need to replace these traps will add significantly to the lifecycle cost of the system, and will probably decrease consumer acceptance and increase the risk of tampering as well. Work is now underway on chemical methods of removing the additives from the trap without damaging it. If successful, this would reduce the life cycle cost of the system in high-mileage applications.

Performance and fuel economy: As with any other type of trap-oxidizer system, this sytem would result in a slight (and probably imperceptible) loss of engine performance, and a small increase in fuel consumption due to the additional work required to overcome the pressure drop through the trap. The effects on fuel consumption for this type of system are estimated as about 2.5 percent for transit buses, 2.0 percent for light-heavy and medium-heavy trucks, and 1.5 percent for line-haul trucks. These values are slightly below those for the bypass-burner/monolith system. This is due to the fact that the self-regeneration process in these traps would occur more often, thus reducing the average backpressure. In addition, unlike the burner system, this type of system would not use any fuel directly.

Estimated Cost: Table 5.2 shows the authors' estimates of the increase in purchase price and in operating and maintenance costs for each of the four major classes of heavy-duty vehicles resulting from the use of a monolith/additive trap-oxidizer system. The basis for this calculation and the general approach used have already been discussed in connection with Table 5.1, and that discussion will not be repeated here. Table 5.2 differs from Table 5.1 in that the trap-oxidizer hardware, and thus the hardware costs, are different. The estimates shown are for a system with the additive reservoir on board; these costs would be reduced somewhat if the additive were supplied in the fuel instead.

The two systems are expected to require roughly the same amount of labor to install, and the same amount of tooling, so the estimates of those two costs are the same in Tables 5.1 and 5.2. However, the development of the additive/monolith system is expected to be much more straightforward than the burner/monolith approach, and thus the estimated R&D cost per unit for these systems has been reduced by one third.

Maintenance costs for the monolith/additive system are expected to be lower, reflecting the system's simplicity. The estimated fuel-economy penalty has also been reduced, to account for the fact that the presence of the monolith results in frequent self-regeneration, so that the average backpressure is lower. This is expected to more than offset the effects of ash buildup in the trap in increasing backpressure. Ash buildup will still occur, however, and will require occasional replacement or cleaning of the trap. Presently, traps must be replaced, but efforts are now underway to develop a means of cleaning the trap after it becomes plugged with additives, rather than replacing it. If these efforts are successful it would reduce the lifecycle cost of these systems substantially, as Table 5.2 indicates.

The net effect of using fuel additive rather than the burner regeneration system is estimated to be a modest savings in life-cycle cost over the monolith/burner system, except in the case of line-haul trucks, where the increased trap-replacement costs due to the additive outweigh the savings from the lower-cost regeneration system. If a practical method of cleaning rather than replacing the trap is found, the additive system would become cheaper for line-haul trucks as well. It should be emphasized that these estimates are very crude, and that the system on which they are based is still undergoing development. The values shown should thus be interpreted carefully, and used with appropriate caution. As with the estimates for the monolith/burner system, the authors have tended to err on the side of optimism in developing these estimates — if unforeseen

Table 5.2
Estimated Cost of Ownership For a Monolith/Additive System

	Light-Heavy	Medium-Heavy	Line-Haul	Transit-Bus
INITIAL COST TO MANUFACTURER				
Trap	$ 72.00	$120.00	$ 240.00	$150.00
Container and Piping	50.00	60.00	120.00	60.00
Additive Reservoir and Pump	60.00	80.00	100.00	80.00
Fail-Safe and Sensor	30.00	30.00	60.00	30.00
Modifications to Vehicle	20.00	40.00	80.00	100.00
TOTAL COST TO MANUFACTURER	$232.00	$330.00	$600.00	$420.00
Assembly Labor (hours)	2.00	3.00	5.00	4.00
Cost @ $20/hour	$40.00	$60.00	$100.00	$80.00
Assembly overhead @ 40%	$16.00	$24.00	$40.00	$32.00
TOTAL COST TO MANUFACTURER	$288.00	$414.00	$740.00	$532.00
Manufacturer's Markup @ 20%	$57.60	$82.80	$148.00	$106.40
Estimated Tooling Cost Per Unit	$5.00	$50.00	$50.00	$100.00
Estimated R&D Cost Per Unit	$10.00	$100.00	$100.00	$200.00
INCREASE IN DEALER COST	$360.60	$646.80	$1038.00	$938.40
Dealer's Markup @ 8%	$28.85	$51.74	$83.04	$75.07
INITIAL COST TO CONSUMER	$389.45	$698.54	$1121.04	$1013.47
OPERATING COSTS				
Vehicle Lifetime (Miles)	120,000	250,000	500,000	250,000
Vehicle Lifetime (Years)	8	8	8	8
Maintenance Costs				
Per 100,000 Miles	$40.00	$40.00	$50.00	$40.00
Discounted Lifetime	$32.01	$66.69	$166.72	$66.69
Fuel Consumption				
Base Fuel Economy (MPG)	16.20	8.81	6.44	6.00
Reduction Due to Trap	2.0%	2.0%	1.5%	2.5%
Cost of Fuel ($/Gallon)	$1.30	$1.30	$1.30	$1.30
Discounted Lifetime Cost	$128.43	$492.01	$1009.62	$903.05
Trap Replacement/Cleaning				
Trap Lifetime (Miles)	120,000	125,000	125,000	100,000
Trap Replacements Needed	0	1	3	2
Cost of Replacement	$300.00	$416.00	$776.00	$476.00
Discount Replacement Cost	$ 0.00	$284.13	$1609.37	$626.31
Cost of Cleaning	$84.00	$84.00	$84.00	$84.00
Discount Replacement Cost	$0.00	$194.07	$174.21	$110.53
TOTAL OPERATING COSTS				
If Trap Can Be Cleaned	$160.44	$752.76	$1350.54	$1080.26
If Trap Must Be Replaced	$160.44	$842.83	$2785.70	$1596.05
TOTAL LIFECYCLE COSTS				
If Trap Can Be Cleaned	$549.89	$1,451.31	$2471.58	$2093.73
If Trap Must Be Replaced	$549.89	$,1541.38	$3906.74	$2609.52

problems develop, the actual values experienced could well be greater than those shown in the table, but they are unlikely to be less.

Safety and environmental effects: The major safety concern with this system is with the on-board storage of the organometallic additive. Most such compounds are highly flammable and some are highly toxic. They could thus be extremely dangerous if released during a crash. In this regard, it is worth noting that one manufacturer has developed an additive which is said to be no more toxic than diesel fuel (J.H. Howitt, personal communication, 1983), so the toxicity problem might be avoidable. Flammability, however, would remain a concern, as would the special problems of additive disposal when the vehicle is scrapped.

The only significant environmental concerns with this type of system would be the potential for routine emissions of the catalytic metal in the additive, and for occasional spills or release of the additive itself. The additives presently under consideration are efficiently collected by the trap itself, so the routine emissions would be a problem only if additive-containing diesel fuel were to be burned in vehicles without traps. This could be avoided by using an on-board additive reservoir, or by using some arrangement of special fuel nozzles similar to the ones for unleaded gasoline. There is, however, considerable incentive to develop an additive which will not be collected by the trap, in order to eliminate the plugging problem. Emissions of such an additive, if it were developed, could conceivably result in some environmental effects.

Other considerations: If catalytic fuel additives are to be supplied in the fuel, rather than mixed into it from an on-board reservoir, some EPA action will probably be required. This will be needed in order to define the appropriate additives and their amounts, and to ensure that the fuel with the additive will be available. This action might usefully be combined with consideration of overall standards for diesel fuel, such as are discussed in Chapter 6. A clear policy statement by EPA, defining which additives would be acceptable under which kinds of circumstances, is also urgently needed in order to reduce manufacturer's uncertainty and permit additional development in this area.

<u>Development status</u>: As discussed in Section 5.1.2 and elsewhere (Weaver, 1983a) the development of additive self-regeneration systems for light-duty vehicles is well advanced. A number of manufacturers have reported data from successful tests of this concept, and industry contacts indicate that a large number of prototype cars using this approach are now on the road. It appears quite likely that light-duty additive self-regeneration systems will be offered for sale in California in 1986.

Little development of this approach using heavy-duty engines has been carried out, possibly because the speed of development in this area has outpaced heavy-duty manufacturers R&D efforts. However, heavy-duty operation would generally be more favorable to this type of system than would light-duty use (with the possible exception of some medium-duty trucks), so the apparent success with light-duty vehicles bodes very well for eventual success in the heavy-duty class as well.

<u>Overall assessment</u>: The rapid and comparatively problem-free development of this type of system in light-duty vehicles augurs well for a similar development in heavy-duty applications. Also working in this system's favor are its comparatively low cost, simplicity, and (from the reported development work to date) reliability. On the other hand, the applicability of any self-regenerating system to all medium-duty trucks is somewhat doubtful, due to the wide variety of operating patterns found. Some sort of hybrid system, using a supplemental heat source for backup, might be workable, however, and this reservation would apply only to a few models of truck.

The major drawback to this system as it is now envisioned would be the clogging of the traps with additive residue, which would require replacing or cleaning the traps several times over the life of a line-haul truck. Since such replacements would be expensive, they would be unlikely to be carried out (at least in the absence of an inspection and maintenance program), resulting in increased emissions. Another, less serious disadvantage would be the need to supply the additive, either in a reservoir on the vehicle (reducing payload and possibly causing some safety problems) or in the fuel (which would generate significant institutional problems). Despite these problems, however, the outlook for this type of system appears very good.

5.3.3 Catalyzed Wire-Mesh Trap/Regeneration by HC and CO Oxidation

System description: A trap-oxidizer system of this type would consist of one or two traps, each containing several cylindrical wire-mesh filtering elements and appropriate manifolding; a system for increasing the HC and CO content of the exhaust; and a set of sensors, controls, and actuators. The trap(s) might be located either as replacements for the engine exhaust manifold or further downstream near the mufflers. The former location is preferable due to the higher exhaust temperatures there, but would not be practical in many applications due to lack of room in the engine compartment. Figure 5.10 shows one possible configuration of this system, with a single trap located near the muffler and a regeneration system based on partial throttling of the engine. The type of system shown would be applicable to most light-heavy and medium-heavy vehicles.

Effectiveness: The Johnson-Matthey trap is somewhat less effective than the ceramic monolith at reducing the total mass of particulate emitted, due primarily to its much lower soot-capturing efficiency. On the other hand, this type of trap removes almost all of the soluble organic fraction of the particulate, and produces a much greater reduction in total mutagenic activity emitted per mile. Thus, this type of system would have less effect on total particulate concentrations and visibility than would a monolith-based system, but would be more effective in reducing human exposure to particulate-borne organics and mutagenic materials.

A special problem with this type of trap is its tendency to increase sulfate emissions at high exhaust temperatures, such as are commonly found in heavy-duty trucks. No test data for traps using Johnson-Matthey's heavy-duty catalyst formulation are available, so the magnitude of this effect is not known. Test data using J-M's light-duty catalyst formulation on a heavy-duty truck indicte that sulfate production is so high as to rule out the use of that formulation, except for light-heavy-duty vehicles. This problem and its implications are discussed further below.

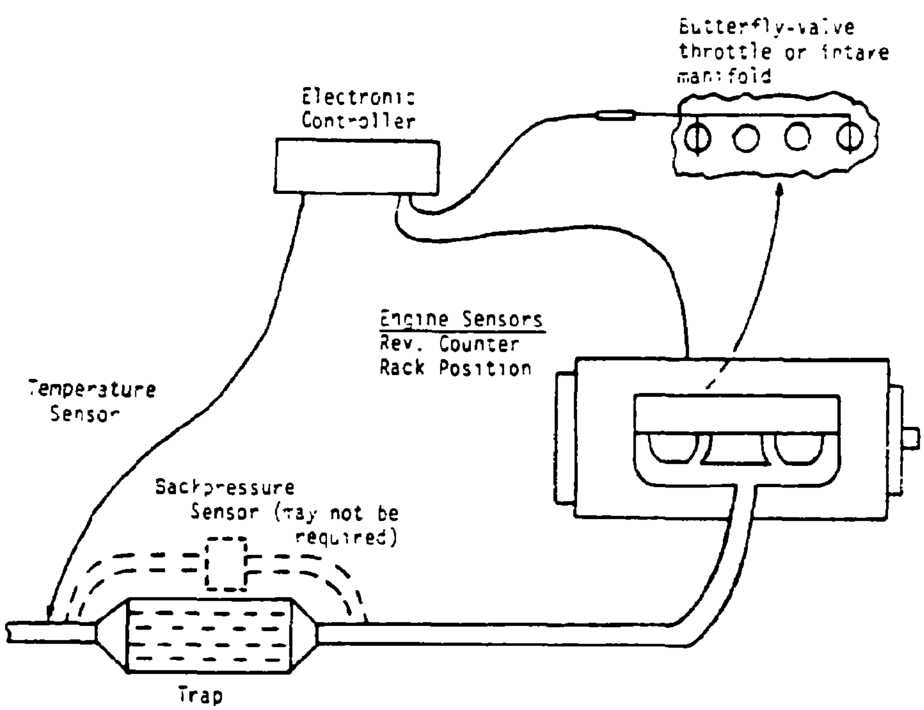


Figure 5.10: System diagram - catalyzed wire-mesh trap-oxidizer and regeneration system.

Durability and reliability: The major concern in these areas is with the loss of effectiveness of the catalyst coating with increasing time and mileage. Catalysts do deteriorate with age, and the Johnson-matthey catalyst seems to be no exception. The available data indicate that the present catalyst should have a useful life of at least 100,000 miles. How much longer it could last is a matter for speculation. A lifetime of 100,000 to 150,000 miles would be adequate for light-heavy vehicles and the lighter end of the medium-heavy duty vehicle fleet. For the larger trucks, which have longer useful lives, it would probably be necessary to replace the trapping material at least once during the truck's lifetime. This would be quite expensive, and it appears unlikely that it would be done in practice.

Performance and fuel economy: As with any other type of trap-oxidizer system, this system would result in a slight (and probably imperceptible) loss of engine performance, and a small increase in fuel consumption due to the additional work required to overcome the pressure drop through the trap. The effects on fuel consumption for this type of system are estimated as about 2.5 percent for transit buses, 2.0 percent for light-heavy and medium-heavy trucks, and 1.5 percent for line-haul trucks. These values are the same as those for the monolith/self-regeneration system, and slightly below those for the bypass-burner/monolith system. This is because these traps' ability to self-regenerate under many driving conditions would reduce the average backpressure, and the regeneration system itself would use only negligible amounts of fuel.

Estimated Cost: Table 5.3 shows the authors' estimates of the increase in owning and operating costs occasioned by the use of a catalyzed wire-mesh trap-oxidizer system in each of the four major classes of heavy-duty vehicles. The analytical approach and many of the assumptions used have already been discussed in Section 5.3.1, in connection with the cost estimates for the monolith/burner system. That discussion will not be repeated here.

The estimated cost of the trap-oxidizer and other components shown in Table 5.3 were derived by scaling up the costs of similar light-duty components, with appropriate adjustments based on engineering judgment and information supplied by Johnson-Matthey. Because of its precious metal content, the catalyzed wire-mesh trap is rather expensive, but this is offset to some degree by the lower-cost regeneration system the

Table 5.3
Estimated Cost of Ownership For a Catalyzed Wire-Mesh System

	Light-Heavy	Medium-Heavy	Line-Haul	Transit-Bus
INITIAL COST TO MANUFACTURER				
Trap	$240.00	$400.00	$800.00	$500.00
Container and Piping	50.00	60.00	120.00	60.00
Regeneration and Control system	60.00	70.00	70.00	70.00
Modifications to Vehicle	20.00	40.00	80.00	100.00
TOTAL COST TO MANUFACTURER	$370.00	$570.00	$1070.00	$730.00
Assembly Labor (hours)	2.00	3.00	5.00	4.00
Cost @ $20/hour	$40.00	$60.00	$100.00	$80.00
Assembly overhead @ 40%	$16.00	$24.00	$40.00	$32.00
TOTAL COST TO MANUFACTURER	$426.00	$654.00	$1210.00	$842.00
Manufacturer's Markup @ 20%	$85.20	$130.80	$242.00	$168.40
Estimated Tooling Cost Per Unit	$5.00	$50.00	$50.00	$100.00
Estimated R&D Cost Per Unit	$5.00	$50.00	$50.00	$100.00
INCREASE IN DEALER COST	$521.20	$884.80	$1552.00	$1210.40
Dealer's Markup @ 8%	$41.70	$70.78	$124.16	$96.83
INITIAL COST TO CONSUMER	$562.90	$955.58	$1676.16	$1307.23
OPERATING COSTS				
Vehicle Lifetime (Miles)	120,000	250,000	500,000	250,000
Vehicle Lifetime (Years)	8	8	8	8
Maintenance Costs				
Per 100,000 Miles	$20.00	$20.00	$20.00	$20.00
Discounted Lifetime	$16.00	$33.34	$66.69	$33.34
Fuel Consumption				
Base Fuel Economy (MPG)	16.20	8.81	6.44	6.00
Reduction Due to Trap	2.0%	2.0%	1.5%	2.5%
Cost of Fuel ($/Gallon)	$1.30	$1.30	$1.30	$1.30
Discounted Lifetime Cost	$128.43	$492.01	$1009.62	$903.05
Trap Replacement Cost				
Trap Lifetime (Miles)	150,000	250,000	250,000	150,000
Trap Replacements Needed	0	0	1	1
Cost of Replacement	$636.00	$976.00	$1896.00	$1176.00
Discount Replacement Cost	$ 0.00	$ 0.00	$1294.99	$730.20
TOTAL OPERATING COSTS	$144.44	$525.36	$2371.30	$1666.59
TOTAL LIFECYCLE COSTS	$707.33	$1480.94	$4047.46	$2973.83

catalyst makes possible. Assembly labor and tooling costs for the wire-mesh system are assumed to be similar to those for the monolith/burner approach, but the manufacturer's R&D per unit would probably be much lower. This is because the wire-mesh system is far simpler than the monolith/burner approach, and has undergone considerable development by Johnson-Matthey.

Because of its simplicity, the maintenance costs of the wire-mesh system are estimated to be well below those for either of the monolith-based systems, and the fuel-consumption penalty for a reasonably efficient trap (in the 60-80 percent range) is expected to be comparable to that of the monolith/additive approach. The major uncertainty with the wire-mesh system (aside from the question of technical feasibility, due to the sulfate problem) lies in the projected lifetime of the catalyst. All catalysts deteriorate with time, and deteriorate more rapidly when exposed to contaminants such as sulfur in diesel fuel. No data on how rapidly the Johnson-Matthey catalyst deteriorates are available, so the authors have attempted a crude estimate, based on the rate of deterioration of catalytic converters. The trap lifetimes shown are rather optimistic, and might require the use of desulfurized fuel to achieve in practice. This greatly increases the uncertainty in the estimates; if trap lifetime were only half as long as that shown in the table, the costs of this type of system would increase enormously. This limitation, as well as the general crudeness of the data, should be borne in mind, and these estimates should be treated with appropriate caution.

<u>Safety and environmental effects</u>: There are no obvious safety concerns with this type of system, beyond the slightly increased risk of fire which is common to all trap-oxidizers. From an environmental standpoint, however, there is an overwhelming concern with potential sulfate emissions. Unless Johnson-Matthey can achieve a very great reduction in sulfate conversion activity at high temperatures, this type of trap will not be usable in heavy-duty applications except with desulfurized fuel. On the other hand, if the sulfate problem can be solved or if desulfurized fuel can be provided, this trap will be quite attractive from an environmental standpoint, due to its activity in reducing gaseous HC, CO, and odor emissions as well as particulates.

<u>Other considerations</u>: The effect of this trap in reducing odor emissions as well as smoke might greatly improve the sociability of diesel trucks, and thus help to reduce consumer

resistance to trap-oxidizers, especially among public relations-conscious organizations such as utilities and other fleet owners.

Development status: Light-duty versions of the Johnson-Matthey system are apparently in the process of being tested in a production-prototype form, and Johnson-Matthey has predicted that they will be introduced in commercial production in time to meet the 1986 California particulate standard. Johnson-Matthey also claims to have developed a heavy-duty catalyst formulation which is now being evaluated by some heavy-duty manufacturers. Limited test data published by Johnson-Matthey (Budd and Enga, 1984) appear to support the claim of lower sulphate conversion. Johnson-Matthey has proposed to install a prototype heavy-duty trap-oxidizer system on a Southern-California Rapid Transit District bus. This project was stalled until recently by the State of California's fiscal problems, but is now in progress. Overall, the development of this system appears to be very advanced, with the possible exception of the development of a solution to the sulfate problem.

Overall assessment: The major advantages of this type of system are that it is well developed — with its implementation in production light-duty vehicles being predicted for 1986 — and that it reduces emissions of hydrocarbons and odor as well as particulates. The simpler regeneration system made possible by the presence of the catalyst is also an advantage. Offsetting this are the higher cost of the trapping medium (this cost is much more significant in heavy than in light-duty vehicles, due to the much greater amount required) and the sulfate emissions problem. It appears that the most promising application of this system is probably in light-heavy duty vehicles, where its cost disadvantage is smaller and the sulfate problem would be minimized. A shift to desulfurized diesel fuel (as suggested in the next chapter) could make the system a very strong contender in every segment of the market.

5.3.4 Ceramic-Fiber Trap/Regeneration by Catalyst Injection

System description: This type of trap-oxidizer system would consist of a number of "candles" made of woven silica-fiber yarn on a perforated metal substrate and impregnated with an inorganic material to improve filtration. These candles would be arranged in one (or two, for a twin-stack exhaust configuration) larger container(s), as shown in Figure 5.11. In addition, the system would include a backpressure sensor, temperature sensor, and control logic; a system for injecting the powdered catalyst into the exhaust stream; and a reservoir of the catalyst. These are also shown in the figure.

__Effectiveness:__ Daimler-Benz reports that this trap's efficiency ranges from about 60 percent to at least 90 percent when clean, and increases rapidly with trap loading (DBAG, 1984). No data concerning the trap's effectiveness on different components of the particulate are available. From analogy to the ceramic monolith, however, it might be expected that the trap would be relatively less effective at capturing the organic fraction of the particulate, and more effective at capturing the sooty part.

__Durability and reliability:__ The durability and reliability of this type of system appear to be extremely good. Daimler-Benz had accumulated more than 280,000 kilometers (175,000 miles) on five traps as of April 1982 (DBAG, 1982), with some 132,000 kilometers on a single trap. The traps were tested in both highway and city driving, and at least some of the tests used an automatically controlled regeneration system. Daimler-Benz does not mention any trap failures in their testing, implying that the reliability of this type of system, even in the prototype stage, must be reasonably good.

Daimler-Benz describes two types of problems with this system. The first, and probably less serious problem is that the powdered additive tends to absorb water from the air and cake together. This greatly complicates the design of the additive metering system. The second problem is that a significant portion of ash is retained in the trap, resulting in an increase in backpressure after prolonged operation. Daimler-Benz is presently searching for a solution to this problem. Unless such a solution could be found, it would be necessary to clean or replace the trap about every 100,000 to 150,000 miles, which would add significantly to the total cost.

__Performance and fuel economy:__ As with any other type of trap-oxidizer system, this system would probably result in a slight loss of engine performance, and a small increase in fuel consumption due to the additional work required to overcome the pressure drop through the trap. For this type of trap, however, Daimler-Benz has indicated that the

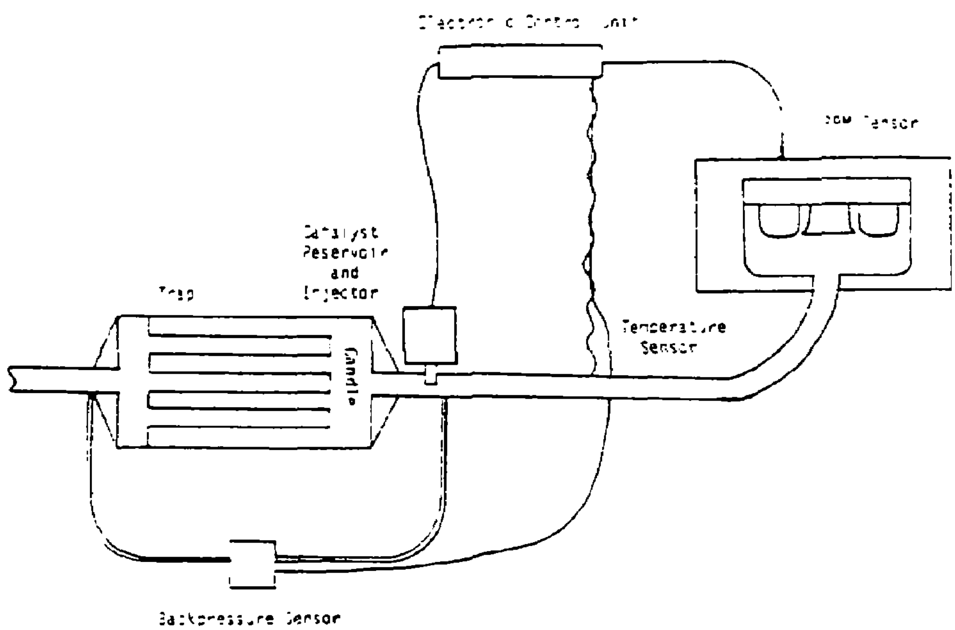


Figure 5.11: System diagram -- Daimler-Benz trap-oxidizer system based on silica fiber "candle" trap with catalytic regeneration.

effects on fuel economy are very small, due to its low backpressure. (H. Hardenburg, personal communication, 1983). It seems unlikely that these effects are completely negligible, however, so a nominal value of one percent for the fuel consumption increase has been assumed in calculating the increased operating cost below.

Estimated Cost: Table 5.4 shows the author's estimates of the increased owning and operating costs due to use of this type of trap-oxidizer system in each of the four major classes of heavy-duty vehicles. No initial cost data of any sort were available for the "candle" trap of for its regeneration system, thus, the estimated initial costs should be treated with great caution. The data shown were estimated by the authors, using engineering judgment, analogy to other trap-oxidizer systems, and the data-base on emissions control technology prepared by Lindgren (1977). They are considered plausible, but the authors have no indication as to whether they are correct. The assembly labor and tooling costs for this system are estimated to be similar to those of the other systems, and thus the same values have been used in the table. The estimated R&D cost, however, is higher than estimates for all but the monolith/burner system. This reflects the fact that only one manufacturer (Daimler-Benz) has been developing this approach, and Daimler would thus be in a position to collect substantial license fees from other manufacturers if it were used.

Since the overall principal is similar, maintenance costs for the "candle" system were estimated to be similar to those of the monolith/additive approach. However, based on Daimler-Benz's statements concerning its low backpressure, the fuel-economy penalty due to this system should be lower than that of the other candidate approaches. This would be offset, to some degree, by the trap's tendency to plug with ash at moderately high mileages, necessitating replacement. According to Daimler-Benz (1984), this occurs at mileages between 100,000 and 150,000 in transit buses. Since other vehicles would probably have larger traps, and generally burn less fuel per mile than transit buses, their traps would be expected to last somewhat longer.

Table 5.4
Estimated Cost of Ownership For A Daimler-Benz "Candle" System

	Light-Heavy	Medium-Heavy	Line-Haul	Transit-Bus
INITIAL COST				
Trap	$ 80.00	$ 130.00	$ 260.00	$ 170.00
Container and Piping	50.00	60.00	120.00	60.00
Regeneration and Control System	140.00	160.00	200.00	160.00
Modifications to Vehicle	20.00	40.00	80.00	100.00
TOTAL COST TO MANUFACTURER	$290.00	$390.00	$660.00	$490.00
Assembly Labor (hours)	2.00	3.00	5.00	4.00
Cost @ $20/hour	$40.00	$60.00	$100.00	$80.00
Assembly overhead @ 40%	$16.00	$24.00	$40.00	$32.00
TOTAL COST TO MANUFACTURER	$346.00	$474.00	$800.00	$602.00
Manufacturer's Markup @ 20%	$69.20	$94.80	$160.00	$120.40
Estimated Tooling Cost Per Unit	$5.00	$50.00	$50.00	$100.00
Estimated R&D Cost Per Unit	$15.00	$150.00	$150.00	$300.00
INCREASE IN DEALER COST	$435.20	$768.80	$1160.00	$1122.40
Dealer's Markup @ 8%	$34.82	$61.50	$92.80	$89.79
INITIAL COST TO CONSUMER	$470.02	$830.30	$1252.80	$1212.19
OPERATING COSTS				
Vehicle Lifetime (Miles)	120,000	250,000	500,000	250,000
Vehicle Lifetime (Years)	8	8	8	8
Maintenance Costs				
Per 100,000 Miles	$40.00	$40.00	$50.00	$40.00
Discounted Lifetime	$32.01	$66.69	$166.72	$66.69
Fuel Consumption				
Base Fuel Economy (MPG)	16.20	8.81	6.44	6.00
Reduction Due to Trap	1.0%	1.0%	0.75%	1.25%
Cost of Fuel ($/Gallon)	$1.30	$1.30	$1.30	$1.30
Discounted Lifetime Cost	$64.22	$246.01	$504.81	$451.52
Trap Replacement Cost				
Trap Lifetime (Miles)	120,000	150,000	150,000	100,000
Trap Replacements Needed	0	1	3	2
Cost of Replacement	$316.00	$436.00	$816.00	$516.00
Discount Replacement Cost	$ 0.00	$297.79	$1692.32	$678.94
TOTAL OPERATING COSTS	$96.23	$610.49	$2363.85	$1197.15
TOTAL LIFECYCLE COSTS	$566.24	$1440.79	$3616.65	$2409.35

As noted above, these estimates are based on even cruder and less complete data than those for the other three candidate systems, and could easily be wrong by a large margin. As with the other systems, the authors have tended to err on the side of optimism, although Daimler-Benz's own expressed optimism concerning this system makes this seem reasonable. These facts should be kept in mind, however, and the estimates shown should be treated with considerable caution.

Safety and environmental effects: Any trap-oxidizer system will pose a slightly increased chance of fire. For this system, however, that increase would be small enough to be negligible. There might also be some safety problems associated with keeping a reservoir of additive powder in the vehicle, but these would be small compared to the problems involved in keeping liquid organometallic additives on board.

In the area of environmental effects, the only significant concern at present is with the emission of the catalyst or its chemical derivatives. The amounts emitted would be fairly small. Only a few grams of additive are required for each regeneration, so a typical heavy-duty vehicle might use five to ten kilograms over its lifetime, and most of that would be retained in the trap. Thus the lifetime emissions of the additive and its derivatives would be of the order of two or three kilograms. Unless some very toxic or otherwise harmful product were found among the chemical derivatives, this emission level would probably be acceptable. The major concern expressed by Daimler-Benz, in this region, is for possible emissions of dangerous chlorinated hydrocarbons. So far, however, none have been detected at dangerous levels (DBAG, 1984).

Other considerations: From the available data, this type of system appears to be one of the most attractive, if not the most attractive, now being considered for heavy-duty vehicles. The fact that it has been developed and tested exclusively by Daimler-Benz -- a major foreign truck manufacturer which has been making a vigorous effort to penetrate the U.S. market -- could lead to a serious competitive disadvantage for American manufacturers. This would be especially serious if the particulate standard allowed too little lead-time for implementation, since Daimler-Benz's work on this system is well ahead of developments by any American manufacturers except possibly GM and Ford. Daimler-Benz has stated that it is confident that it could have such a system in production by 1990; no other manufacturer has as much as expressed confidence that a trap oxidizer system can be built at all.

Development status: As was stated above, Daimler-Benz has successfully tested a number of prototypes of this type of system in both city and highway driving for extended mileages. The system now appears to be undergoing minor modifications and changes based on the data developed in these tests. Daimler's development schedule (DBAG, 1982) shows vehicle application beginning in early 1984, with testing of prototype vehicles in 1985 and full production for the 1989 model year. This schedule has apparently slipped some, but a Daimler-Benz spokesman (DBAG, 1984) has indicated that the company is still confident of production status by 1990.

Overall assessment: Some caution in judging the ultimate potential for this type of system is necessary, due to the fact that only one manufacturer appears to be developing it, and thus all of the available data are from one source. Potential problems could have been glossed over or neglected, and it might not be equally applicable to other manufacturer's designs. From the available data, however, this appears to be among the best designs for heavy-duty trap-oxidizer systems, except perhaps in very high-mileage applications. If the problem with trap plugging at high mileage can be solved, this would be an extremely attractive design in those applications as well. Furthermore, this is among the most developed types of systems, and the remaining development tasks appear to be straightforward. Thus it would appear that this type of system will be a very strong contender in the market.

6.0 EFFECTS OF FUELS ON DIESEL EMISSIONS

The nature and quality of the fuel being burned is known to affect the emissions from virtually every class of engine, including both direct injection and indirect-injection diesels. These effects can be either positive (reduced emissions) or negative, depending on the fuel and the engine. The recent disruptions in the supply of oil, coupled with the rapid increase in its cost, have led both to changes in the quality of petroleum-derived diesel fuels and to considerable interest in the development of alternative, non-petroleum based fuels. This has generated concern for the possible effects of changes in diesel fuel composition and/or quality on emissions. This chapter briefly addresses some of these concerns, and examines some of the problems and opportunities for regulatory action in this area.

As is true of most topics related to diesel combustion, the area of fuel effects on emissions is highly complex, with much experimental data and little clear theoretical understanding. Furthermore, the experimental data themselves are difficult to interpret, and transient-test data are very scarce. It should be understood that this chapter represents only a first look at a very complex subject. Firm policy recommendations in this area would need to be based on a comprehensive study of diesel combustion, diesel fuel demand, competition from other products such as jet fuel, and the economics and technology of the petroleum refining industry. All but the first of these topics are well beyond the scope of this study.

6.1 DIESEL FUEL PROPERTIES

Automotive diesel fuel is a complex blend of hydrocarbons, with boiling points falling generally in a range between those of gasoline (a mix of light hydrocarbons) and heavy residual fuel oil. It is thus a "middle distillate" fuel. Other middle distillate fuels include jet fuel, kerosene, and the lighter grades of fuel oils. The diesel fuel sold in the United States is of two types: diesel #1, which contains lower molecular weight (lighter) hydrocarbons, which boil in the range from 180 to 250 C; and diesel #2, which contains higher molecular weight (heavier) hydrocarbons, which boil in the range from 200 to

350 C. Diesel #1 is also sometimes known as city-bus (C-B) fuel, since it is used primarily by bus fleets, which pay a premium for it because it produces lower smoke emissions. Diesel #2 (also known as truck-tractor or T-T fuel) is used for almost all other purposes, and makes up the vast preponderance of the diesel fuel sold.

Diesel fuel is made up of three primary types of hydrocarbons: paraffins (straight-chain hydrocarbons), cycloparaffins, and aromatics. The three groups are distinguished by their differing molecular structures, which in turn lead to different physical and chemical properties, some of which affect the combustion process. Aromatic hydrocarbons are distinguished from the other two classes by the presence of one or more "benzene-ring" structures, composed of six carbon atoms strongly bonded into a hexagon (they are distinguished from the cycloparaffins, which also have a ring structure, by the weaker bonding in the cycloparaffin ring). Figure 6.1 shows some typical examples of each group. In addition to the hydrocarbons, diesel fuel also contains a small amount of organically-bound sulfur (0.1 to 0.5 percent by mass), and other elements such as vanadium, cobalt, lead, aluminum and barium, may also be present in trace amounts.

In addition to their differing structures, the hydrocarbons in diesel fuel differ in their volatilities (boiling points), which are closely related to their molecular weights. Lower molecular weight hydrocarbons boil at a lower temperature, so that the boiling point of a fuel sample will increase with prolonged heating as the lighter of its constituent hydrocarbons boil off first. This provides a convenient way of characterizing the mix of molecular weights in a fuel: one specifies the initial boiling point, the "10 percent point" (the temperature at which 10 percent of the mass has boiled away, the 20 percent point, and so forth up to the 90 percent point and the end-point, which is the temperature at which all of the fuel has evaporated). In general, excessively low "front-end" (initial boiling point or 10 percent point) and excessively high "back-end" (90% point or end-point) temperatures are regarded as undesirable; the former because they can lead to vapor-lock in the fuel system, and the latter because they indicate the pressure of high-molecular-weight hydrocarbons, which can cause fuel-system plugging and flow problems in cold weather.

The quality of diesel fuel is most often measured in terms of its cetane number (or its calculated cetane index, which is an approximation of the cetane number). The cetane number measures the ease or difficulty of igniting the fuel after it is injected into the combustion chamber. High cetane-number fuels ignite readily; low-cetane fuels take

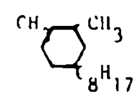
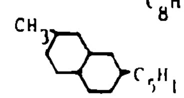
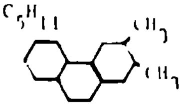
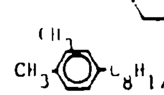
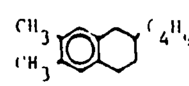
Group Type	General Formula	C_{16} Example	Structure
Paraffins	C_NH_{2N+2}	$C_{16}H_{34}$	$CH_3-(CH_2)_{14}-CH_3$
Monocycloparaffins	C_NH_{2N}	$C_{16}H_{32}$	
Dicycloparaffins	C_NH_{2N-2}	$C_{16}H_{30}$	
Tricycloparaffins	C_NH_{2N-4}	$C_{16}H_{28}$	
Benzenes	C_NH_{2N-6}	$C_{16}H_{26}$	
Tetralins	C_NH_{2N-8}	$C_{16}H_{24}$	
Naphthalenes	C_NH_{2N-12}	$C_{16}H_{20}$	

Figure 6.1: Typical hydrocarbon molecules in diesel fuel. (Source: Hilden, et alia, 1982)

longer to ignite. Rapid ignition reduces the time available for the fuel to mix with air in the pre-combustion stage, which reduces the amount of energy released during premixed burning. This reduces noise and stress on the engine, and improves fuel economy (late ignition has the same effect as injection retard on fuel economy). A cetane number of 50 to 55 indicates a premium quality fuel, while one from about 45 to 50 is good quality. The ASTM standard for diesel fuel specifies a minimum cetane number of 40, but such a fuel is considered to be of marginal quality.

Cetane number is measured by testing the ignition qualities of the fuel in a special single-cylinder cetane engine. Although there is a growing consensus that the present cetane measurement does not adequately measure the ignition properties relevant to today's engines, there is as yet no widely accepted substitute measure. Most of the difficulty involves the use of special cetane-improving fuel additives, some of which appear to give good results in the cetane test but poor results in multicylinder engine.

Other common measures of diesel fuel quality are the mass fraction of aromatic compounds, the back-end volatility is seldom of concern, due to the competition by gasoline and jet fuels for the lighter hydrocarbons. The fraction of aromatic compounds is a concern, because these compounds are more difficult to ignite, which reduces the fuel's cetane number. A large aromatic content also tends to increase smoke and particulate emissions, an effect which will be discussed below. A high sulfur content (above about 0.5 percent by mass) is considered undesirable because of the deposition of sulfates as sulfuric acid in the exhaust, which leads to unacceptable rates of engine and exhaust-system corrosion. The SO_2 and sulfates produced from the sulfur are also significant pollutants, which makes it undesirable from an emissions standpoint as well. Recent data developed by Chevron Research (1984) also implicates fuel sulfur as a major factor in increasing particulate emissions, a point which is discussed at greater length below.

Figure 6.2 shows the trends in the nationwide averages of these quality indices for diesel #2 since 1960. As this figure indicates, the last two decades have seen a steady decline in the average cetane number of the fuel sold, and this decline has become especially marked since 1976. The average fraction of aromatics in the fuel and the 90 percent point have increased markedly as well. Of the four quality indices, only the average sulfur content has remained more or less the same. More recently, average sulfur content has begun to increase as well, and the amount of fuel with high sulfur content (above 0.5 percent sulfur) has increased sharply (Pless, 1984). This general decline in diesel fuel

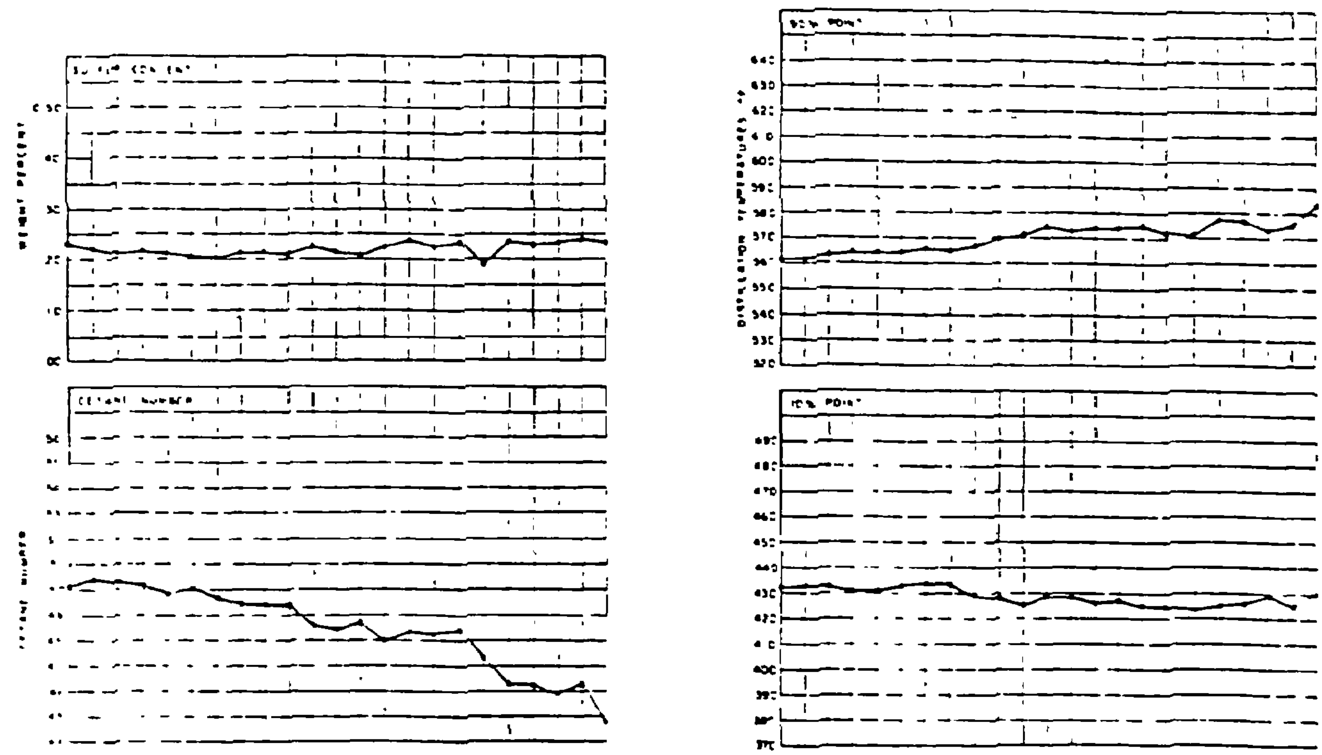


Figure 6.2: Trends in quality indices for diesel #2 (T-T) fuel since 1960. (Source: U.S. Department of Energy, 1982)

quality is due to the need to process heavier and lower-quality crude oils as more desirable oil resources are exhausted. These lower quality crudes contain more heavy hydrocarbons and more aromatics than the higher quality oils. Low-quality crudes are usually also richer in sulfur, but the sulfur content of the refined fuel has been kept in check somewhat by consumer resistance, due to the destructive effects of high sulfur fuel on engines. This has required an increasing amount of desulfurization treatment for diesel fuel and other middle distillates.

The generally heavier nature of present-day crudes, combined with increased competition by jet fuels and other middle distillates for the lighter fraction of the diesel #2 range has led to some advocacy (e.g. Barry et alia, 1979) of relaxing the present back-end volatility requirements on diesel fuel, to permit an increase in the 90 percent point, and thus in the total amount of heavy hydrocarbons permitted in the fuel. European diesel fuel is already formulated in this way. Barry estimates that such a change would permit an additional 4.5 percent of total crude oil to be converted into diesel fuel. This additional diesel fuel would be obtained at the expense of comparatively low-valued residual oil, which would help to reduce the price of diesel fuel slightly.

6.2 EFFECTS OF CHANGES IN DIESEL FUEL QUALITY ON EMISSIONS

As was mentioned above, data on the effects of fuel quality and composition on emissions are, in general, scarce, confusing, inconsistent, and difficult to interpret. Transient-test emissions and particulate data are especially scarce, due to the recency of the transition to transient testing and the difficulty and expense of setting up a transient test cell. These have resulted in transient test cells being reserved for certification and critical engine-development tests. Fuel effects, since they are not under the manufacturer's control, have received a lower priority. Thus, most of the data on fuel effects in heavy-duty engines have been compiled using the older 13-mode testing procedure, and generally do not include particulate measurements, although smoke and hydrocarbon measurements — from which a qualitative estimate of particulate effects can be made — are generally provided. In contrast to the heavy-duty situation, light-duty transient-test data on fuel effects are plentiful. However, it is not clear to what extent these data are applicable to heavy-duty engines.

The frequent inconsistency of the available emissions/fuel effects data, and the difficulty of interpreting them, derive from a number of sources. Perhaps the most important source is the complexity of diesel fuel itself, which is only incompletely characterized by the indices in use. There is also a serious problem with correlation between variables; aromatic content and cetane number are inversely related in most diesel fuels, for instance, which makes it very difficult to separate their effects. A third source of confusion is the fact that today's engines are very finely tuned to produce maximum fuel efficiency with minimum pollution. A change in fuels may cause the engine to operate "off-design", and thus increase pollutants quite apart from any inherent effects of the fuel. The nature and magnitude of this effect may be quite different between different engines, and different engines may be set to achieve optimal results for different values of the fuel quality indices. This effect probably accounts for much of the observed inconsistency in experimental results. This also points up the importance of obtaining test data in a wide range of engines before making policy decisions.

A final difficulty in interpretation is caused by the fact that fuel effects on emissions are generally rather small — at least for the range of fuels which could reasonably be considered for use in diesels — while the random variation and drift in the pollutant measurements are relatively large, so that the two effects are frequently of the same order. As a result, statistical techniques are required to extract any clear indication of trends, and few researchers have accumulated enough data for statistical techniques to provide much certainty. Three studies which have evaluated large amounts of data are those of Burley and Rosebrock (1979) with a light-duty indirect injection engine, and of Wade and Jones (1983), and Bykowsky and coworkers (1983), both of which who combined the published results from many papers in an effort to discern overall trends. More recent work by Chevron Research (1984), and ongoing studies by Cummins, Caterpillar, and other manufacturers should greatly expand our understanding of fuel effects on heavy-duty engines.

<u>Cetane number and aromatic content:</u> The effects of these two variables are discussed together, since a fuel's cetane number is closely associated with its aromatic content. Figure 6.3 shows this correlation.

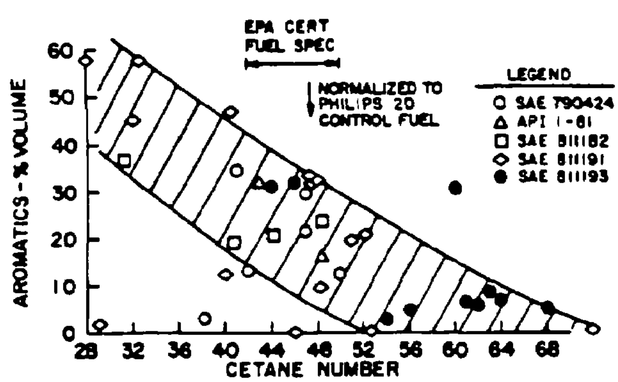


Figure 6.3: Correlation between cetane number and aromatic content for diesel #2 fuel. (Source: Wade and Jones, 1983)

A low cetane number means that the fuel takes longer to ignite after it is injected into the combustion chamber, thus there is more time available for it to mix with the air. This means that more energy is released in the rapid premixed burning phase of combustion, with a consequent increase in noise and stress on the engine. Premixed burning also tends to increase NO_x emissions, due to the high temperatures reached. Partially offsetting this, is the effect of the ignition delay itself, which is similar to the effect of retarding the injection timing. The increased ignition delay also has many of the ill effects of injection retard — reduced power, increased fuel consumption, and increased HC and particulate emissions.

Figures 6.4 through 6.6 show the effects of fuel aromatic content in NO_x, HC, and particulate emissions for light-duty (indirect injection) engines. In order to eliminate the effects of engine-to-engine variations, the values plotted in this figure have been normalized by the values for the same engines operating on a special, highly consistent, diesel fuel — Philips diesel #2 control fuel. These figures show a considerable variability, but there is a general trend toward increasing particulate emissions with increasing aromatic content, and a slight upward trend in NO_x emissions as well. Qualitatively similar effects to those shown could be expected in the indirect-injection engines used in light-heavy trucks. However, recent work at General Motors (Bergin, 1983) has shown that the effects of fuels on emissions depend heavily on the engine load, so any quantitative extrapolation from the lightly-loaded light-duty test cycle to the very heavily loaded heavy-duty cycle is dangerous.

Figure 6.7 shows the effects of cetane number on NO_x, HC, and smoke emissions for a number of heavy-duty diesel engines, obtained using the old EPA 13-mode test for NO_x and HC, and the EPA 3 mode test for smoke. Again, the results have been normalized to those obtained using Phillips control fuel. As the figure indicates, both hydrocarbons and smoke increase sharply as cetane number goes below about 44, indicating a probably similar trend for particulates. The few heavy-duty transient cycle particulate data available (Bunting, 1979; Dietzmann et alia, 1981) show a similar trend to increasing particulate emissions as cetane decreases. (N.B. — the plots in Figures 6.4 through 6.7 have not been corrected for differences in other, possibly confounding variables. They should thus be treated with caution, especially where unusual fuels are concerned).

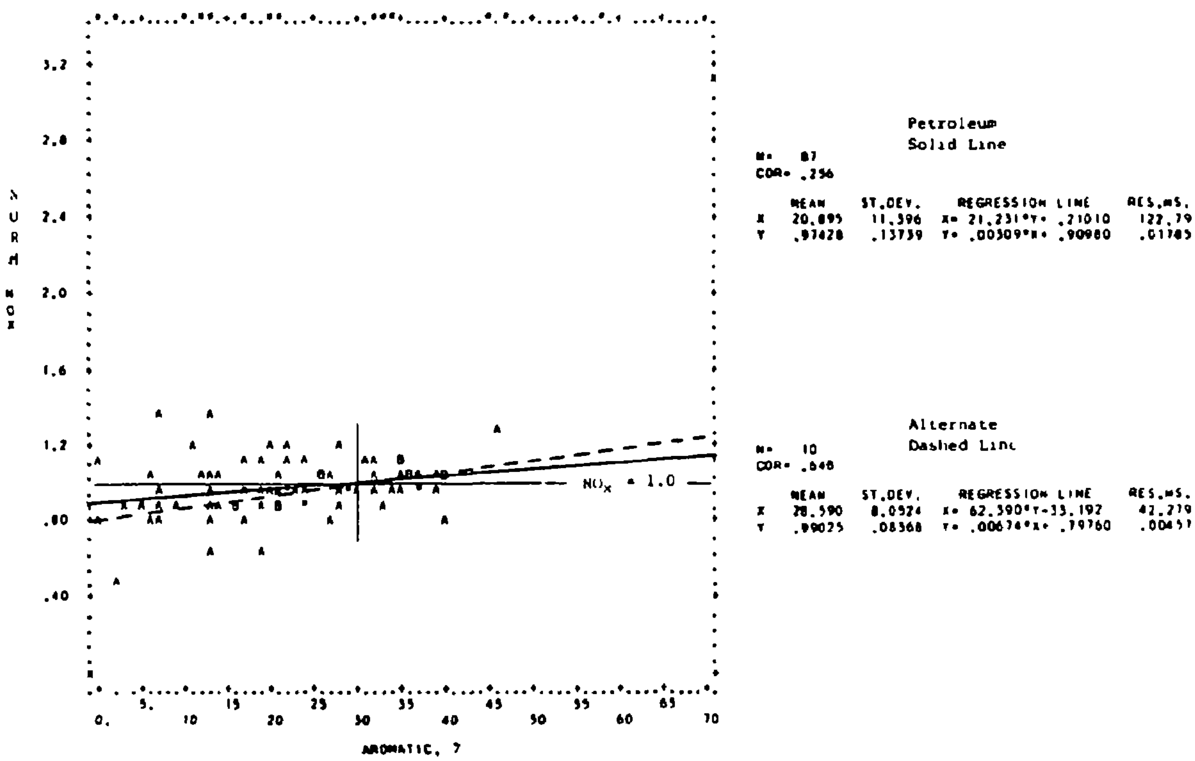
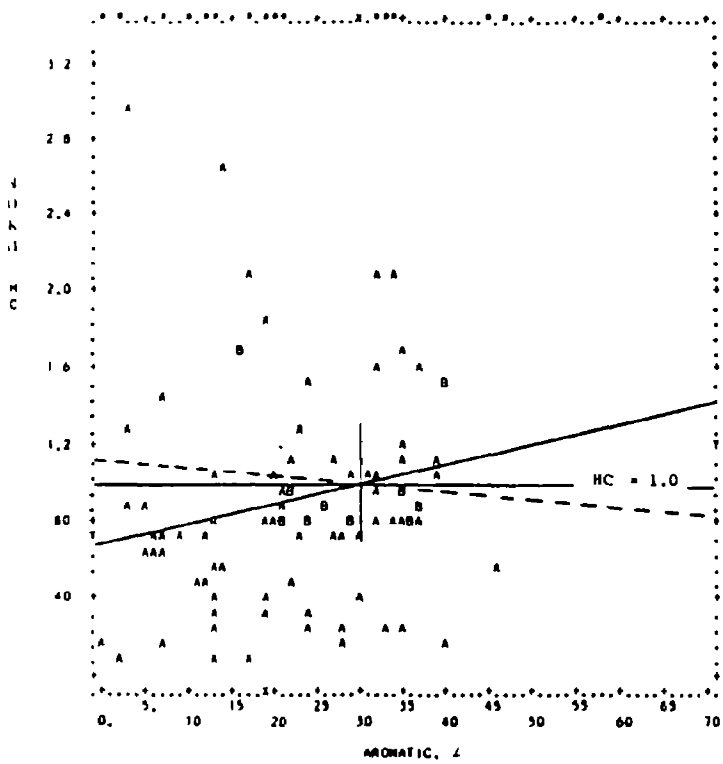


Figure 6.4: Effect of fuel aromatic content on NO_x emissions by light-duty IDI diesels. (Source: Bykowski, et alia, 1983)



Petroleum
Solid Line

N= 83
COR= .141

	MEAN	ST.DEV.	REGRESSION LINE	RES.MS.
X	21.430	11.289	X= 2.7817*Y+ 18.968	126.46
Y	.88527	.57197	Y= .00714*X+ .73224	.32461

Alternate
Dashed Line

N= 10
COR=-.086

	MEAN	ST.DEV.	REGRESSION LINE	RES.MS.
X	28.590	8.0324	X=-2.1452*Y+ 30.746	72.401
Y	1.0050	.52442	Y=-.00548*X+ 1.1046	.11752

Figure 6.6: Effect of fuel aromatic content on hydrocarbon emissions by light-duty IDI diesels. (Source: Bykowski et alia, 1983)

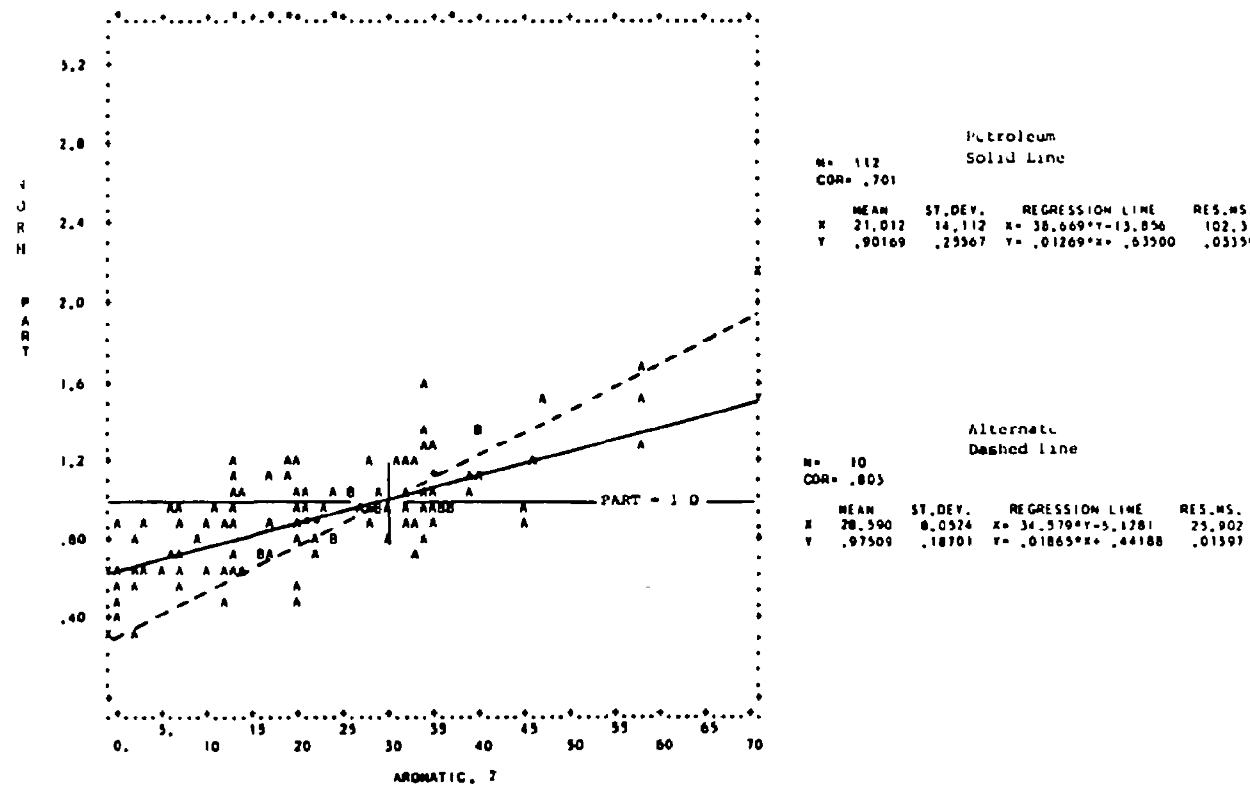
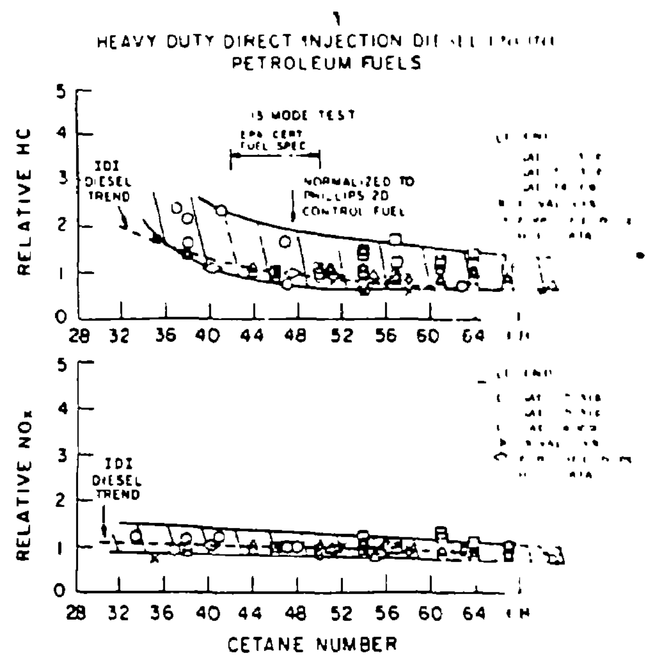


Figure 6.5: Effect of fuel aromatic content on particulate emissions by light-duty IDI diesels. (Source: Bykowski et alia, 1983)



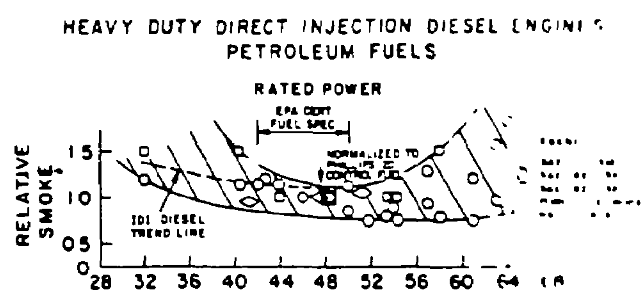


Figure 6.7: Effects of fuel cetane number on hydrocarbon, NO_x and smoke emissions from heavy-duty DI diesel engine, measured on the EPA 13-mode test (Source: Wade and Jones, 1983).

In addition to their effects on ignition, aromatic hydrocarbons seem to play a direct role in the formation of soot. At high temperatures, the ring structure breaks down to form acetylene (Kerns, 1983), which seems to be an important preliminary step in the formation of soot (Weaver, 1983b). It also appears likely that the aromatic structures themselves play an important role in providing nuclei for the soot formation process. Thus the effects of cetane number on particulates may in fact be due more to the inverse relationship between aromatics and cetane number than to ignition effects as such. Burley and Rosebrock (1979) and Bykowski et alia (1983) both found that aromatic carbon content was a better predictor of particulate emissions than was cetane number at least in light-duty prechamber engines. In particular, Burley and Rosebrock found that the achievement of high cetane numbers by means of cetane-improving additives increased particulate emissions, which is the reverse of what would be expected if cetane number alone were the more important property. At cetane numbers below the ASTM standard, however, ignition effects appear to be more important. Wade and coworkers (1984) found that the use of cetane improvers to bring a 32.5 cetane fuel up to 47.5 reduced particulate emissions substantially, although emissions were still not as low as a 47.5 cetane fuel without improvers.

Volatility: Both the "front-end" and the "back-end" volatilities (initial and final boiling points) of diesel fuel affect emissions. If the initial boiling point is too low (i.e., the fuel contains too many light hydrocarbons) then HC emissions tend to increase. On the other hand, high 90 percent and end-points are correlated with increases in smoke opacity, and particulate emissions. Figure 6.8 shows the trends in particulate emissions with changes in back end volatility, from Bykowski's study of light-duty engines. While in each case there is a great deal of scatter in the data, the trend does appear to be slightly upward for petroleum-based fuels. NO_x does not appear to be strongly affected by back-end volatility.

Data on the effects of back-end volatility on DI particulate emissions are very scarce. Some indications of trends can be gotten from studies of the effects on smoke opacity, however. Figures 6.9a and 6.9b show plots of the trends in smoke emissions with increasing back-end volatility (a) and total volatility (b). Again, the trend appears to be upward with decreasing volatility, although the slope of the trend line is heavily dependent on the specific engine. Heavy-duty engine data obtaned by Chevron Research (1984) also show a small positive correlation between particulates and back-end volatility.

A possible explanation for both the general increase in particulate emissions with increasing back-end boiling point and the wide variations in the magnitude of this effect can be found by hypothesizing that the effect is due to the changed density and viscosity of the fuel, rather than

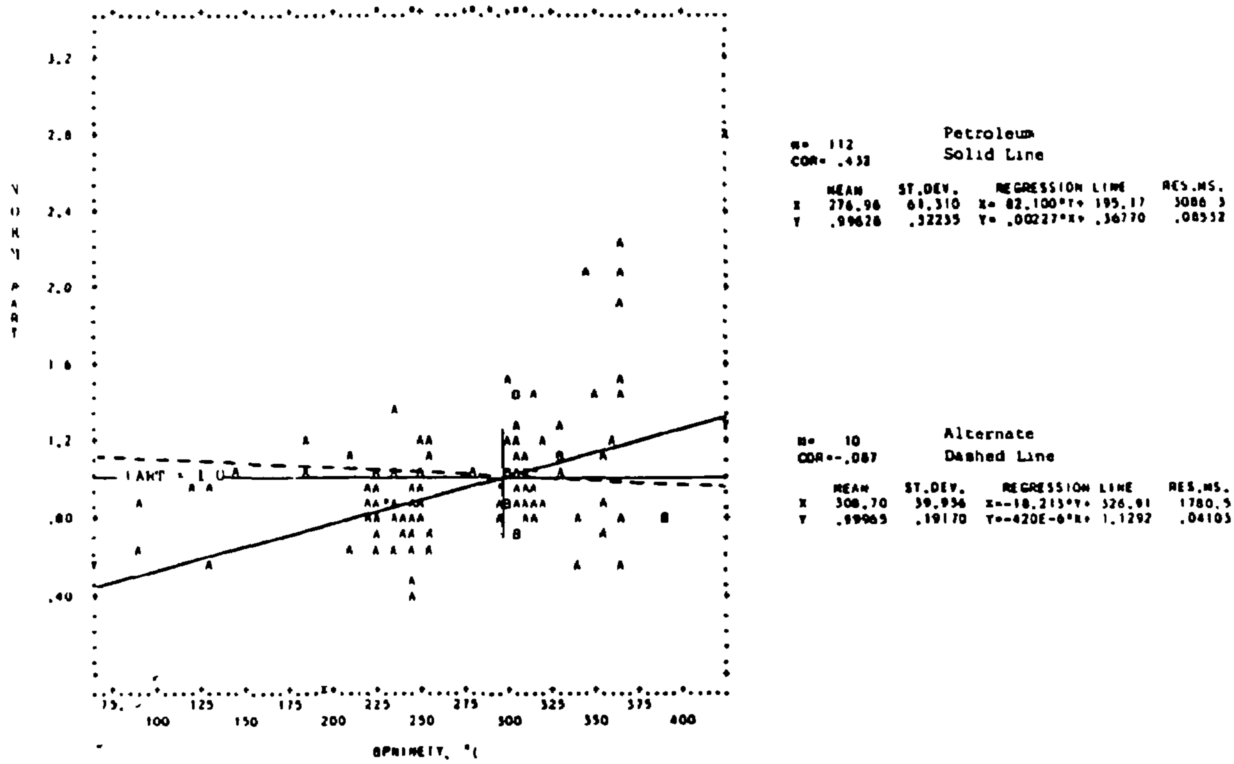
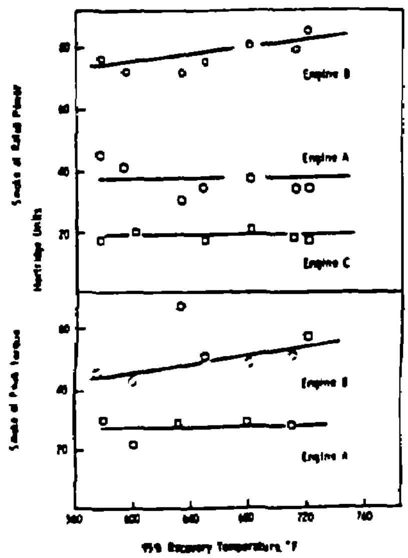
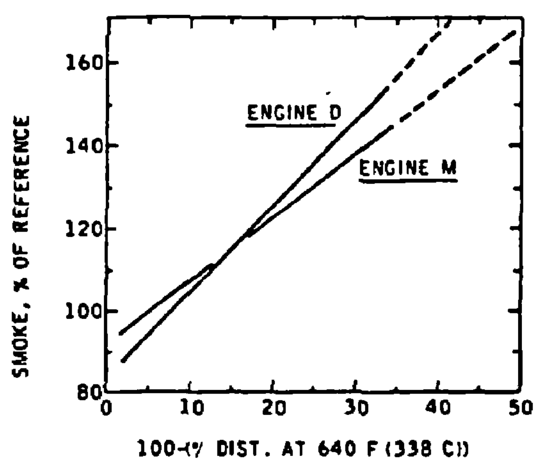


Figure 6.8: Effect of changing 90% boiling point on particulate emissions from light-duty IDI diesels (Source: Bykowski et alia, 1983).



(a) Smoke opacity vs. 95% distillation temperature (Source: Bykowski et alia, 1979)



(b) Relative smoke vs. fraction distilling above 140° F. (Source: Gross and Murphy, 1978)

Figure 6.9: Effect of changing volatility on smoke emissions from heavy-duty diesels.

to any special combustion characteristics of the hydrocarbons involved. Diesel injection pumps meter fuel by volume, not by mass. thus an increase in density will result in more fuel entering the cylinder, a higher equivalence ratio (ratio of fuel to oxygen), higher temperatures, and greater power. The higher equivalence ratio increases soot production. The increased viscosity of the fuel, which reduces the efficiency of atomization and fuel-air mixing, would also contribute to soot formation to some degree. Finally, a small increase in the soluble fraction of the particulate might be expected, since the hydrocarbons in a high-boiling point fuel would condense more easily, even though the hydrocarbon emissions as a whole might be decreased. Figure 6.10, which shows that particulate emissions seem to be a strong function of density, lends credence to this hypothesis.

Again, great caution should be used in extrapolating the emissions effects shown in Figures 6.8 and 6.10 from light-duty to heavy-duty engines, even to heavy-duty prechamber engines. Work by Bergin (1983) indicates that even the <u>sign</u> of the change in particulate emission due to a change in 90 percent point may be different at high load conditions — at very high loads, he found that increasing the 90 percent point decreased particulate emissions. This may be the reason for the comparatively slight effect of the 95 percent point on smoke in direct injection engines, as indicated on Figure 6.9.

<u>Sulfur Content:</u> The sulfur content of diesel fuel has, of course, a direct and linear effect on an engine's emissions of sulfur dioxide (SO_2) and sulfates, but until recently, was thought to have little direct effect on other pollutants.

However, recent work by Chevron Research (1984) indicates that fuel sulfur content has a much greater effect on particulate emissions than was previously thought. The primary effect of sulfur on particulate emissions is through the formation of sulfates. During combustion, most of the sulfur in the fuel is oxidized to SO_2, and emitted as SO_2 gas. A small fraction, however, is further oxidized to SO_3, and is collected as particulate matter during the emissions test. This material proceeds to react with water in the exhaust and in the atmosphere to form sulfuric acid, H_2SO_4. Presently, sulfates make up about 10 to 20 percent of total particulate emissions measured on the transient test. However, since sulfate emissions are not affected by the combustion modifications that reduce the hydrocarbon and soot fractions of the particulate, they will make up a larger and larger fraction of the total as these other sources are reduced.

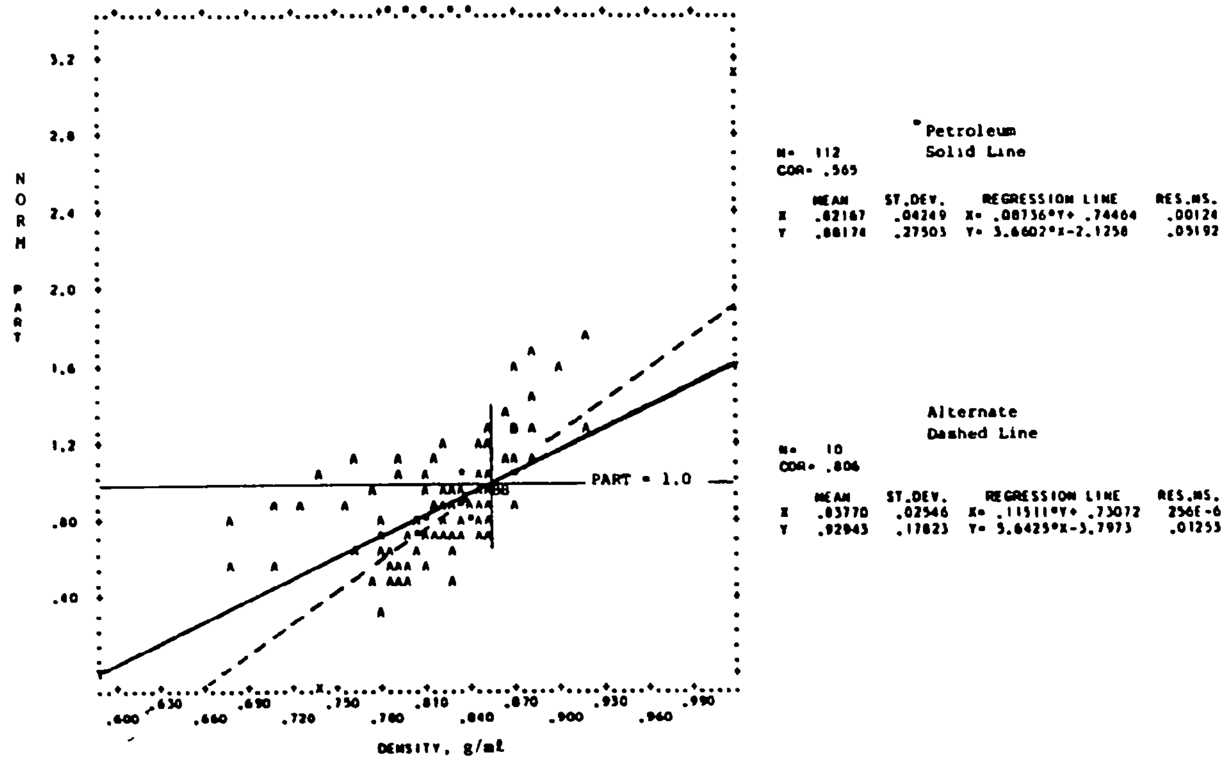


Figure 6.10: Effect of changes in fuel density on particulate emissions in IDI diesels. (Source: Bykowski, et alia, 1983)

In addition to its direct effect in increasing the sulfate component of the particulate matter, Chevron found that high sulfur content also appears to increase the soluble organic fraction of the particulate matter. No explanation for this effect has yet been advanced. Overall, Chevron's data give the following correlation equation for particulate emissions as a function of fuel sulfur content, aromatic content, and 90 percent boiling point in steady-state tests on a Cummins NTC 290 engine.

$$P = 0.00135\ A + 0.000232\ T + 0.387\ S + 0.0225 \qquad (6.1)$$

where
- P is particulate emissions in grams per BHP-hr
- A is the aromatic content in weight percent
- T is the 90% boiling point in ^{o}F
- S is the sulfur content in weight percent

This equation predicts that reducing the sulfur content of diesel fuel from 0.49 percent by weight (the present ASTM standard for diesel #2 is 0.5 percent) to 0.05 percent should reduce particulate emissions by .17 g/BHP-hr, or 42 percent. Figure 6.11 shows a number of particulate measurements obtained by Chevron with different fuels, plotted against the particulate emissions level predicted by Equation 6.1. As can be seen, the equation does a good job of predicting emissions over a fairly large range.

In transient testing, overall particulate emissions are higher, and thus the use of low-sulfur fuel would have a smaller percentage effect, even though the absolute reduction in emissions would be expected to be about the same. The directional effects of low-sulfur fuel on emissions have been confirmed by transient tests conducted at Southwest Research Institute (Chevron, 1984), and by Cummins Engine (L. Broering, personal communication, 1984). The Cummins tests measured a reduction from 0.79 g/BHP-hr with .54 percent sulfur in the fuel to 0.55 g/BHP-hr at 0.03 percent sulfur, a reduction of 0.24 g/BHP-hr. This compares rather well with the .20 g/BHP-hr reduction predicted by Equation 6.1.

The Chevron data also cast considerable doubt on the conclusions of previous research into fuel effects on emissions. Most such research had identified aromatic content and back-end volatility as the properties most affecting emissions, and related them to emissions changes means of linear regressions. Because of the strong correlation between sulfur content and aromatics, and between sulfur and back-end volatility in diesel fuels, it appears that much of the effect of the sulfur was erroneously ascribed to aromatics and/or volatility in the earlier studies.

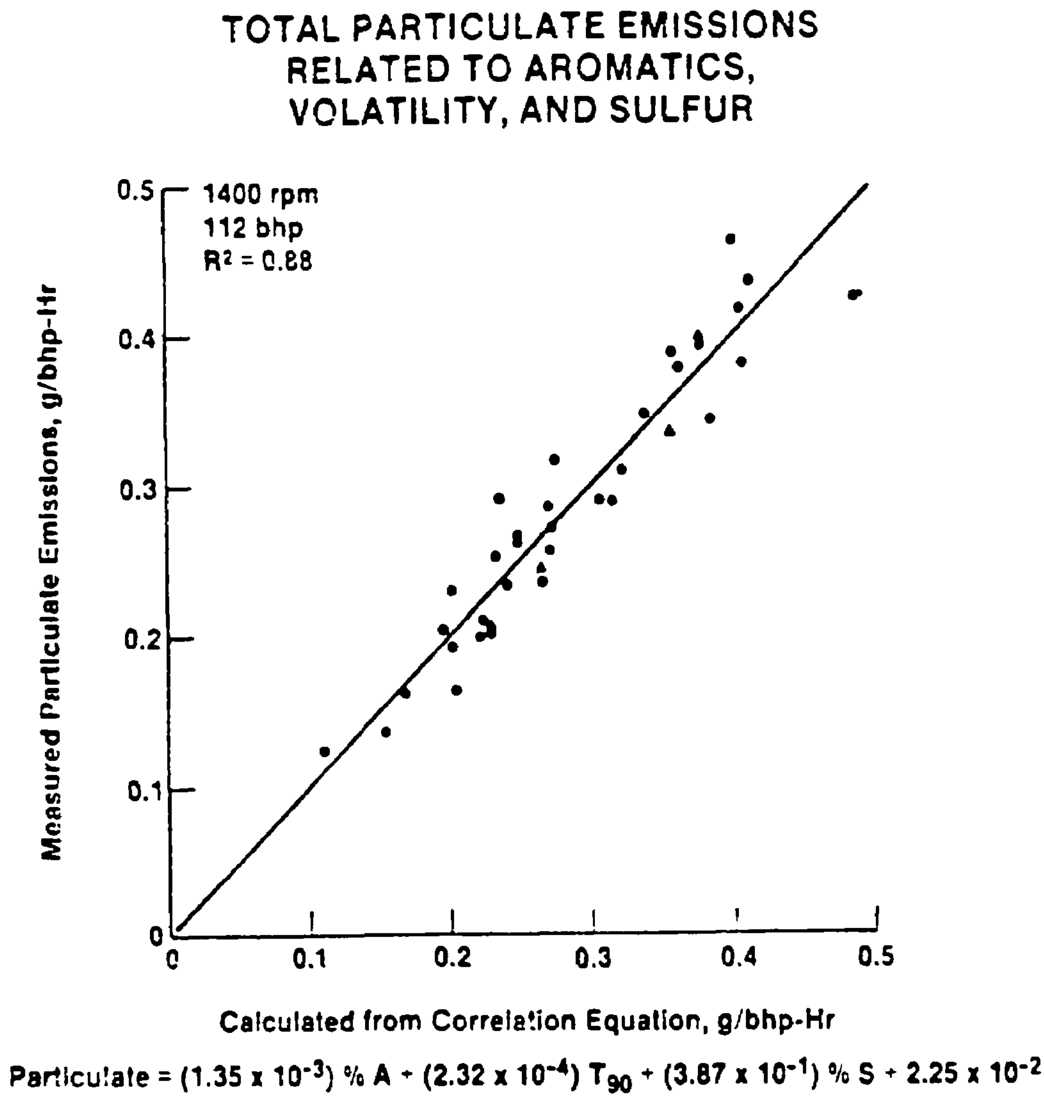


Figure 6.11: Actual particulate emissions vs. emissions predicted from fuel composition using equation 6.1 (Source: Chevron, 1984).

Beyond its effect on direct emissions of particulates, fuel sulfur has an important indirect effect on ambient particulate levels. This is because a portion of the SO_2 emitted is converted to sulfate particles by reactions in the atmosphere. Recent estimates by the California Air Resources Board (1984) indicate that, in urban areas, the secondary sulfate and nitrate particles found due to diesel emissions can be much greater in mass than the diesel's direct emissions of particulate matter.

6.3 POTENTIAL REGULATORY ACTIONS TO IMPROVE FUEL QUALITY

This section briefly outlines some apparently feasible regulatory actions which might be taken in regard to diesel fuel, either to prevent further deterioration in diesel-fuel quality or actually to improve it. Three possible approaches are discussed: regulatory limits on cetane numbers and/or aromatic content, possible changes in the permissible "high-end" boiling point for diesel fuel, and stringent limits on its sulfur content. These approaches are not mutually exclusive -- in fact, the synergetic effects between them make it appear that the optimal strategy might be a combination of all three. These points are discussed in detail below.

Limitations on cetane number and/or aromatic content: Given the strong effects of decreasing cetane and/or increasing aromatic content on emissions, and the trend toward decreasing average cetane numbers in fuel, there is a strong case to be made for a standard specifying the minimum permissible cetane number or the maximum permissible aromatic content for highway diesel fuel. The two are closely related, and for particulate emissions it appears that the aromatic content and not the cetane number may be determining. In the absence of cetane-improving additives, a cetane-number standard would also serve to limit aromatic content. However, such additives do exist, and seem likely to see increasing use as crude oil quality declines. The most likely response by refiners to a minimum-cetane-number standard would be to use such additives to meet it. The additives do not seem to improve the particulate-emission performance of the fuel as much as would be expected from their effects on cetane. Thus, to control particulate emissions, a standard setting a maximum permissible aromatic content would be desirable, in addition to or in place of a minimum cetane standard.

Based on the emissions effects discussed in Section 6.2, a minimum cetane number of about 42, combined with a maximum aromatic content of around 35 percent, seems like a reasonable standard. This would place a floor on diesel fuel quality somewhat below the present average quality, but above the present minimum. This would require quality improvements by some refiners -- about 30 percent of diesel fuels sampled by the MVMA fell below these limits in 1983 (Pless, 1984). This, in turn, would necessarily reduce the supply and increase the price of diesel fuel. A precise estimate of the degree of price increase is beyond the scope of this study, but an approximate indication of its magnitude is given by a CARB study (CARB, 1984), which reported refiners' estimates of the cost of meeting a 25 percent aromatics standard. The estimates ranged from zero to $4.09 per barrel, and averaged $1.74 or about 4 cents per gallon. A reduction to 35 percent aromatics would have a smaller effect -- probably only one or two cents per gallon.

Such a standard might lead to improvements in emissions and fuel economy beyond those which would be expected from the change in properties alone. This would result from the fact that, with a firm statutory minimum on fuel quality, engine manufacturers could adjust the engine parameters for optimal performance on that fuel. As things now stand, an engine must be able to operate reasonably satisfactorily on very low-quality fuel, since such fuel is likely to be encountered sometime during the engine's life. The fuel economy benefits from this readjustment could be expected to partially offset the increased price of the fuel and there would probably be some savings in maintenance, repairs and reduced engine wear. Thus the net cost to the truck owner would not be great, and might even be negative.

Changes in permissible "back-end" boiling points: The relationship between the "back-end" boiling point and emissions is sufficiently weak that it would be very difficult to justify any mandatory decrease. Indeed, under some circumstances, it might be justifiable to increase slightly the maximum now set by the standard for ASTM diesel #2. Such an increase would significantly increase the available stock of diesel fuel, and could be expected to result in a decrease in its price. Such an approach would be especially attractive in combination with a stricter limit on cetane and aromatic content, since the additional fuel made available by increasing the end-point would offset the decrease in usable fuel occasioned by the more stringent quality regulations. Most or all of the effect of high-boiling-point fuels on emissions appears to be due to their greater density. Since reducing the aromatics content also reduces density, a small increase in boiling point would only return the fuel to where it had been, and would thus have a minimal effect on emissions. Such a change would also act as a sugar coating on the pill, making the quality regulations more acceptable to refiners.

Desulfurization: Reducing the sulfur content of diesel fuel is desirable for a number of reasons. Such an action would reduce total SO_2 emissions, and would thus reduce acid deposition and the acidification of the environment, as well as secondary particulate formation. In addition, it would reduce human exposure to SO_2 and sulfates. Since diesel exhaust is emitted close to ground level, and frequently in areas of concentrated population, the reduction in human exposure would be much greater than for the removal of an equivalent amount of sulfur from a utility stack or a copper smelter. In addition, lowering the sulfur content of the exhaust would make catalytic traps both more attractive and (since the activity of the catalyst could then be increased) more effective. In addition to reducing particulate emissions, this would also drastically reduce emissions of hydrocarbons and odor from the diesels, and would have a significant effect in reducing CO as well. Considered alone, any one of these effects might not justify the cost of desulfurization, but, in combination, the benefits of all together appear to outweigh the costs (CARB, 1984).

High-sulfur stocks of diesel fuel already undergo desulfurization, in order to comply with market requirements for a noncorrosive exhaust. As Figure 6.2 indicates, the average sulfur content of diesel fuel changed very little between 1960 and 1982; despite a major shift to high-sulfur crude oil. More recently, however, both the average sulfur level and the incidence of high-sulfur fuels seem to be increasing. Desulfurization is accomplished by treating the fuel with hydrogen in the presence of a catalyst, so that the sulfur is removed as hydrogen sulfide. A more severe version of the same process also decreases the aromatic content and increases the cetane number of the fuel, since the hydrogen can also combine with the unsaturated aromatic structures to convert them to saturated cycloparaffins. A regulatory limit on sulfur would be met by increasing the fraction of diesel fuel which is treated in this manner, and by increasing the severity of the treatment. According to the CARB (1984), the cost of desulfurization would be about two or three cents per gallon, which would correspond to a cost of about $2,000 to $3,000 per ton of SO_2 removed. This is about two to four times the cost of SO_2 removal from power-plant exhaust: a cost which society has demonstrated it is willing to pay. Given the numerous other benefits of desulfurization, this approach deserves very careful evaluation.

A major synergetic benefit is also possible with widespread desulfurization in combination with improvements in aromatics and cetane. Since aromatic saturation is only a more severe version of the processs that removes sulfur from diesel fuel, that the incremental cost of de-aromatization would be smaller. The reverse is also true; if a maximum aromatic content standard were in effect, the additional cost of desulfurization would be lessened. However, de-aromatization requires higher pressures than desulfurization, and thus cannot easily be retrofitted to a desulfurization unit (desulfurization, on the other hand, is inherent in the de-aromatization process). Thus it would be advantageous to consider implementing both such standards simultaneously, in order to reduce the necessary capital expenditures for compliance.

7.0 EMISSIONS STANDARDS FOR HEAVY-DUTY DIESEL ENGINES

This Chapter addresses a number of questions relating to the establishment of specific numerical standards for heavy-duty diesel NO_x and particulate emissions. In doing so, it draws heavily on the discussion in the preceding five sections, especially Chapters 4 on engine-out emissions control technologies and five on trap-oxidizers. This Chapter begins with a discussion of the regulatory history for heavy-duty diesel engines, including both those standards now in force and recent studies and proposals. This discussion is given in Section 7.1. Section 7.2 then moves on to discuss two closely related issues — subdivision of the heavy-duty class into multiple subclasses, and the effects of a standard based on emissions averaging on the cost and feasibility of compliance. From there, Section 7.3 proceeds to address the central issues in this study — the feasible levels of NO_x and particulate standards for both the near term (1987-1988) and the intermediate term (1990-1991). Section 7.4, finally, summarizes ERC's recommendations with regard to emissions standards.

<u>Caveat</u> — It has been necessary to omit discussion of a number of issues which are closely related to heavy-duty standard setting from this report. These issues include EPA's proposals with respect to the assessment of useful life for heavy-duty vehicles, multiplicative rather than additive deterioration factors, in-use durability testing, and the requirement to show reasonable likelihood of scheduled maintenance. Each of these issues is important in its own right, and each deserves careful evaluation before being included in a final regulation. All, however, are beyond the scope of the present study.

7.1 PREVIOUSLY PROPOSED STANDARDS

Table 7.1 shows Federal and State of California emissions standards for heavy-duty diesel engine hydrocarbon + NO_x, NO_x alone, smoke, and particulate emissions through model year 1986, as well as EPA's current proposed regulations for 1987 and later years. The situation in the 1983-1985 period is actually much more complex than that shown in the table — the establishment and subsequent delays in implementation of transient-cycle

Table 7.1

Historical and Proposed Federal and California Emission Standards For Heavy-Duty Diesel Engines

Year	California		Federal			
	$HC + NO_x$	NO_x	$HC + NO_x$	NO_x	Smoke Opacity (%) Accel/Lug/Peak	Particulates
1973	16	—	—	—	40/20/—	**
1974	16	—	16	—	20/15/50	**
1975	10	—	16	—	20/15/50	**
1976	10	—	16	—	20/15/50	**
1977	—	7.5	16	—	20/15/50	**
1978	—	7.5	16	—	20/15/50	**
1979	—	7.5	10	—	20/15/50	**
1980	6	—	10	—	20/15/50	**
1981	6	—	10	—	20/15/50	**
1982	6	—	10	—	20/15/50	**
1983	6	—	10	—	20/15/50	**
1984	4.5++	5.1++	10++	10.7++	10/15/50	**
1985	4.5++	5.1++	—	10.7+	20/15/50	**
1986	4.5++	5.1++	—	10.7+	20/15/50	**
1987	4.5++	5.1++	—	6.0*	20/15/50	0.6+*
1988	4.5++	5.1++	—	6.0*	20/15/50	0.6+*
1989	4.5++	5.1++	—	6.0*	20/15/50	0.6+*
1990 and on	4.5++	5.1++	—	4.0*	20/15/50	0.25+++*

All values are g/BHP-hr, measured on the steady-state (13 mode) test, except as noted.

*	EPA Proposed standard.
**	Not regulated, but controlled to some degree by smoke standards.
—	Not regulated.
+	EPA transient test
++	Manufacturers option: $HC + NO_x$ in steady state or NOx alone in transient test.
+++	Transient test, special standards proposed for line-haul and transit buses.

emissions testing and numerous other regulatory changes have resulted in a complex patchwork of rules, regulations, extensions and exceptions during that period.

The stringent heavy-duty NO_x and particulate regulations which are now proposed for 1987 and later years have a lengthy regulatory history. EPA first issued a notice of proposed rulemaking (NPRM) for tightened NO_x standards, and an advanced notice of proposed rulemaking (ANPRM) for heavy-duty particulate standards in 1979 (EPA, 1979b; 1979c). The standard levels proposed then were 4.0 g/BHP-hr for NO_x and 0.25 g/BHP-hr for particulates. These were to apply to the 1986 and subsequent model years. The 0.25 g/BHP-hr particulate level was to be attained through the use of trap-oxidizers, which were expected to be available in 1986. In addition to these very ambitious numerical standards, the new proposals also included a change in the test cycle to be used in certification (from the 13-mode steady state test to the present transient test), and changes in the computation of useful life and deterioration factors. Hearings on these proposals were not held until July of 1982, by which point it had become clear that the numerical standards proposed for 1986 could not be achieved, and that more lenient standards and/or a longer lead time would need to be granted.

Rules requiring the transient test procedure were subsequently promulgated for 1984, then delayed (at the manufacturer's option) until 1985 due to the manufacturers' difficulties in implementing the test. No further regulatory action was taken on NO_x and particulate levels until October, 1984, when EPA proposed standards of 6.0 g/BHP-hr NO_x and 0.6 g/BHP-hr particulates for model year 1987, to be followed by 4.0 g/BHP-hr NO_x and 0.25 g/BHP-hr particulates for most heavy duty vehicles. The 1990 proposals also included two proposals for special treatment of sub-groups of heavy-duty vehicles: a more lenient particulate standard of 0.4 g/BHP-hr for line-haul trucks, and a more stringent standard of 0.1 g/BHP-hr for transit buses. In outline, at least, these proposals closely resemble the recommendations of this report.

In connection with the proposed new standards, EPA has begun rulemaking proceedings to establish non-conformance penalties for manufacturers whose engines are found to be in violation. Previously, the penalty for non-conformance was denial of the right to sell the offending engines, or wholesale recalls for repair of engines already sold. The desire to reduce the chance of such draconian penalties has led manufacturers to allow a substantial margin of safety between the emissions level specified in the standard and the engine's projected emissions. With the use of non-conformance penalties, the need for this margin of safety is reduced.

7.2 ISSUES RELATED TO STANDARDS: EMISSIONS AVERAGING AND SUBDIVISION OF THE HEAVY-DUTY CLASS

As the discussion in Chapter Two has indicated, heavy-duty diesel vehicles are by no means a homogenous group, and the engines that power them are only slightly more homogeneous. It makes sense to question, then, whether a single standard can or should be applied to these different groups. A closely related issue concerns emissions averaging: to what extent should manufacturers be permitted to trade-off emissions between different engine models and types? How should such a system work? What, precisely, should be averaged: grams per horsepower hour, lifetime emissions, or what? The answers to these questions could have major implications for completion and survival in an industry which has already been seriously damaged by recession.

7.2.1 Subdivision of the Heavy-Duty Class

Any system of subclassifying vehicles or engines for regulatory purposes should meet several basic criteria. First and most important, it should be logical — it should group vehicles and/or engines with similar characteristics together, and separate those which differ in important ways. Secondly, it should be clear — both manufacturers and regulators should be able to determine rapidly and unambiguously what class a specific vehicle or engine falls into. In addition, the regulations should provide little incentive or opportunity for a manufacturer to defeat the classification scheme. Finally, such a system should be simple — the smallest possible number of subclasses consistent with the previous requirements should be established, in order to minimize confusion, duplication of time and effort, and regulatory inflexibility.

In Chapter Two, the authors have proposed a classification scheme for heavy-duty engines and vehicles which they consider to form an appropriate basis for regulation. This scheme divides the heavy-duty class into four subclasses: light-heavy, medium-heavy, line-haul, and transit bus. The division was made on the basis of vehicle and engine technical characteristics and vehicle operating patterns, with specific attention to the effects of these characteristics on emission patterns and on ability to comply with regulations. Thus each of these four groups is much more homogeneous (with respect to those characteristics which concern environmental regulators) than is the class of heavy-duty vehicles as a whole. A very similar scheme to this one has largely been adopted by EPA in its recent rulemaking proposals for heavy-duty NO_x and particulate emissions (EPA, 1984a).

The classification scheme used in this report forms a suitable framework within which to consider subdividing the heavy-duty class. The actual degree of subdivision desirable, however, would depend on the nature of the regulations being proposed and the costs and benefits of regulation in each class. The first and most obvious division, desireable in the case of either a strict NO_x or a strict particulate standard, would be between light-heavy duty engines and those for the other three classes. Light-heavy duty engines resemble the small high-speed diesels developed for passenger cars and light trucks more than the larger engines used in the other classes of heavy-duty vehicles. Presently, almost all light-heavy duty engines use indirect injection, and they are thus able to attain emissions levels that will not be attainable by the larger DI engines for several years. The small, high-speed DI engines now being introduced into this class by Cummins and Isuzu will probably have higher emissions levels than the current IDI engines, but they generally employ very advanced technology, and would thus be able to reduce emissions more readily. The current IDI engines will also be able to take advantage of the rapid development of electronic controls for light-duty engines. Thus, it appears that engines on the light-heavy class would be able to meet a stringent engine-out emissions control standard several years before any of the other classes.

The same is probably true of trap-oxidizer technology. A trap-forcing standard for light-duty diesel cars and trucks will go into effect in 1987, and at least some manufacturers appear to be able to meet it. If trap-oxidizers are successfully applied to light-duty trucks in 1987, no more than another year should be needed to apply them to light-heavy duty vehicles. A trap-forcing standard for these vehicles would thus become feasible in 1988, or about the same time at which a more stringent engine-out standard would be attainable.

Transit buses are another group which should be considered for stricter standards. The reason in this case is not technological (transit-bus engines are similar in technology to other medium-heavy duty engines) but operational. Bus emissions result in much more human exposure per gram of pollutant than do emissions from most other vehicles. Thus a good case can be made for imposing the strictest technologically feasible emissions standards on buses, even if standards for other classes are relaxed for economic reasons. In line with this approach, there has been some discussion recently of requiring the use of methanol engines for transit buses, in order to minimize NO_x and particulate emissions. This, however, amounts to a design standard, rather than the kind of performance standard that EPA has previously used for motor vehicles, and thus could lead to inefficiencies. A more rational approach would be to specify strict NO_x and particulate standards, which could be met by use of a methanol engine or by any other feasible means.

It is worth questioning, also, whether an EPA standard is the best vehicle for achieving the desired goal of reduced transit-bus emissions. As one alternative, a change in financing criteria by the Urban Mass Transit Administration could be just as effective, and possibly more flexible. There is precedent in the use of these criteria to achieve social goals — the recent requirement of handicapped access for buses is one example. Since transit buses are purchased almost exclusively by public or semi-public transit agencies, some sort of program aimed at these agencies might well be even more effective than a standard for manufacturers, and could also be easier to implement.

A final group that should be singled out for special attention are the line-haul trucks. These trucks are used primarily outside of urban areas, so the human exposure and environmental degradation per gram of emissions is lower for them than for most other heavy-duty vehicles (they are the exact opposite of the transit buses in this). At the same time, these trucks consume a large fraction of the total fuel used by the heavy-duty class, because of the enormous distances they travel. Strict particulate regulations would increase fuel consumption by several percent, and strict NO_x regulations could increase it by as much as 10-15 percent, so it is worth considering whether such regulations are worthwhile in this class. It is also worth considering whether such regulations could be enforced — line-haul truckers are notoriously independent and technically adept, and the cost of increased fuel consumption due to trap-oxidizers and/or NO_x controls would certainly be adequate motivation for tampering.

A major problem with separate treatment of line-haul trucks is the difficulty in defining them. The division between line-haul trucks and the medium-heavy group is much fuzzier than those between medium-heavies and light-heavies, or medium-heavies and transit buses. Line-haul engines are very similar in size and characteristics to the larger medium-heavy engines, and are sometimes used on medium-heavy trucks where additional power is required. If line-haul engines were subject to a more lenient standard, there would be a strong incentive for each manufacturer to classify its engines as line-haul, and it would be difficult to show unequivocally that a given engine was or was not intended for line-haul service.

Any solution to this problem would need to be structured in such a way as to avoid disrupting the truck engine market, and create a minimum of artificial distinctions. One approach to this problem would be a case-by-case exemption -- anyone seeking to purchase an engine meeting the more lenient standards for line-haul trucks would have to produce a permit, which would be issued upon his or her demonstration that the vehicle being purchased was for use in line-haul service. EPA, in its notice of proposed rulemaking (1984a), has proposed to define line-haul vehicles as those gross weights exceeding 60,000 pounds. Other, possibly feasible approaches have been suggested by Cummins (1983) and by the EMA (1982b), but all of these proposals have the disadvantage that they don't discriminate between the large tractor trailers used in interstate service (which contribute little to urban air pollution) and similar trucks used for heavy hauling within an urban area (which contribute a great deal).

At this point, there is too little information on the relative costs and benefits of line-haul truck emissions to make a firm recommendation as to whether to treat them separately or on the same basis as the medium-heavy group. For the light-heavy group, however, the differences in technological readiness are quite clear. Thus an earlier implementation date than 1990 is recommended. For transit buses, the technological feasibility of control is no better than for medium-heavy trucks, however, the cost-benefit ratio is significantly better. Thus it is recommended that a strict standard (or action of some other form to the same effect) for transit buses should be considered even if a more moderate standard is adopted for other heavy-duty vehicles.

7.2.2 Emissions Averaging Regulations

Emissions averaging can, in theory, reduce the cost of environmental protection by allowing manufacturers to obtain the greatest reductions in emissions from those engines on which this is technically easiest, while relaxing standards on those engines which are difficult to bring into compliance. In the area of heavy-duty diesel engines, however, this theoretical benefit would be accompanied by some serious practical problems, which could lead to both disruption of the competitive environment and to circumvention of the intent of regulations. For this reason, it is necessary to examine the specific structure of an emissions-averaging regulation with considerable care.

The most commonly conceived form of emissions averaging is one which simply weights each engine's emissions levels by it annual sales to arrive at an average emissions level for a given manufacturer. Even if it is assumed that averaging is restricted only to heavy-duty diesel engines, such a standard would still favor the manufacturer with the broadest product line, and could be expected to have major deleterious effects on competition in the industry. Such a standard would also result in less protection of the environment.

As an example, consider the case of a stringent NO_x emissions standard. Stringent control of NO_x emissions in DI engines increases fuel consumption, and results in poor performance and driveability. For manufacturers such as GM and International Harvester, however, this would be a minor problem, since they would be able to average in the very low NO_x emissions of their indirect-injected light-heavy duty engines. By achieving their NO_x control in these lighter engines, they would be able to set their heavy-duty engines for higher NO_x, better performance, and better fuel economy, thus gaining a devastating competitive advantage. At the same time, this practice would impair the overall protection of the environment, since the light-heavy duty engines have shorter lives and lower power levels, and thus a reduction of 1 g/BHP-hr in such an engine has much less effect than in a larger, longer-lived model.

Careful design of any emissions averaging regulation would be required in order to avoid undesirable results such as those described. One possible approach would be to weight each engine's brake-specific emissions by its rated horsepower and expected lifetime mileage. This would be more representative of each engine's effects, but it would still tend to favor light-heavy duty manufacturers, since the average horsepower in use is a smaller fraction of the rated horsepower for these engines than for the other heavy-duty classes. This also fails to account for the differences in contributions to urban pollution levels between different classes — an additional gram of lifetime NO_x emissions from a transit bus, for instance, is much more harmful than an additional gram from a line-haul truck. Thus, to achieve real equity an averaging scheme would need to account for estimated life, average power levels, and use patterns, as well as brake-specific emissions.

An alternative, and possibly simpler approach, would be to allow averaging of emissions only within specific subclasses of heavy-duty vehicles — for instance, allowing bus emissions to be offset only against other bus emissions. One workable subclassification for this purpose would be the scheme of light-heavy, medium-heavy, line-haul, and transit bus proposed in this report. This approach would eliminate most of the perverse incentives inherent in a simple averaging schcme, while retaining the advantage of simplicity. Reducing the range of engines over which emissions can be averaged would reduce the manufacturer's flexibility, however, and thus reduce the benefits of averaging. It might also introduce some unnecessary competitive dislocations, since some manufacturers with only one or two engine models in a subclass would be at a disadvantage.

7.3 ACHIEVABLE NO_x AND PARTICULATE STANDARDS

In setting an achievable motor-vehicle emissions standard, it is necessary to consider six questions.

1. What is the lowest emissions level technically achievable in new engines?

2. How is this technical limit affected by other emissions standards and/or other possible changes in the environment?

3. How much deterioration in emissions will occur during that portion of the vehicle's life covered by the regulation?

4. How much allowance for engine-to-engine, test-to-test, and laboratory-to-laboratory variation in emissions measurements must be allowed in order to avoid having to remove an engine from production solely due to statistical fluctuations?

5. How much margin should the manufacturers be allowed? (This might be rephrased as "How close to the fire shall we hold their feet?")

6. What level of control is necessary and justified, in order to provide maximum protection to the environment at an acceptable cost?

The first two questions — the limits of technical possibility and the effects of other regulations — have been addressed in the previous chapters. Achievable engine-out emissions levels and the NO_x-particulate tradeoff were discussed in Chapter 4. Estimates of the near-term and intermediate-term limits of technical feasibility for the NO_x-particulate tradeoff — developed in Chapter 4 — will form the basis for the analysis here. In addition, this discussion will consider the effects of trap-oxidizers, as discussed in Chapter 5. Possible changes in the environment — such as the changes in diesel fuels discussed in Chapter 6 — will be considered only by default; it will be assumed that no major changes in diesel fuel quality or other environmental variables with effects on emissions will occur. As this report deals only with the technology of emissions control, the last question posed will not be addressed here.

7.3.1 Translation from Low-Mileage Emissions to Standards

Questions three through five on the list above are very important ones, yet they are frequently neglected in environmental analyses. There is a tendency to regard the technically feasible low-mileage emissions level and the technically feasible standard as the same. This tendency is wrong — the low mileage emissions level is only one factor entering into the determination of a feasible standard. Other, equally important, concerns are the variability of emissions, the portion of the engine's or vehicle's life that the standard is to apply to, the degree of deterioration that can be expected in that time, and the auditing and verification procedures. The effect of each of these concerns must be accounted for in order to determine a technologically feasible standard. In addition, in the use of "technology-forcing" standards such as those contemplated for heavy-duty diesel engines, the speculative nature of the projected technically feasible low-mileage emission level should also be taken into account, and some slack should be provided to compensate for the uncertainty in the projection.

The three questions concerning deterioration, variability, and slack can usefully be combined into a single one: "How far above the technological limit for low mileage emissions should the standard be set?" In this way it is possible to combine in one number all the necessary allowances. In estimating feasible values for this number, it is instructive to consider the allowances recommended by the manufacturers themselves. Each of the five major U.S. engine manufacturers recommended a set of diesel NO_x and particulate standards to EPA in 1982, and each provided an estimate of the low-mileage emissions target that would be necessary to meet this standard. These values, and the ratios between them, are shown in Table 7.2.

Table 7.2

Manufacturer's Recommendations for Heavy-Duty Emissions Standards

	NO_x			Particulate		
Manufacturers	Standard	Low-Mileage Target	% Margin	Standard	Low-Mileage Target	% Margin
Mack	8.0	6.5	23	0.79	0.50	58
Cummins	7.5	6.7	12	0.80	0.66	21
International	10.0	7.7	30	0.68	0.44	55
Harvester	8.0	6.1	31	0.77	0.50	54
	7.0	5.9	30	0.79	0.51	55
	6.0	4.6	30	0.83	0.54	54
Caterpillar	6.0	5.3	13	0.60	0.46	30
General Motors	8.0	6.05	32	0.85	0.54	37
	10.7	8.09	32	0.70	0.44	37

As Table 7.2 indicates, different manufacturers differ strongly in the allowances beyond the basic low-mileage emissions level that they recommend. These values range from 12 to 32 percent for NO_x, and from 21 to 58 percent for particulates. On the basis of the information shown, and ERC's own analysis of the issue, the authors recommend minimum margins of 10 percent and 25 percent for NO_x and particulates respectively. Thus the emissions standard for NO_x should be at least 10 percent, and the standard for particulates at least 25 percent, above the estimated technological limit for low mileage emissions. These factors include allowances for deterioration, random variation, and some error in the estimate of technical feasibility, either for the industry as a whole or for some manufacturer.

These margin levels are comparatively strict, and will not be easy to meet. They have been derived using the following assumptions.

1. The standard is based on averaging within classes or across a manufacturer's entire heavy-duty product line, as discussed in Section 7.2.2, reducing the effects of random variation in tests and of differences in the emissions control abilities of different engines.

2. Average full-life NO_x deterioration factors are taken equal to zero, and average particulate deterioration is 15 percent.

3. Deterioration is measured over the full estimated useful life of the engine.

4. Manufacturer's recommended maintenance procedures are followed throughout the durability test.

5. Reasonably representative and statistically valid auditing procedures are followed.

6. Reasonable non-conformance penalties for non-compliance are in effect.

Under these assumptions, the technologically feasible standard levels can approach the feasible low-mileage emissions levels rather closely. Generally, the statistical variation in emissions from engine to engine and from test to test is a major concern in setting the margin of compliance, so that random variations in test results do not result in failing an audit. However, averaging across the entire product line should reduce this concern, since the standard deviation of the mean of several measurements on different engines would be less than the standard deviation of the measurements themselves. In addition, the use of nonconformance penalties would reduce the adverse consequences of failing an audit, and thus make a greater probability of failure tolerable.

These qualifying assumptions should be noted carefully, and their validity in any specific instance should be checked. Use of similarly tight margins in circumstances where the assumptions above do not apply could well result in regulations which are effectively beyond the limits of technical feasibility, or which result in an unwarranted level of risk for manufacturers.

7.3.2 Limits of Feasibility for NO_x and Particulate Standards

Estimates of the technological limits on near-term and intermediate term NO_x and particulate emissions have already been presented in Section 4.4. Because of the inverse relationship between NO_x and particulate emissions, these estimates were presented graphically, in the form of a plot of the lowest achievable particulate emissions versus NO_x. These graphs can be adapted to indicate the lowest feasible particulate standard as a function of the NO_x standard. This is done by multiplying the NO_x coordinate of every point on the graph by 1.10 (corresponding to the 10 percent margin for deterioration, random variation, and slack derived in Section 7.3.1) and multiplying the particulate coordinate of each point by 1.25 (corresponding to a 25 percent margin).

Figure 7.1 shows both the estimated technological limit for low-mileage emissions and the standard derived from that limit for heavy-duty diesels in the near term. Figure 7.2 shows the same data for intermediate term engine-out technology. Both of these figures have been based on the data in Figure 4.12, and thus all of the reservations and cautions concerning those data apply here as well. In particular, the engine-out emissions frontier for the intermediate term is somewhat speculative, due to the general unavailability of data, and should be better defined before being used in setting a final rule.

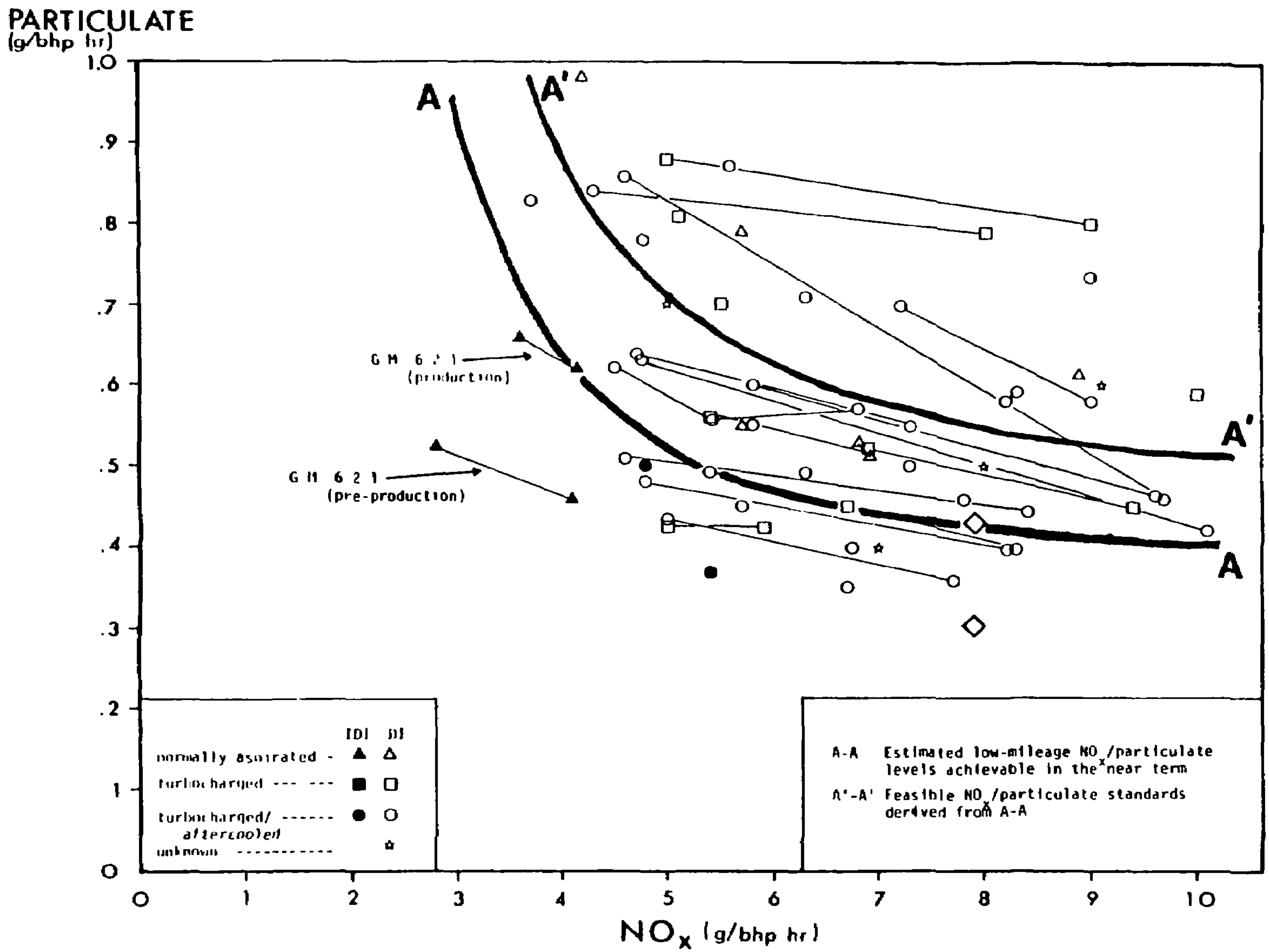


Figure 7.1: Estimates of achievable near-term particulate emissions standards vs. NO_x standards for heavy-duty diesel engines.

Energy and Resource Consultants Inc

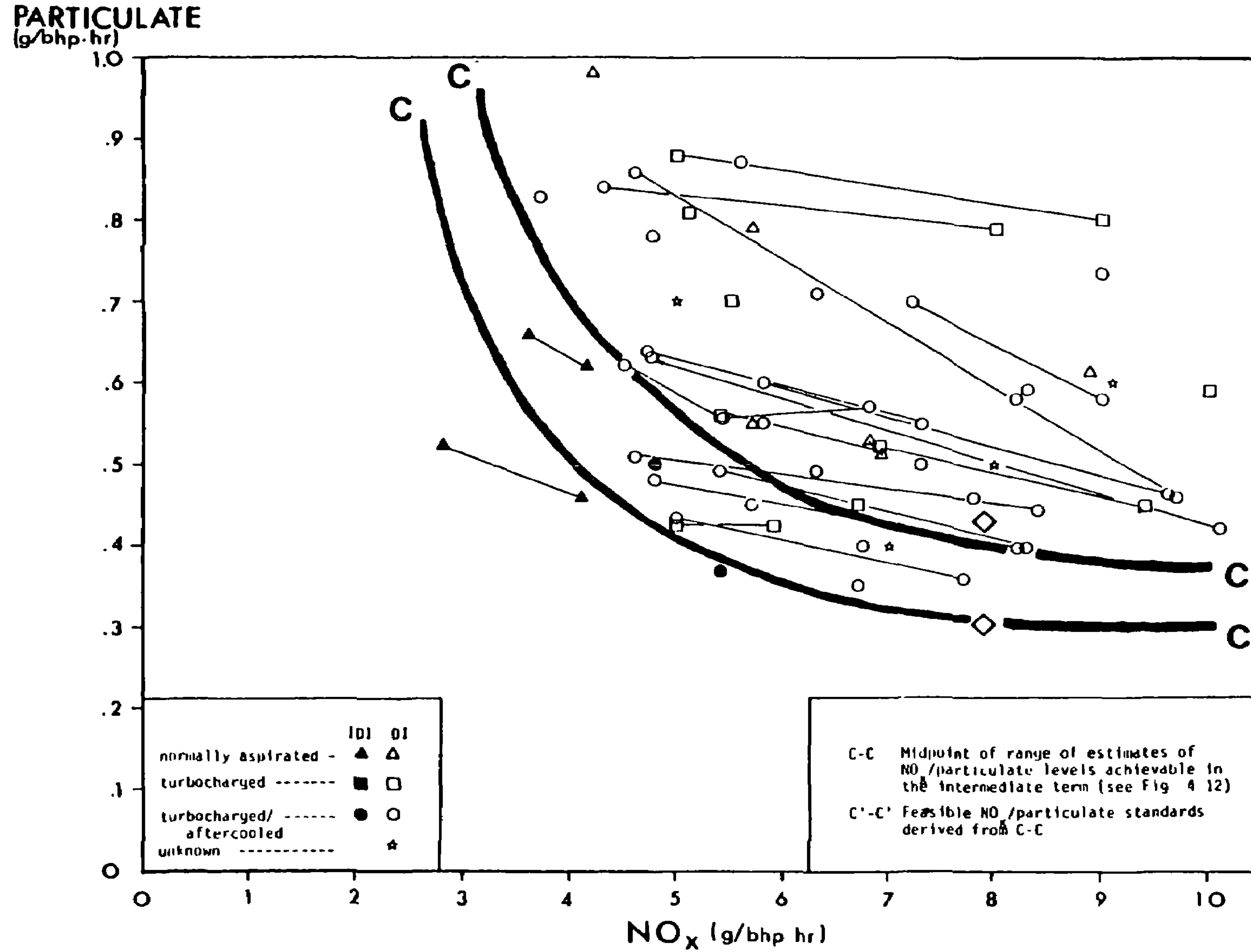


Figure 7.2: Estimates of achievable intermediate-term particulate emissions standards vs. NO_x standards for heavy-duty diesel engines.

Figures 7.1 and 7.2 show the levels of standards estimated to be achievable with engine-out control technology. In the near term, engine-out technology is all that will be available. In the intermediate term, however, trap-oxidizers will also be available for particulate control. The effect of trap-oxidizers on the achievable particulate standard can be estimated by multiplying the particulate coordinates of the curve in Figure 7.2 by 0.25, reflecting a trap-oxidizer efficiency level of 75 percent. This level has been selected in order to avoid ruling out catalytic wire-mesh trap-oxidizers, which cannot achieve as great an efficiency as the monolith and silica-fiber traps. Monolith trap efficiency is generally about 90 percent, and the silica-fiber trap should be in the 80-90 percent range. However, the wire-mesh trap has other beneficial characteristics (odor, HC, and CO reduction, as well as reducing the soluble organic fraction of the particulate) which makes it undesireable to rule it out of consideration. For purposes of computing the low-mileage target emissions, however, a trap efficiency of 85 percent or more should be assumed, reflecting the greater efficiency possible with the monolith and candle systems.

7.3.3 Alternatives for Emissions Standards

This section offers several possible scenarios for future NO_x and particulate emissions standards. All of the five are technically feasible by the criteria discussed above; they differ in areas such as the relative stringency of control (i.e., the willingness to impose economic penalties on the industry in order to reduce emissions) and the degree of concentration on reducing NO_x as opposed to particulate emissions. Because of the limited technological capabilities in the near term, all five scenarios are identical until the intermediate term — 1990 for the medium-heavy, line-haul, and transit bus classes, and 1988 for the light-heavy duty class. Beyond this point, the scenarios differ.

Table 7.3 describes and names each of the emissions scenarios considered, and indicates the numerical standards and the estimated low-mileage emission levels associated with each. These scenarios are further discussed below.

1. Moderate Control Scenario - This scenario includes only a single, emissions standard to go into effect in 1987, with no tightening of the standard in 1990. It includes an engine-out NO_x standard of 6.0 g/BHP-hr (chosen because this number is one being considered by EPA), combined with the feasible particulate standard for that NO_x

Table 7.3

Numerical Standards and Low-Mileage Emissions Levels for Five Feasible Heavy-Duty Regulatory Scenarios

Scenario	Date	NO_x Standard	NO_x LMT	Particulate Standard	Particulate LMT
1. Moderate Control					
Light-Heavy	1986	6.0	5.5	0.62	0.50
All Others	1987	6.0	5.5	0.62	0.50
2. Moderate NO_x/Best Engine-Out Particulate					
Light-Heavy	1986	6.0	5.5	0.62	0.50
	1988	5.0	4.5	0.56	0.45
All Others	1987	6.0	5.5	0.62	0.50
	1990	5.0	4.5	0.56	0.45
3. Moderate NO_x/Trap Oxidizers					
Light-Heavy	1986	6.0	5.5	0.62	0.50
	1988	5.0	4.5	0.14	0.08
All Others	1987	6.0	5.5	0.62	0.50
	1990	5.0	4.5	0.14	0.08
4. Strict NO_x/No Trap-Oxidizers					
Light-heavy	1986	6.0	5.5	0.62	0.50
	1988	4.0	3.6	0.72	0.58
All Others	1987	6.0	5.5	0.62	0.50
	1990	4.0	3.6	0.72	0.58
5. Strict NO_x/Trap-Oxidizers					
Light-Heavy	1986	6.0	5.5	0.62	0.50
	1988	4.0	3.6	0.18	0.09
All Others	1987	6.0	5.5	0.62	0.50
	1990	4.0	3.6	0.18	0.09

standard. Meeting these standards would require only near-term technology such as improved turbocharging, charge-air cooling, and fuel injection systems. Thus the economic impact of the regulations would be less than for the other scenarios. Some such impact would still occur, however — the NO_x limitations would increase fuel consumption by several percent in the near term for instance.

2. Moderate NO_x, Best Engine-Out Particulate Control - This scenario includes the same regulations as the moderate control scenario in 1987, followed in 1990 by a moderate NO_x standard and the strictest feasible engine-out particulate standard given that NO_x standard. Compliance with this standard would require the use of electronic governor and fuel injection timing controls, high-precision fuel injection, and extensive engine optimization, but probably not EGR. Most of these would be added by the manufacturers anyhow, in order to improve fuel consumption. Thus the economic impact of this scenario would be fairly low — the major effect would be due to an increase in fuel consumption of a few percent due to the NO_x controls.

3. Moderate NO_x, Strict Particulate Control with Trap-Oxidizers - This scenario is identical to Scenario 2, except that a tighter particulate standard — requiring the use of trap-oxidizers — is adopted. The economic impact of this scenario would be greater, due to the added cost and fuel consumption of the trap-oxidizers.

4. Strict NO_x Scenario, No Trap-Oxidizers - This scenario assumes that strict control of NO_x emissions is necessary, and that higher costs in fuel economy and particulate emissions are an acceptable price to pay for this. It consists of an NO_x standard of 4.0 grams per BHP-hr, together with the most stringent engine-out particulate standard achievable at the NO_x level. The initial cost of this scenario would be moderate, but the cost in fuel economy would be very high.

5. Strict NOx Scenario with Trap-Oxidizers - This scenario assumes that strict control of both NO_x and particulate emissions is necessary, and that society is willing to absorb substantial costs in order to achieve

this. It consists of the same NO_x regulations as the fourth scenario, combined with a particulate standard which is strict enough to require trap-oxidizers. The economic impact of this scenario would be significant — to the moderate initial cost and high fuel-economy costs of the fourth scenario would be added the high initial costs and moderate fuel-economy costs of trap-oxidizers.

None of these scenarios would need to be applied across the board — different groups within the heavy-duty class could be regulated according to different philosophies. Indeed, it is strongly recommended that this approach be considered. In particular, it is recommended that a very strict approach (corresponding to Scenario 5) be considered for transit buses, while a moderate trap-oxidizer standard such as in Scenario 3 should be considered for light-heavy and medium-heavy trucks. For line-haul trucks, a moderate engine-out particulate standard such as Scenario 2 should be considered. These standards appear likely, on the basis of ERC's qualitative analysis, to produce the best tradeoff between emissions, fuel-economy, and initial cost. However, qualitative analysis is not enough to justify a quantitative standard — thus it is only recommended that these levels be considered, and not necessarily adopted. This consideration should include a firm quantitative analysis of the costs and benefits of each approach, and this quantitative analysis should be used as the basis for regulation.

7.4 RECOMMENDATIONS

The author's recommendations for emissions standards and related issues can be summarized as follows:

1. In establishing regulations for heavy-duty engines, EPA should consider separately the four major subclasses discussed in Chapter 2. This does not necessarily mean that different regulations should be adopted for each subclass. Rather, the costs and benefits of regulation should be considered separately for each subclass, and the best regulation for that subclass (which might or might not be the same as for some other subclass) should be adopted.

2. Special consideration should be given to accelerating the imposition of strict emissions standards on light-heavy engines (since they are capable of meeting these standards more quickly) and to imposing very strict standards on transit buses. Special consideration should be given to imposing less strict standards on line-haul trucks.

3. Any scheme for emissions averaging must be very carefully designed in order to prevent it from being used in ways which would result in greater emissions overall. One simple approach would be to permit averaging only within subclasses of heavy-duty engines. If averaging across subclasses is permitted, it should properly account for the expected lifetime, expected average power level, and expected fraction of urban operation of each engine.

4. Figure 7.1 is a plot of estimated feasible particulate standards versus the NO_x standard in the near term (1987 or 1988). Because the technology involved is not radically different from what is now in use, this frontier is considered to be fairly well defined. Any emissions standards applying to that period should be chosen to fall on or above this frontier.

5. Figure 7.2 shows the estimated feasible engine-out particulate standards as a function of the NO_x standard for intermediate-term (1990 or 1991) application. The information in this figure is much more uncertain than that in Figure 7.1, and should be clarified by additional research before being used as a basis for regulation. Feasible trap-oxidizer based standards for the intermediate term can be obtained by multiplying the feasible engine-out standard by 0.25, reflecting an average trap efficiency of 75 percent.

6. Light-heavy duty engines could comply with standards similar to those in Figures 7.1 and 7.2 more quickly than the other heavy-duty classes. Implementation dates of 1986 for the near-term standard and 1988 for the intermediate-term standard appear to be feasible.

8.0 SUMMARY AND CONCLUSIONS

Chapters Two through Seven of this report have presented largely separate, although interelated, analyses of a number of issues related to diesel particulate standards and control. These issues range from definition of representative classes of heavy-duty vehicles (Chapter Two) and defining the requirements for commercial feasibility (Chapter Three) to detailed technical analyses of engine-out and aftertreatment control technologies (Chapters Four and Five). Chapter Six deals with the effects of fuels on emissions, with special attention to the effects of changes in fuel quality. Chapter Seven, the final technical chapter, draws together the analysis from the preceding chapters to derive estimates of feasible near and intermediate-term heavy-duty particulate standards. This chapter also discusses a number of other issues related to particulate control regulations.

Except for Chapter Seven, the analyses presented are largely independent and separable. Because of this, as well as the very large amount of information presented and the large number of conclusions reached, the summary and conclusions have been divided into sections, with a separate section for each chapter. These are given below.

CHAPTER 2: CLASSIFICATION OF HEAVY-DUTY ENGINES AND VEHICLES

Summary - Chapter Two examines the heavy-duty vehicle and heavy-duty engine industries in the United States, and presented ERC's classification scheme for heavy-duty vehicles. The structure of the heavy-duty vehicle industry is quite different from that for light-duty vehicles. Heavy-duty trucks are not standardized - rather, they are sold with a wide variety of options as to engine model, drivetrain, body type, and auxiliary equipment. Thus, not all heavy-duty vehicle manufacturers produce engines, and not all engine manufacturers produce vehicles. Since engines, rather than vehicles, are the regulated items in the heavy-duty class, this report deals mainly with engine manufacturers. The major heavy-duty diesel engine manufacturers in the U.S. are Cummins Engine, Caterpillar Tractor, Mack Trucks, Detroit Diesel-Allison Division of General Motors, and International Harvester. A number of foreign firms, notably Daimler-Benz (Mercedes), Fiat (IVECO) and Volvo also import heavy-duty diesel engines installed in their own trucks.

ERC has proposed a classification of heavy-duty vehicles along functional lines, rather than strictly by weight class. This classification is used throughout the report, and serves as the basis for a number of important conclusions. Four classes of heavy-duty vehicles were defined: light-heavy duty (primarily pickup trucks and vans, with some specialized types); medium-heavy duty (all unitary trucks, and all other large heavy-duty vehicles except those in the next two classes); line-haul trucks (large, heavy, extremely powerful tractor-trailer combinations used for long-haul trucking); and transit buses. Although these classes still exhibit considerable heterogeneity, they are much more homogeneous in their essential characteristics than is the class of heavy-duty vehicles as a whole.

Conclusions - The major conclusions of Chapter Two are given below.

1. Heavy-duty vehicles are a very heterogeneous group, far more so than light-duty vehicles.

2. This heterogeneity can be reduced to a manageable level by subdividing the heavy-duty class into four subclasses: light-heavy, medium-heavy, line-haul, and transit bus. These should be considered separately for regulatory purposes.

CHAPTER 3: COMMERCIAL FEASIBILITY AND HEAVY-DUTY ENGINES REQUIREMENTS FOR EMISSIONS CONTROL TECHNOLOGIES

Summary - Chapter Three examines the requirements which an emissions control device must meet in order to be considered commercially feasible in heavy-duty service. These requirements are both technical and economic. The major criteria for feasibility are the following: effectiveness, durability, reliability, cost, and the effects of the technology on the fuel economy, performance, durability, and reliability of the engine. In addition, it is necessary to consider the technology's effects on safety and maintenance requirements, its resistance to tampering, weight and bulk, ease or difficulty of manufacturing and system integration, and possible environmental effects.

The criteria for feasibility in heavy-duty vehicles are generally more stringent than those for emissions controls in light-duty service. This is due to the more rigorous usage of heavy-duty engines and equipment, as well as to the greater technical sophistication of the users and the much larger amounts of money involved. Both of these latter traits would tend to encourage tampering with emissions-control devices which degrades fuel economy, reliability, or performance. Since heavy-duty engines are designed to be rebuildable indefinitely, a sufficiently strict emissions standard could even prove counter productive (as well as very destructive to the industry), since older engines not subject to the standard could be rebuilt and substituted for new ones if that were economically favorable. This would be most likely to occur as the result of a strict NO_x standard, since such a standard would have a highly adverse effect on performance and fuel economy.

<u>Conclusions</u> - The following conclusions result from the discussion in Chapter Three.

1. The criteria for commercial feasibility of emissions controls in heavy-duty service are different from, and generally more stringent than, those for light-duty applications. This is especially true of economic criteria such as fuel economy effects.

2. The importance of individual criteria is different for different subclasses of heavy-duty vehicles. In light-heavy vehicles, for instance, first cost is the dominant concern. For line-haul trucks, in contrast, the initial cost of the technology is negligible compared to the potential cost of losses in fuel economy and performance.

3. Heavy-duty engine purchasers, especially those buying heavy trucks, have substantially more freedom of choice than purchasers of light-duty vehicles. Thus they can switch engines to avoid a poor performer, and could even substitute uncontrolled rebuilt engines for new ones if that were economically favorable. They may also be more likely to tamper with emissions control devices which have serious deleterious effects in costs of performance.

4. As a result, there are limits on environmental agencies' power to reduce heavy-duty emissions by means of new engine standards. Too severe a standard would be *counterproductive. This possibility should be borne in mind during standards* development.

CHAPTER 4: ENGINE-OUT EMISSIONS CONTROL FOR HEAVY-DUTY ENGINES

Summary - Chapter Four deals with the potential for control of heavy-duty particulate emissions by means of "engine-out" methods, which are techniques to reduce the amount of particulate in the exhaust as it leaves the engine. Engine-out technologies are distinguished from aftertreatment technologies, which rely on separate processing to purify the exhaust.

Chapter Four begins with an examination of the fundamental physics and chemistry of combustion and pollutant formation in the diesel engine. This discussion concluded that the commonly observed tradeoff between reduced NO_x and increased particulate emissions in diesel engines is a fundamental characteristic of the combustion process, and thus is subject only to very limited control. The same is true for the tradeoffs between NO_x and fuel economy, and NO_x and hydrocarbon emissions. The best prospects for improvement in these tradeoffs appear to lie in improved control of injection timing and other engine variables, and in technologies such as charge-air cooling which increase the oxygen content of the charge in the cylinder while reducing the peak combustion temperature.

Chapter Four also examines present and future engine-out emissions control technologies for heavy-duty diesels. Because of the NO_x/particulate tradeoff, both NO_x and particulate control technologies were examined (in practice, of course, a given technology may often provide either NO_x or particulate control, depending on the settings of engine parameters). Many technologies show present or future promise for improving on the NO_x/particulate and NO_x/fuel-economy tradeoffs. Promising technologies which could be implemented by 1987 or 1988 include improved engine/turbocharger matching, improved charge-air cooling, and high-pressure/high-precision fuel-injection systems.

In the intermediate term (1990 or 1991), the technology with the greatest promise is optimal electronic control of fuel injection timing, coupled with an electronic governor and (for a low NO_x standard) electronically-modulated exhaust-gas recirculation (EGR). EGR would be necessary to meet a low NO_x standard without gross degradation in fuel economy, but would not be used otherwise, due to its deleterious effects on engine durability. In the longer term (after 1991), uncooled or "adiabatic" engine technology offers the promise of substantial decreases in particulate emissions, at little or no cost in increased NO_x. However, this technology is still in the early stages of development, and any predictions as to when or if it will become available would be premature.

The last part of Chapter Four deals with the average engine-out emissions levels which are estimated to be attainable by 1987-88, and by 1990-91 (near-term and intermediate-term periods, respectively). Since NO_x and particulate emissions are interrelated, they were considered together. A plot of measured particulate emissions levels vs. NO_x levels for heavy-duty engines reveals three fairly distinct groups: Group I, consisting of standard technology engines with parameters set to meet present Federal regulations; Group II, containing standard-technology engines set to meet California's more restrictive NO_x standard; and Group III, which contains more advanced-technology engines (many of which are still in the prototype state). These groups are shown in Figure 4.11.

Group I engines generally exhibit low particulates but high NO_x, while those in Group II have low NO_x but high particulates. Group III engines display lower NO_x and lower particulates, thus improving on the tradeoff relationship defined by Groups I and II. It is estimated that the average engine in the 1987-88 time frame could attain a performance level similar to that of Group III, while the advanced technologies now under development could improve on that level by an uncertain (but substantial) amount. Estimates of the NO_x/particulate tradeoff curves achievable in the near-term and intermediate-term time frames are plotted along with current engine data in Figure 4.12. These curves play an important role in the derivation of feasible standards in Chapter Seven.

Conclusions - Chapter Four defined a number of important conclusions with regard to engine-out emissions control. The most significant of these are repeated below.

1. The NO_x/particulate and NO_x/fuel economy tradeoffs displayed by present-technology engines are due to the fundamental nature of the combustion process in the diesel engine, and thus are under only very limited control by the engine designer.

2. Technologies having some potential to improve on the NO_x/particulate tradeoff include high-pressure/high-precision fuel injection, turbocharging with charge-air cooling, improvements in engine efficiency, electronic engine controls, the uncooled or "adiabatic" diesel engine, and indirect injection.

3. Injection timing retard and exhaust gas recirculation do not improve on the NO_x/particulate tradeoff, but are likely to be used to adjust NO_x and particulate levels along the tradeoff curve.

4. Turbocharging, charge-air cooling, improved fuel-injection, and electronic engine controls all have beneficial effects on fuel consumption and performance, thus they are likely to be introduced independently of any emissions standards.

5. When used to reach low NO_x levels, injection timing retard significantly degrades fuel economy, and is thus likely to be supplemented or supplanted by EGR, which has a lesser effect on fuel consumption. Otherwise, EGR would not be used, since it is regarded as detrimental to engine durability.

6. Indirect injection results in a major loss in fuel economy, thus it is only economically feasible in light-duty and light-heavy duty engines, where it is already universal (although small DI engines are being introduced into the light-heavy class). Because of the advantages of IDI and the technological sophistication of new DI engines in this class, light-heavy duty engine manufacturers are presently able to achieve emissions levels which the larger direct-injected (DI) heavy-duty engines will not be able to attain until about 1989, and could probably attain significantly lower levels (corresponding to an intermediate-term standard) by 1988.

7. Technologies likely to be available for common use in DI engines in the near term are turbocharging/charge-air cooling, improved fuel injection, engine efficiency improvements, and injection timing retard. Aggressive application of all of these techniques, combined with optimization, could produce an average low-mileage NO_x/particulate tradeoff curve similar to line A-A in Figure 4.12.

8. Technologies likely to be in common use in the intermediate term include those listed for the near term, plus electronic engine controls and still further improvements in charge-air cooling and engine optimization. By aggressive application of these techniques, combined with EGR for very low NO_x levels, engine manufacturers could probably attain an average low-mileage NO_x/particulate tradeoff curve lying between lines B-B and B'-B' in Figure 4.12.

CHAPTER 5: TRAP-OXIDIZER SYSTEMS FOR HEAVY-DUTY VEHICLES

Summary - The trap-oxidizer is a particulate control system consisting of a durable filter (the "trap") which removes particulate material from a vehicle's exhaust system, combined with a system for regenerating the trap by burning off ("oxidizing") the collected material. Chapter Five discusses the present state of trap-oxidizer technology, with special attention to the relatively small amount of work that has been done on trap-oxidizers for heavy-duty vehicles.

Trap-oxidizer technology for light-duty vehicles is quite advanced. One trap-oxidizer equipped car is now in production, and many models are expected to be available by 1987. However, heavy-duty vehicles have a number of characteristics which will make the application of trap-oxidizers more difficult. The most important of these is the much greater lifetime mileage typical of heavy-duty vehicles -- as much as 500,000 to 1,000,000 miles in line-haul trucks. Other problems include the fragmentation of the industry, and the fact that many different models of engine may be offered in a single truck chassis, implying that the chassis would need to accommodate many different models of trap-oxidizers as well. These difficulties, as well as the lesser amount of development work in the heavy-duty area, will increase the lead-time required for the introduction of trap-oxidizers in heavy-duty vehicles. Even making favorable assumptions, heavy-duty trap-oxidizers are unlikely to be available before 1990 or 1991. The most advanced manufacturer in trap-oxidizer development appears to be Daimler-Benz which has developed a highly successful heavy-duty trap-oxidizer system that it states it is "confident" will be ready for production in 1990.

Tampering and institutional resistance would be significant problem with trap-oxidizers in heavy-duty use. Trap-oxidizers would almost certainly degrade fuel consumption slightly, which could lead to their removal by truck owners or users. These problems would be most severe in the line-haul and medium-heavy truck classes, which are also the groups in which the durability and reliability issues are of greatest concern. In contrast, application of trap-oxidizers to light-heavy vehicles would be much simpler — for these much smaller engines, a straightforward adaptation of light-duty technology would be possible. Because of this, light-heavy trap-oxidizers could be available well before the other classes — probably as early as 1988.

Four generic types of trap-oxidizer systems now appear promising for heavy-duty use. These are: (1) a ceramic monolith trap, regenerated by a diesel fuel burner; (2) a ceramic monolith trap with continuous regeneration by means of catalytic fuel additives; (3) a catalytic wire-mesh trap, using one of several inexpensive regeneration systems; and (4) a trap using woven silica yarn on a perforated metal substrate, with regeneration by the injection of catalysts into the exhaust. This last is the system developed by Daimler-Benz. It is too early to predict which of these may be adopted for heavy-duty use, although the monolith/additive system appears to be the current leader in light-duty applications. System descriptions and cost estimates were developed for trap-oxidizer systems using each of these approaches in each of the four classes of heavy-duty vehicles.

The first cost estimates for these systems ranged from \$426-\$499 in a light-heavy vehicle up to \$1121-\$1253 in a line-haul truck. Total (discounted) life-cycle costs, including the cost of extra fuel consumed, maintenance, and replacement traps, ranged from \$560-\$715 for the light-heavy vehicle up to \$3462-\$4047 in the line-haul truck. Cost estimates for medium-heavy vehicles and transit buses lay between these two extremes. From a cost-effectiveness standpoint, the most effective trap-oxidizer systems would be those in transit buses, due to the much greater human exposure per unit of pollutant emitted. These would show a cost effectiveness index many times that of light-duty trap-oxidizers. The cost effectiveness of trap-oxidizers in medium-heavy trucks would be about twice that for light-duty vehicles, and that for light-heavy trucks would be comparable, but somewhat greater. The cost effectiveness of trap-oxidizers on line-haul trucks is questionable, since they spend comparatively little time in urban areas. For this reason, as well as the difficulties posed by the enormous lifetime mileages (and consequent durability requirements) for these trucks, it is worthwhile considering the exemption of line-haul trucks from any trap-oxidizer standard.

<u>Conclusions</u> - The major conclusions of Chapter Five were as follows.

1. Trap-oxidizer technology for light-duty diesel vehicles is highly advanced -- one trap-oxidizer-equipped cars model is now in production, and many more are expected by 1987.

2. Trap-oxidizer technology for heavy-duty vehicles is much less advanced, due to a slower start and the greater difficulty of the development task. Except for light-heavy vehicles (which could use an adaptation of the light-duty technology) heavy-duty trap-oxidizer systems are not likely to be available before 1990 or 1991. Trap-oxidizer systems for light-heavy vehicles could be available by 1988 if — as expected — successful trap-oxidizer systems for light-duty vehicles appear by 1987.

3. At least four generic types of trap-oxidizer systems now appear promising for heavy-duty use. However, there are unanswered questions and unresolved technical difficulties associated with each, and it is premature to predict which, if any, of them will eventually be adopted.

4. Generic cost estimates for each of the four promising trap-oxidizer systems in each class of vehicles are given in Tables 5.1 to 5.4. In general, these costs are quite high. Discounted life-cycle costs range from $566-$715 for light-heavy vehicles, up to $3462-$4047 for line-haul trucks, with costs for medium-heavy trucks generally around $1500 and those for transit buses around $3,000.

5. A large fraction of the total lifecycle cost of the trap-oxidizer system in the heavier trucks is due to increased fuel consumption, maintenance expenses, and trap replacement. These costs could be avoided by removing the trap shortly after purchase. Without an effective enforcement program, this practice could be expected to become widespread.

6. The cost effectiveness of trap-oxidizers in light-heavy and medium-heavy vehicles would be greater than that in light-duty cars and trucks, while that for transit buses would be many times greater. The cost effectiveness of trap-oxidizer control on line-haul trucks is doubtful, since they spend little time in urban areas. This suggests that transit buses should receive the highest priority for regulation, while consideration should be given to exempting line-haul trucks.

CHAPTER 6: EFFECTS OF FUELS ON DIESEL EMISSIONS

Summary - Chapter Six reviews the effects of fuel variables on heavy-duty emissions. and discusses the possible effects of the current degradation of fuel quality on emis-

sions. The major quality indices for diesel fuel are cetane number, aromatic content (this is closely correlated with cetane number), volatility, and sulfur content. The recent trend toward heavier and lower-quality crude oils has led to degradation in most of these indices, with the effects on cetane number, aromatic content, and sulfur content being the most significant. Cetane number and aromatics content have a strong effect on particulate emissions, with aromatic content seeming to be the more important of the two. Thus, a continuation of the trend toward lower cetane can be expected to lead to higher emissions in use, and cetane-improving additives (since they do not affect the aromatic content) are unlikely to improve this greatly.

The effects of volatility on emissions do not seem to be very significant, at least within the range of present day diesel fuels. Thus, volatility changes are not of major concern. Sulfur content, on the other hand, is significant, both alone and in conjunction with catalytic trap-oxidizers. Sulfate formed from fuel sulfur contributes significantly to particulate emissions, and high sulfur fuels may also increase the organic fraction of the particulates. The precious-metal catalysts in catalytic trap-oxidizers can oxidize SO_2 to additional sulfate, which then combines with water to form sulfuric acid. This material is then emitted to the atmosphere. Although the sulfate conversion problem can probably be controlled, the steps required to do so will also make regeneration more difficult. Reducing the sulfur content of diesel fuel would eliminate this problem, and would also eliminate a small but significant contribution to urban SO_2 levels (including secondary particulate formed by SO_2 oxidation in the atmosphere) and acid deposition. There would be synergetic benefits as well — the de-aromatization process used to reduce aromatic content and upgrade cetane ratings can also be used to remove sulfur from diesel fuel. Thus, the cost of both operations might not be much more than that of either one alone, and this cost would probably be rather small — of the order of a few cents per gallon.

<u>Conclusions</u> — The major conclusions of Chapter Six were the following.

1. There has been a substantial degradation in the average quality of diesel fuel, especially in cetane number and aromatic content. This can be expected to lead to greater in-use emissions than would otherwise be experienced.

2. The aromatic content of diesel fuel has the greatest effect on particulate emissions, and this effect seems to be partly independent of the aromatics effect on

cetane number. Thus, cetane improving additives may not reduce particulate emissions, even though they restore the cetane number to an acceptable level. Thus, from an emissions standpoint, a regulatory limit on aromatic content, as well as or instead of cetane number, might be in order.

3. The volatility levels of diesel fuel have only minor effects on emissions, at least within the range of experiments. Thus, fuel volatility does not seem to merit any special concern at this point.

4. Poor-quality diesel fuel results in higher fuel consumption, and poor performance, as well as increased emissions. In addition, the need to tolerate a broad range of cetane numbers makes it more difficult to achieve low NO_x levels and may harm fuel economy. Thus, regulations to fix a narrower range of cetane and/or aromatic content might provide economic benefits which would partially or wholly offset the greater cost of producing the fuel. This possibility should be investigated further.

5. There is a potential for a highly beneficial synergism between fuel desulfurization, improvements in Cetane, and reduction in aromatic content, all of which can be accomplished in essentially the same process. The benefits of desulfurization would include reduced human exposure to SO_2-reduced secondary particulate formation a small reduction in acid precipitation, and increased ability to use catalytic traps. Catalytic traps greatly reduce diesel odor, HC, and CO emissions, as well as reducing the soluble organic portion of the diesel particulate. The feasibility of this approach should be investigated carefully.

CHAPTER 7: EMISSIONS STANDARDS FOR HEAVY-DUTY DIESEL ENGINES

<u>Summary</u> — Chapter Seven, the final technical chapter, draws together the results of all of the preceding analysis to arrive at conclusions regarding the feasible levels of particulate standards. Due to the interrelationship between NOx and particulates, feasible NOx standards are considered as well. In addition, the chapter deals with several other, related issues, such as the effects of emissions averaging and the possible subdivision of the heavy-duty clas for regulatory purposes.

Chapter Seven begins by discussing the present and proposed heavy-duty NOx and particulate regulations, then moves on to a discussion of the issues involved in emissions averaging and subdivision of the heavy-duty class for regulatory purposes. A major concern with emissions averaging relates to the comparability of different classes of heavy-duty engines. A reduction of 1 gram/BHP-hr from a light-heavy engine results in a much smaller effect on environmental quality than an equivalent reduction in a larger engine, due to the much smaller number of BHP-hr generated over the engine's life. This could be avoided by weighting each engine's emissions by its rated power and/or estimated life, but this would greatly complicate the regulation.

Another solution to the averaging problem would be to permit averaging only within subclasses of engines, e.g., within the light-heavy class, the line-haul class, etc. This would retain many of the benefits of a more general averaging standard (reduced cost of compliance and reduced uncertainty), while ensuring a rough comparability of the emissions being averaged. This would also facilitate the establishment of separate numerical standards and/or standard effective dates for the different classes, which is itself a good idea. There would be a cost, however, in reduced flexibility, and this approach might unfairly penalize some manufacturers who have only one or two engine lines in a given subclass.

Light-heavy duty diesels are able to adopt light-duty emissions control technology, and thus could meet a stringent emissions standard more quickly than the engines in the other classes. Since this group seems likely to increase rapidly in size, it would be worthwhile to consider an earlier implementation date for standards in this group. Transit buses should also be singled out for special regulatory concern, due to the fact that bus emissions result in much more human exposure than those from most other vehicles. On the other hand, consideration should be given to exempting line-haul trucks from any extremely stringent standard, due to the fact that they operate mostly outside urban areas, while they would suffer disproportionately from any adverse effects on fuel economy or durability.

The last part of Chapter Seven deals with feasible emissions levels and emissions standards. First, the relationship between low-mileage emissions and a feasible standard is developed. Next, this relationship is combined with the estimated low mileage NOx/particulate tradeoff curves developed in Chapter Four to obtain plots of the feasible particulate <u>standard</u> as a function of the NOx standard for both the 1987-88 and

1990-91 time frames. Finally, these plots are used to derive feasible particulate standards corresponding to a number of different regulatory scenarios.

All the scenarios assume an initial (1987-88) NOx standard of 6.0 g/BHP-hr, for which the feasible particulate standard is 0.62 g/BHP-hr for medium-heavy, line-haul, and transit-bus vehicles. The scenarios differ in their assumptions concerning the 1990 standard -- two NOx levels (6.0 and 4.0 grams) and three levels of particulate control (no change from 1987-88, strictest feasible engine-out control, and strictest feasible control with trap-oxidizers) are considered. Feasible particulate standards for these scenarios range from 0.72 g/BHP-hr (for strict NOx with no trap-oxidizers) to 0.16 (Moderate NOx with trap-oxidizers). These estimates assume that emissions averaging is in use, a 40 percent average quality level (AQL), the use of full electronic engine controls (which are important in limiting deterioration), and the use of non-conformance penalties rather than more draconian measures to deal with non-compliance.

<u>Conclusions</u> — The major conclusions and recommendations developed in Chapter Seven are the following.

1. In establishing regulations for heavy-duty engines, EPA should consider the four major subclasses of heavy-duty vehicles separately. This does not necessarily mean that different regulations should be adopted for each subclass. Rather, the costs and benefits of regulation should be considered separately for each subclass, and the best regulation for that subclass should be adopted.

2. Special consideration should be given to imposing earlier emissions standards on light-heavy engines, and to imposing strict standards on transit buses. Special consideration should be given to imposing less strict standards on line-haul trucks.

3. Emissions averaging should be permitted in order to minimize the effects of random variation and to permit a wider variety of engine models to be offered. Any emissions regulation must be carefully designed in order to allow maximum flexibility without introducing unfair competitive advantages or jeopardizing air quality goals.

4. Figure 7.1 is a plot of estimated feasible particulate standards versus the NO_x standard in the near term (1987). Because the technology involved is not radically

different from what is now is use, this frontier is considered to be fairly well defined. Any emissions standards applying to that period should be chosen to fall on or above the frontier.

5. Figure 7.2 shows the estimated feasible engine-out particulate standard as a function of the NO_x standard for intermediate-term (1990 or 1991) application. The information in this figure is much more uncertain, and should be clarified by additional research before being used as a basis for regulation. A feasible trap-oxidizer based standard can be derived from the feasible engine-out standard by multiplying it by 0.25, reflecting a trap-oxidizer efficiency of 75 percent.

APPENDIX A: SUMMARY OF THE REVIEWERS' COMMENTS

The review draft of the report was completed in March, 1984, and dispatched to interested parties for review in May. Six organizations (all of which were manufacturers either of heavy-duty engines, heavy-duty vehicles, or both) returned comprehensive written comments; a further three organizations and individuals supplied shorter comments by telephone. Several of the reviewers also supplied additional data in areas of interest along with their comments.

In their comments, the reviewers pointed out a number of minor errors and a few major errors in the draft report, as well as identifying a number of sections in which the wording of the report was apparently unclear. The errors so identified have been corrected in the final report, and the obscure sections revised to clarify their intent. These modifications require no further comment. Every reviewer who returned comments also took exception to some of the major conclusions and recommendations of the report, and presented counter-arguments or data to support his views. These arguments have been carefully considered, and in some cases have led to modification of the conclusions and recommendations. This Appendix describes some of the major issues raised by the reviewers presents the authors' response to them, along with a description of the changes — if any — made in the final report as a result.

Useful Life and Nonconformance Penalties

The sections of the draft report dealing with useful life were written before EPA's November, 1983 rulemaking on the subject. The draft thus erroneously discussed useful life and deterioration factors in terms of half-life rather than the full-life based rules. In addition, the draft report took no notice of EPA's proposal to make use of monetary non-conformance penalties for non-compliance with the emissions regulations, rather than prohibiting the sale of non-complying engines. Both of these errors have been corrected in the final report.

These corrections have had offsetting effects on the amount of slack required between the feasible low-mileage emissions level and the feasible standard. Increasing the useful life increases the amount of slack required, while the switch to non-conformance penalties decreases it. Given the low deterioration factors typical of heavy-duty diesels, the latter effect is the more important. The estimated slack requirements for NOx and particulate emissions have thus been reduced from 15 percent and 30 percent to 10 percent and 25 percent, respectively.

<u>Classification Scheme For Heavy-Duty Vehicles</u>

Several reviewers took issue with the classification scheme proposed for heavy-duty engines and vehicles. Most felt that since EPA regulations apply to heavy-duty <u>engines</u>, any classification scheme used should reflect only engine characteristics — the argument being that the same engine might be used in several different classes of trucks. This objection arose mostly in connection with the suggested exemption of line-haul engines from stringent controls — with several reviewers suggesting that the development of two versions of the same engine for line-haul and medium-heavy use would increase development costs and administrative difficulties.

This argument ignores the fact that it is the vehicle, not the engine, which determines usage patterns, and thus determines the feasibility and cost-effectiveness of emissions control. Exemption of line-haul <u>engines</u> rather than line-haul vehicles from stringent emissions control standards would result in many line-haul engines being placed in medium-heavy trucks, with a consequent increase in urban emissions.

The argument also overstates the degree to which engines are actually used across different classes. True line-haul engines are specialized for that purpose (through the shape of the torque curve, engine/turbocharger matching, and rated RPM), and are not generally used in medium-heavy trucks. Similarly, engines specialized for stop-and-go driving in medium-heavy trucks are not well suited to line-haul use. Transit-buses also have special engines, such as the Cummins NHHTC and Detroit Diesel-Allison's bus engines, as do light-heavy duty vehicles. Although some manufacturers would have to develop two engine versions for line-haul and medium-heavy use, this is commonly done in any case due to the differences in torque curves and driveability requirements. The proposed implementation of the line-haul exemption on a <u>case-by-case basis would also</u> reduce <u>administrative and inventory problems</u>

with the two engine versions, since engines built to the more lenient standard would presumably need to be special-ordered by the holder of the exemption.

Tampering

The report suggests that tampering with trap-oxidizers and engine-out NOx controls is likely to be especially prevalent in the line-haul class, and less of a problem in the medium-heavy, transit-bus, and light-heavy classes. Several reviewers took issue with this, arguing that the desire for an economical and reliable vehicle is not limited to the line-haul class, and that tampering would thus probably be common in the other classes as well.

This argument ignores the special sociology and economics of line-haul trucking. Most medium-heavy and light-heavy trucks are owned by commercial operations whose major business is not trucking — e.g. utilities, stores, tradesmen, etc. Trucking costs are generally a minor factor in their overall costs, and thus a small increase in these costs is not of major concern. Such organizations, since their trucking operations are generally local to their area of business, are also more concerned about public relations and public image, both of which could be expected to suffer if their illegal tampering became known.

Line-haul trucking, on the other hand, is dominated by individuals and fleets for which trucking is the major or the only business, and the cost of operating the trucks their major operating expense. Under these circumstances, even a small increase in cost per mile may become significant enough to prompt illegal action. The sociology of the industry, which is characterized by extreme independence and distrust of government regulation (as well as active defiance of troublesome laws such as speed limits) would also tend to promote such actions. For this reason, the authors consider tampering and similar activities to be a much more severe problem in the line-haul class than in others.

Electronic Controls

The draft report contained a rather optimistic assessment of the potential of electronic control systems for improvements in emissions, fuel-economy, and driveability. Most of the reviewers felt that the assessment overstated the potential benefits of electronics, and several expressed doubts that electronic controls would offer any significant emissions benefits at all. On the basis of additional research in the area and new information, we consider the first point to be well taken, and have revised the discussion of electronics accordingly. However, we still expect significant and important benefits from their use. These benefits would be especially marked at low NOx levels, since precise timing and optimization become increasing important as timing is retarded. In the light of the confidential data available to us, and of the startling results in light-duty emissions control via electronics that have been reported in the literature, we do not believe that the doubter's position (that electronics will offer no significant benefits) can be supported.

Trap-Oxidizers

Several reviewers objected to the report's characterization of light-duty trap-oxidizer technology as "well-developed", and expressed doubt that trap-oxidizers for either light or heavy-duty vehicles could be feasible any time in the foreseeable future. Some reviewers also commented that the assessment of the Daimler-Benz "candle" trap was overly optimistic, and that the cost estimates for ceramic monolith traps were much lower than prices indicated by the trap's suppliers.

With regard to the first two points, the authors feel that developments since the completion of the draft report have only tended to confirm their assessments. As of this writing, one light-duty manufacturer (Mercedes) is presently selling trap-oxidizer equipped vehicles in California, and several other manufacturers are expected to introduce such systems in 1986 or 1987. We believe it is thus fair to characterize the technology as "well-developed". Our assessment of the Daimler-Benz trap-oxidizer system for heavy-duty vehicles has also been confirmed by Daimler-Benz itself. In testimony before the EPA, a Daimler-Benz spokesman stated that Daimler is "confident" that the system described could be in production by 1990.

The authors' estimates of trap-oxidizer prices are apparently much lower than those being quoted now by trap manufacturers (the reviewers cited figures of up to $1,000 for traps for a line-haul truck). However, except in light-duty vehicles, trap-oxidizers are not yet in mass production, and thus costs could be expected to be higher. There is probably also a large premium being charged for the supplier's RD and engineering support. The report's estimates are for traps in large-volume production, for which the economics would be very different. Considering the comparatively low prices of similar components such as catalytic converter substrates, the authors do not feel that prices as high as those indicated by the reviewers can long exist in a competitive market under mass production.

Special Treatment for Light-Heavy Duty Engines The draft report had recommended not only earlier but also more stringent emissions standards for light-heavy duty engines, on the grounds that the IDI engines used in this class are inherently cleaner than the larger DI engines. Several reviewers objected to this recommendation. The objections were based on two premises: first, that the establishment of the suggested standards would eliminate the small DI engines now being introduced into the light-heavy duty class; and second, that IDI engines are not, in fact, inherently cleaner than DI engines, and thus could not comply with a more stringent standard.

Both of these points have merit — the standards proposed in the draft report would effectively have eliminated DI engines from the light-heavy class, with a consequent loss in fuel economy. Additional data on the emissions capabilities of IDI engines also indicate that their advantage over DI engines may be less than we had estimated, and that very advanced DI engines might be able to attain the same emissions levels as the best IDI's. We have modified the relevant sections of the report accordingly, and are no longer recommending a more stringent numerical standard in the light-heavy class. Because of the technology similarity between light-heavy and light-duty engines and vehicles, however, we still believe that light-duty emissions control technology could be adapted to this class, and thus that these vehicles would be capable of complying with a given emissions standard several years before any of the heavier classes.

One commenter also expressed the opinion that operation patterns in the light-heavy class are not in fact very similar to those of light-duty trucks, and thus that adaptation of light-duty technology would not be straightforward. This opinion was not supported by any data, however, nor are the authors aware of any but impressionistic data bearing on the question of light-heavy duty use patterns. Examination of the operating characteristics for light-duty trucks, however, indicates that a substantial fraction of them operate at least occasionally in the kind of fully-loaded, cargo-hauling mode which is said to be typical of light-heavy operation, and thus that any feasible emissions control systems for these trucks would need to be able to cope with such operation. For this reason, we consider that any adaptations required to convert feasible light-duty technology to light-heavy use would be minor ones of degree, rather than kind, and that the required lead-time would thus be short.

Definition of Feasible Standards

Several commenters objected to the report's estimates of the low-mileage emissions levels attainable, and to the estimates of achievable standards derived from these. These commenters generally made two points: that the emissions levels shown were over-optimistic, and that they were "speculative" (i.e. not based on demonstrated technologies), and should thus be discounted.

We consider the second point to be without merit — for any emissions standard to be technology-forcing requires that it be set lower than the level that can be achieved with demonstrated technology. Estimating the emissions levels attainable with such a standard will thus always require "speculation". The issue of over-optimism is more debatable. However, this is basically a matter of engineering judgement, and such judgements can be verified only by the test of time. We believe that the estimates shown fairly reflect the potential for emissions control in heavy-duty engines, and We are encouraged in our position by the fact that General Motors (1984b) has apparently arrived at very similar estimates of achievable engine-out particulate levels at moderate NOx. We acknowledge, however, the speculative nature of the estimates given, especially for the intermediate term, and have emphasized the need for additional study in the report.

Sulfur Effects in Diesel Fuel One commenter suggested making extensive revisions to the sections dealing with fuel quality to reflect our newly-developed understanding of the effect of sulfur in fuels on particulates. On the basis of our review of the issues and of the new data available (notably Chevron, 1984 and CARB, 1984) we agree with this suggestion, and we have modified the relevant sections extensively as a result.

Cost and Supply Effect of Diesel-Fuel Standards

The draft report suggested that EPA further investigate setting standards for minimum cetane and/or maximum aromatic content in diesel fuel, as well as possible limits on its sulfur content. Several reviewers apparently interpreted this as recommending such standards, and stated that the report should have addressed the effects of such standards on the costs and supply of diesel fuel. The draft report had stated that such standards would reduce the supply and increase the cost of the fuel, but no quantitative estimates of these effects were available. The subsequent appearance of the CARB study (CARB, 1984) provided some useful order-of-magnitude data, which are cited in the final report.

The draft report had suggested a minimum cetane number of 44, and a maximum aromatic content of 30 percent as a suitable fuel-quality standard. One reviewer objected to these limits, suggesting values of 40 cetane and 40 percent aromatics instead. Subsequent data on the distribution of quality indices in current diesel fuels (Pless, 1984) led to a compromise suggestion of 42 cetane and 35 percent aromatics in the final report.

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APPENDIX C: ORGANIZATIONS CONTACTED

California Air Resources Board
Caterpillar Tractor Company
Chevron Research Corporation
Corning Glassworks
Cummins Engine Company
Detroit Diesel Allison Division of General Motors
Ford Motor Company
Freightliner Corporation
International Harvester
IVECO
Johnson-Matthey, Inc.
Lubrizol Corporation
Mack Trucks
Mercedes-Benz of America
Ontario Research Institute
Renault
Southwest Research Institute
U.S. EPA Office of Mobile Source Emissions
Volkswagen
Volvo-White Trucks