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Estimated Economic Impact of New Emission Standards for Heavy-Duty On-Highway Engines

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Estimated Economic Impact of New Emission Standards for Heavy-Duty On-Highway Engines

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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TABLE OF CONTENTS

SECTION 1 INTRODUCTION 1-1

SECTION 2 COST METHODOLOGY 2-1

SECTION 3 BASELINE 1998 TECHNOLOGY ASSUMPTIONS 3-1

3.1 LIGHT HEAVY-DUTY DIESEL ENGINES 3-2
3.2 MEDIUM HEAVY-DUTY DIESEL ENGINES 3-2
3.3 HEAVY HEAVY-DUTY DIESEL ENGINES 3-3
3.4 URBAN BUSES 3-3
3.5 LIGHT HEAVY-DUTY GASOLINE ENGINES 3-3
3.6 HEAVY HEAVY-DUTY GASOLINE ENGINES 3-4

SECTION 4 DIESEL ENGINE TECHNOLOGY PROJECTIONS 4-1

4.1 IMPROVED FUEL INJECTION 4-1

4.1.1 Electronic Unit Injection 4-1
4.1.2 Improved Injector Nozzles 4-8
4.1.3 Rate Shaping and Multiple Injections 4-8

4.2 COMBUSTION CHAMBER MODIFICATIONS 4-9

4.2.1 Compression Ratio Increases 4-10
4.2.2 Piston Bowl Shape 4-11
4.2.3 Four Valves Per Cylinder 4-12
4.2.4 Reduced Oil Consumption 4-12

4.3 EXHAUST GAS RECIRCULATION 4-12
4.4 TURBOCHARGER IMPROVEMENTS 4-16

4.4.1 Variable Geometry Turbochargers 4-18
4.4.2 Other Turbocharger Improvements 4-21

4.5 AFTERCOOLER IMPROVEMENTS 4-21
4.6 OXIDATION CATALYSTS 4-22
4.7 LEAN NO_x CATALYSTS 4-23
4.8 SELF-REGENERATING PARTICULATE TRAPS 4-25
4.9 CLOSED CRANKCASE 4-27

TABLE OF CONTENTS (CONTINUED)

SECTION 5 DIESEL ENGINE TECHNOLOGY COSTS 5-1

5.1 FUEL SYSTEM UPGRADES 5-1

5.1.1 Cam-driven EUI 5-1
5.1.2 Common Rail Injection Systems 5-3

5.2 COMBUSTION CHAMBER UPGRADES 5-5

5.2.1 Two Valves to Four Valves 5-6
5.2.2 Variable Valve Timing 5-6
5.2.3 Improved Oil Control 5-8
5.2.4 Combustion Chamber Optimization 5-9

5.3 EXHAUST GAS RECIRCULATION 5-10

5.3.1 Internal EGR 5-11
5.3.2 Hot EGR 5-11
5.3.3 Cooled EGR 5-12

5.4 TURBOCHARGER UPGRADES 5-16

5.4.1 Variable Geometry Turbochargers 5-18
5.4.2 Improved Wastegate Control 5-20

5.5 ADVANCED OXIDATION CATALYSTS 5-20
5.6 LEAN NO_x CATALYSTS 5-22
5.7 CONTINUOUSLY REGENERATING TRAPS 5-24
5.8 CLOSED CRANKCASE SYSTEMS 5-26

SECTION 6 GASOLINE ENGINE TECHNOLOGY PROJECTIONS 6-1

6.1 COMBUSTION CHAMBER IMPROVEMENTS 6-2
6.2 FUEL INJECTION IMPROVEMENTS 6-4
6.3 IGNITION (SPARK) TIMING IMPROVEMENTS 6-5
6.4 EXHAUST GAS RECIRCULATION IMPROVEMENTS 6-6
6.5 ELECTRONIC CONTROL WITH ADAPTIVE LEARNING 6-9
6.6 CATALYTIC CONVERTER IMPROVEMENTS 6-12

SECTION 7 GASOLINE ENGINE TECHNOLOGY COSTS 7-1

7.1 IMPROVED COMBUSTION CHAMBER AND FUEL INJECTION 7-1

7.2 IMPROVED ELECTRONIC CONTROL 7-2

TABLE OF CONTENTS (CONCLUDED)

7.3 ELECTRONIC EGR 7-2
7.4 IMPROVED SPARK TIMING 7-4
7.5 IMPROVED CATALYSTS 7-5
7.6 SYSTEM CALIBRATION 7-5

SECTION 8 ADVANCED 2004 TECHNOLOGY TRENDS 8-1

8.1 LIGHT HEAVY-DUTY DIESEL ENGINES 8-1
8.2 MEDIUM HEAVY-DUTY DIESEL ENGINES 8-3
8.3 HEAVY HEAVY-DUTY DIESEL ENGINES 8-3
8.4 URBAN BUSES 8-5
8.5 LIGHT HEAVY-DUTY GASOLINE ENGINES 8-5
8.6 HEAVY HEAVY-DUTY GASOLINE ENGINES 8-6

REFERENCES R-1

APPENDIX A — COST ANALYSIS DETAILS A-1

LIST OF ILLUSTRATIONS

Figure 4-1 DDC electronic unit injector 4-2

Figure 4-2 Bosch cam-driven electronic unit injectors 4-3

Figure 4-3 Schematic diagram of Nippondenso's ECD-U2 system 4-4

Figure 4-4 ECU-U2 system components 4-5

Figure 4-5 HEUI system components 4-6

Figure 4-6 Schematic diagram of HEUI system components 4-6

Figure 4-7 HEUI cross section 4-7

Figure 4-8 Comparison of SAC and VCO type nozzles 4-8

Figure 4-9 HEUI rate shaping device 4-10

Figure 4-10 Piston bowl designs 4-11

Figure 4-11 Schematic of hot EGR system 4-14

Figure 4-12 Schematic of a cooled EGR system 4-15

Figure 4-13 Schematic of an electronic EGR system 4-17

Figure 4-14 Garrett VNT-45 turbine housing assembly 4-18

Figure 4-15 Honda wing turbo 4-19

Figure 4-16 Wing turbo control system 4-20

Figure 4-17 Holset moveable shroud VGT 4-20

Figure 4-18 Caterpillar 3406B air-to-air aftercooled engine 4-22

Figure 4-19 Johnson Matthey's continuous regenerative trap 4-26

Figure 6-1 Schematic showing the different crevice volumes 6-3

Figure 6-2 Schematic of an electronic fuel injection system 6-5

Figure 6-3 Distributorless ignition system schematic for V-10 engine 6-6

LIST OF ILLUSTRATIONS (CONCLUDED)

Figure 6-4 An electronic EGR system schematic and valve 6-8

Figure 6-5 Electronic control unit schematic 6-10

Figure 6-6 Cross-section view of an oxygen sensor 6-11

Figure 6-7 Oxygen sensor placement configurations 6-12

LIST OF TABLES

Table 1-1 On-highway engine categories 1-2

Table 2-1 On-highway heavy-duty engine assumptions 2-2

Table 2-2 Mileage accumulation rates for heavy-duty diesel vehicles (miles per year) . . 2-3

Table 5-1 Incremental cost for improved cam-driven EUI fuel systems 5-3

Table 5-2 Incremental cost for HEUI systems 5-5

Table 5-3 Incremental cost for 4-valve medium heavy-duty engines 5-7

Table 5-4 Incremental cost for variable valve timing 5-8

Table 5-5 Incremental cost for oil control 5-9

Table 5-6 Incremental cost for combustion optimization 5-10

Table 5-7 Incremental life-cycle cost for hot EGR systems 5-13

Table 5-8 Incremental life-cycle cost for low-flow cooled EGR systems 5-15

Table 5-9 Incremental life-cycle cost for high-flow cooled EGR systems 5-17

Table 5-10 Incremental life-cycle costs for variable geometry turbocharger upgrades . . . 5-19

Table 5-11 Incremental life-cycle costs for improved wastegate control 5-21

Table 5-12 Incremental cost for advanced oxidation catalysts 5-23

Table 5-13 Incremental life-cycle costs for lean NO_x catalysts 5-25

Table 5-14 Incremental life-cycle costs for particulate trap catalyst 5-27

Table 5-15 Incremental life-cycle costs for crankcase systems 5-29

Table 7-1 Incremental costs for three-way catalysts 7-6

Table 8-1 Likely technologies for diesel engine control 8-2

Table 8-2 Likely technologies for gasoline engine control 8-2

SECTION 1
INTRODUCTION

In July of 1995, members of the Engine Manufacturers Association (EMA) signed a joint Statement of Principles (SOP) with the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) to further reduce emissions from heavy-duty engines below the standards which will go into effect in 1998. The oxides of nitrogen (NO_x) emission levels from heavy-duty engines used in vehicles over 8,500 pounds (lbs) gross vehicle weight (GVW) will drop from the current level of 5.0 grams per brake horsepower-hour (g/bhp-hr) to 4.0 g/bhp-hr in 1998. The SOP proposes that engine manufacturers meet a combined standard of 2.4 g/bhp-hr for non-methane hydrocarbon (NMHC) and NO_x emissions by 2004.

To reach these low NO_x levels and keep particulate matter (PM) emissions at the current levels (0.1 g/bhp-hr for trucks, 0.05 g/bhp-hr for urban buses) or lower, manufacturers will look to combinations of reoptimized combustion chambers, fuel systems, air handling systems, electronic controls and aftertreatment. While manufacturers suggest that the SOP goals of 2.4 g/bhp-hr NO_x plus NMHC at current PM levels will not be easy to meet, they agree that these goals are possible to meet by 2004. The methods that they might use to reach the SOP goals are the content of this report.

Descriptions of technologies and costs of technologies to meet the proposed 2.4 g/bhp-hr NO_x plus NMHC standards were obtained through candid conversations with heavy-duty engine manufacturers, equipment manufacturers, manufacturers associations, research organizations, and various publications. We used this information to present a coherent set of likely technologies for meeting these future standards. When information was not provided or only partially provided, engineering and economic judgement was used to provide additional details. As most of the information was gathered through confidential conversations with engine manufacturers and equipment suppliers, average costs were used to develop costs for technologies without reference to specific manufacturers.

In Section 2 of this report, the cost methodology used in determining the incremental costs of various technologies is described. Section 3 of this report discusses what technologies engine manufacturers might use to meet the 1998 standard of 4.0 g/bhp-hr NO_x for light, medium and heavy heavy-duty diesel engines, diesel urban bus engines, and light and heavy heavy-duty gasoline engines. These vehicle categories, associated vehicle class and gross vehicle weight ratings are shown in Table 1-1.

Sections 4 and 5 provide technology and cost descriptions, respectively, of various components that could be used to meet the SOP goals for heavy-duty diesel engines. Sections 6 and 7 provide technology and cost descriptions, respectively, of various components that could be used to meet advanced standards for heavy-duty gasoline engines.

The final section discusses what technologies engine manufacturers might use to meet the proposed 2004 standard of 2.4 g/bhp-hr NO_x plus NMHC for the various categories of diesel and gasoline engines, summarizing the findings of Sections 4 and 6.

Table 1On-highway engine categories

Fuel	Category	Vehicle Class	Gross Vehicle Weight Rating (lbs)
Diesel	Light	2B — 5	8,500 — 19,500
Diesel	Medium	6 — 7	19,501 — 33,000
Diesel	Heavy	8	33,000 +
Diesel	Urban Bus	Urban Bus	—
Gasoline	Light	2B — 3	8,500 — 14,000
Gasoline	Heavy	4 — 8	14,000 +

SECTION 2
COST METHODOLOGY

In determining the costs of complying with the proposed 2004 emission standards, one must look at the differential costs between engines produced to meet the 1998 4.0 g/bhp-hr NO_x standard and those to meet the proposed 2004 2.4 g/bhp-hr NO_x plus NMHC standard. In developing these cost estimates, the life-cycle cost of compliance for an "average" engine was used for each of the engine category. The incremental life-cycle cost of compliance include: manufacturer's variable costs (for components, assembly labor and labor overhead), manufacturers's fixed costs (for research & development and tooling), and consumer operating and maintenance costs. Incremental costs for each technology are detailed in Section 5 for diesel engine components and Section 7 for gasoline engine components. Incremental costs were based upon the cost increment from engines meeting the 1998 standard and those meeting the proposed 2.4 g/bhp-hr NO_x plus NMHC standard.

In developing the cost estimates, average engine parameters were used for each engine category. Those assumptions are shown in Table 2-1. Production volumes are given in engines produced per engine line per year and were taken from average 1994 sales figures. A typical engine manufacturer may have one to three engine lines within a given weight class. In this report, the light heavy-duty gasoline and diesel category includes only engines certified to an engine standard.[1]

Assembler labor rates were obtained from U.S. Department of Labor (DOL) statistics for the Michigan and Midwest regions [1][2] and inflated to 1995 dollars using DOL labor cost indices [2]. Based upon this information, labor rates used in this report are $17.50 per hour plus a 60 percent fringe rate providing a cost of direct labor of $28 per hour.

All real costs calculated in this report are in 1995 dollars with future costs discounted at

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1 Manufacturers of complete vehicles with a GVWR of 8,500 to 10,000 pounds (Class 2B) have the option to certify these vehicles as light-duty trucks rather than certifying just the engine. These engines have not been included in this report.

2 Numbers in brackets refer to references at the end of the report.

Table 2 On-highway heavy-duty engine assumptions

Fuel	Heavy-Duty Category	Cylinders	Displacement (l)	Lifetime Mileage	Lifetime Years	Production Volume[a]	Fuel Economy (mpg)
Diesel	Light	8	6	145,000	10	75,000	14
Diesel	Medium	6	8	280,000	13	30,000	10
Diesel	Heavy	6	13	560,000	12	26,000	6
Diesel	Urban Bus	4	9	513,000	15	4,000	4
Gasoline	Light	8	6	145,000	11	55,000	10
Gasoline	Heavy	8	7.5	145,000	11	15,000	6

[a]Production volumes represent yearly production volumes of one typical engine line for a typical manufacturer

7 percent per annum.[3] R&D costs are expected to occur over a three year period ending one year prior to engine production. Tooling costs are expected to occur one year prior to engine production. Both R&D and tooling costs are expected to be recovered over the first five years of engine sales. Cost of money was assumed to be 7 percent per annum for these calculations.

Fuel prices for life cycle cost calculations were taken from a U.S. Department of Energy publication, *Petroleum Marketing Monthly*, July 1995, and represent average fuel prices throughout the United States with taxes. All future operating costs were calculated based upon the mileage accumulation rates shown in Table 2-2, which are consistent with those used in EPA's emissions factor model MOBILE5a.

In most cases, component costs were built up from incremental costs using the Retail Price Equivalent formula. The basic formula used for Retail Price Equivalent (RPE) in this analysis is shown below:

$$RPE = \{[DM + DL + LO] \times [1 + SO + SP]\} \times \{1 + MO + MP + DO + DP\} + R\&D + TE$$

[3] EPA and the Office of Management and Budget recommend 7 percent per annum for manufacturer fixed costs. The authors consider this rate also appropriate for truck and engine purchasers because of their investment opportunities as businesses.

where:

DM = Direct Materials

DL = Direct Labor

LO = Labor Overhead

SO = Supplier Overhead

SP = Supplier Profit

MO = Manufacturer Overhead

MP = Manufacturer Profit

DO = Dealer Overhead

DP = Dealer Profit

R&D = Research & Development

TE = Tooling Expenses

Labor overhead in these analyses is assumed to be 40 percent of the cost of direct labor as cited in Lindgren [3]. Manufacturer overhead, manufacturer profit, dealer overhead and dealer profit, when added together, are assumed to be 29 percent as cited by Jack Faucett Associates [4].

Table 3 Mileage accumulation rates for heavy-duty diesel vehicles (miles per year)

Vehicle Age	Heavy-Duty Engine Category			
	Light	Medium	Heavy	Bus
1	22,517	26,081	62,176	34,200
2	20,009	25,204	58,663	34,200
3	17,779	24,357	55,348	34,200
4	15,798	23,538	52,220	34,200
5	14,038	22,746	49,269	34,200
6	12,474	21,982	46,485	34,200
7	11,084	21,243	43,858	34,200
8	9,849	20,528	41,380	34,200
9	8,752	19,838	39,042	34,200
10	7,777	19,171	36,836	34,200
11	4,923	18,527	34,754	34,200
12		17,904	32,790	34,200
13		17,302	7,179	34,200
14		1,579		34,200
15				34,200
Total	145,000	280,000	560,000	513,000

We have also used a 29% mark-up for supplier overhead and profit where applicable. For parts supplied by suppliers (where *DM* and *DL* are supplier direct materials and direct labor), the following formula is used:

$$RPE = \{[DM + DL \ x \ 1.4] \ x \ 1.29 \ \} \ x \ 1.29 + R\&D + TE$$

Where the manufacturer builds the parts or the part costs are given in terms of manufacturer costs, the formula becomes:

$$RPE = \{[DM + DL \ x \ 1.4]\} \ x \ 1.29 + R\&D + TE$$

In this variation, *DM* is assumed to be material costs of parts to engine manufacturers and *DL* is engine manufacturer direct labor.

Where little description of new technologies existed, engineering judgement was used. Information obtained from manufacturers was used to bracket developed costs. In most cases, development costs were developed by estimating component costs then comparing the total costs to cost increases cited by the manufacturers and suppliers between current and future technologies.

The estimates presented in this report represent costs in the first year of production of new or improved components. Production costs related to direct and indirect labor are likely to fall in subsequent years, as workers gain skill, develop shortcuts, and improve the flow of tasks. Costs for materials are also likely to decline over time (though not as rapidly as labor costs), as methods for reducing waste are developed. The phenomenon of falling production costs over time was originally identified in aircraft production, and has since been observed in a wide variety of industries. Research into this phenomenon has found strikingly stable relationships between cumulative output and average labor and material costs. Each doubling of cumulative output appear to result in a nearly fixed percentage reduction in a given average costs. Graphs of these relationships have come to be known as "learning curves" or "progress curves." Thus, if a longer time horizon is considered as the basis for estimating per-unit costs for emissions control hardware, the average costs are likely to be significantly lower than those presented here [5-16].

SECTION 3
BASELINE 1998 TECHNOLOGY ASSUMPTIONS

With 1998 just on the horizon, manufacturers are beginning to tool up for their new generation of engines capable of producing less than 4.0 g/bhp-hr NO_x. Manufacturers are improving some engine families, scrapping others and introducing new ones. The higher emitting 2-stroke engines are being phased out and the cleaner 4-stroke engines will define the on-highway heavy-duty engine market in the United States. Very few mechanically-injected engines will survive past 1998 due to fuel economy and diagnostic improvements that customers are beginning to expect with electronically-controlled engines. The manufacturers will use improved fuel injection and control together with combustion chamber modifications to reach the 4.0 g/bhp-hr NO_x standard. By using electronic fuel injection systems on their engines, manufacturers expect not to need oxidation catalysts on any engines except urban buses, which must certify to lower particulate standards than other heavy-duty vehicles. Engineering design goals will most likely require engines to produce 3.7 g/bhp-hr NO_x or less and 0.07 g/bhp-hr PM[4] to maintain emissions system durability over the useful life of the engine.

The following subsections will describe the technologies that manufacturers will use in the various categories of engines to meet the 1998 standard.

3.1 LIGHT HEAVY-DUTY DIESEL ENGINES

Better electronic control, improved fuel injection, better air handling and modified combustion chamber design will be what manufacturers use to meet the reduced NO_x standard for engines in this category. The DI engines will utilize high pressure electronic unit injection with some using the newly developed Hydraulic-actuated Electronically-controlled Unit Injectors (HEUI). This latter system provides fuel injection relatively independent of engine speed and also provides rate shaping for improved emissions and fuel economy. Electronic control of fuel injection will become more advanced using upgraded control algorithms and computer systems. Catalysts may

[4] Urban buses will most likely have engineering design goals of 0.035 g/bhp-hr PM to meet the lower urban bus particulate standard.

be used to reduce particulates since typical light heavy-duty diesel engine (LHDDE) particulates are higher in soluble organic faction (SOF) than heavier engines, but manufacturers will strive not to use them. However, some of the higher-emitting engines that survive into 1998 might use newly designed catalysts with good SOF reduction efficiency and low sulfate formation properties.

The LHDDE market includes both indirect injection (IDI) and direct injection (DI) engines. GM is currently producing an IDI engine in this class which meets the 1998 standard. IDI engines produce lower NO_x emissions and are more tolerant of exhaust gas recirculation for NO_x control. However, IDI diesel engines are less fuel efficient than DI diesel engines (but still more efficient that gasoline engines of similar power rating).

3.2 MEDIUM HEAVY-DUTY DIESEL ENGINES

Medium heavy-duty diesel engines (MHDDEs) have also shown improvements over the last few years. While many mechanical injection engines met 1994 emissions standards with catalytic aftertreatment, MHDDE manufacturers will most likely move to electronic control on all of their on-highway engine lines to meet 1998 standards. Electronic fuel injection options include high pressure electronic unit injectors and common rail injectors as well as electronic unit pump and electronic distributor pump systems. The HEUI system and systems like it will be prevalent on these engines, giving better fuel injection control and some modest rate shaping. Engines will receive some changes in combustion chamber and fuel system design, and more precise tuning will be possible by using more sophisticated electronic control. Catalysts may be used on a small segment of this market to control particulates while NO_x emissions are reduced, but manufacturers will aspire to meet this standard without them.

3.3 HEAVY HEAVY-DUTY DIESEL ENGINES

Heavy heavy-duty diesel engines (HHDDEs) will all be electronically controlled with electronic unit injection systems capable of high injection pressures (25,000+ psi). Further optimization of combustion chamber parameters such as air flow, swirl, piston bowl shape, oil control and injection spray pattern will occur on these engines enabling them to meet the 4.0 g/bhp-hr NO_x standard. In some engines, injector rate shaping or split injection might be used. These engines usually have cylinder liners, better ring packs, better oil control and lower surface-to-volume ratios than the lighter engines and thus have less SOFs in their particulate emissions. For this reason, oxidation catalysts are less effective in particulate reduction for this class of engine and most likely will not be used. Particulate control in this engine class will most likely come from improvements in air and fuel handling systems such as higher pressure injection and better turbocharger matching.

3.4 URBAN BUSES

Urban bus engines (UBEs) will follow the development of the heavy heavy-duty engines, but will most likely require catalysts for additional particulate emission reduction since they must meet a 0.05 g/bhp-hr PM standard.

3.5 LIGHT HEAVY-DUTY GASOLINE ENGINES

Due to the use of three-way catalysts and sequential multi-port fuel injection systems with closed loop control, light heavy-duty gasoline engines (LHDGEs) are already below the 1998 standard and close to meeting the proposed 2004 standard. In the last few years, gasoline engine manufacturers have learned to make three-way catalyst systems durable and effective for this class by using higher temperature catalytic materials, better fuel control and combustion chamber improvements. High turbulence heads, better matching of air flow and EGR between cylinders, better air/fuel ratio control and improved three-way catalysts have produced 1996 certified emission levels that approach or meet the proposed 2004 standard.

3.6 HEAVY HEAVY-DUTY GASOLINE ENGINES

Emissions reductions in heavy heavy-duty gasoline engines (HHDGEs) have lagged behind the lighter category. Some of the 1994 engines in this class still use carburetors or throttle-body fuel injection systems and oxidation catalysts. Manufacturers are moving to multi-port fuel injection systems with better air-fuel control to minimize fuel rich operation and thereby limit catalyst degradation. In addition, manufacturers are currently working with higher temperature palladium-only and tri-metal three-way catalysts to improve catalyst conversion efficiencies and durability. Better combustion chamber and intake manifold design will also occur in the next few years on this class of engine.

SECTION 4

DIESEL ENGINE TECHNOLOGY PROJECTIONS

Achieving low NO_x and PM emissions simultaneously presents the diesel engine manufacturer with a large challenge. Some of the more effective strategies to reduce NO_x emissions tend to increase PM emissions and vice-versa. While manufacturers will try to utilize technologies that have a "flatter" NO_x versus PM curve, reaching low NO_x emissions while keeping PM emissions low will require a combination of technologies. Likely technologies that might be used to meet the proposed 2.4 g/bhp-hr NO_x plus NMHC emissions standard for diesel engines are discussed below. Costs of these technologies are discussed in Section 5.

4.1 IMPROVED FUEL INJECTION

Fuel injection parameters have a dramatic impact on the nature of combustion in diesel engines. Injection timing, pressure, duration, and rate, as well as nozzle configuration and design determine events such as ignition delay and combustion rate through their effect on air-fuel mixing. Consequently, engine manufacturers will continue to focus on fuel injection in an effort to reduce emissions and improve engine performance. Among the more recent advances in fuel injection technology are the development of the electronic unit injection and common rail injection systems, and the use of rate shaping or multiple injections. Further optimization of injector nozzle designs is also being pursued.

4.1.1 Electronic Unit Injection

Electronic unit injection (EUI) offers benefits over even advanced pump-line-nozzle fuel injection systems due to the ability to achieve high injection pressures and to specify parameters such as start of injection and injection duration at different engine loads and speeds. The high injection pressure is beneficial because it aids in fuel atomization in the combustion chamber and reduces PM emissions. Several engine manufacturers already employ electronic unit injection in their 1994 engines, and as discussed in Section 3, use of EUI will increase substantially with the 1998 model year. It is expected that EUI will be widespread in most HDDEs by 2004. Different types of EUI systems are discussed below.

4.1.1.1 Cam-Driven Electronic Unit Injection

A cross-section of DDC's electronic unit injector is shown in Figure 4-1. It employs a cam-driven plunger in conjunction with a high-pressure solenoid valve. The solenoid valve opens and closes a passage allowing fuel to escape from the injector body. To begin injection, the solenoid valve is closed and fuel pressure in the injector rises in response to the plunger movement (the start of injection must occur during the period when the cam drives the plunger downward). The fuel in the injector is quickly (within 1 msec) pressurized to the point where it is forced through the injector nozzle. Injection is stopped by opening the solenoid valve, thereby causing a fuel pressure drop in the injector. As the plunger returns to the top position, fuel is replenished in the injector via an inlet port on the side of the injector.

Bosch has developed a similar type of cam-driven electronic unit injector, shown in Figure 4-2. The Bosch injectors operate under the same principle as the DDC injector, with the notable exception that fuel is replenished through the solenoid valve. Electronic controls are used to energize the solenoid valve based on driver input and information provided by sensors for RPM, boost pressure, coolant temperature, etc. Both types of these electronic unit injectors are best suited for engines having four valves per cylinder as this allows for vertical mounting of the injector in the center of the cylinder. Both types of injectors can provide injection pressures as high as 28,000 psi.

4.1.1.2 Common Rail Electronic Unit Injection

High fuel injection pressures can also be implemented by using a so-called "common rail" system. "Common rail" refers to a reservoir of high pressure fuel which is made available to each unit injector, or alternatively to a rail of high pressure oil which is used to actuate the injectors. An example of the first of these types of common rail systems is Nippondenso's ECD-U2 system shown in Figure 4-3. Fuel injection is controlled by an electronic three-way valve (TWV). Injection begins when the TWV is switched such that the pressure above the hydraulic piston changes from the common rail pressure to the leakage, or atmospheric pressure. This quick pressure drop lifts the hydraulic piston, which is connected to the injector needle, and the high pressure fuel is released into the combustion chamber through the nozzle. The quantity of fuel injected is based upon the pulse width sent to the TWV by the electronic control unit. Components of the ECD-U2 system are shown in Figure 4-4.

Developed by Caterpillar and Navistar through a joint development agreement, the Hydraulically-actuated Electronically-controlled Unit Injection (HEUI) system utilizes a common rail of pressurized oil and provides high injection pressures throughout an engine's entire speed-load range. The system is relatively independent of speed, and offers full electronic control of injection timing and duration, along with the possibility for rate shaping via a spill control device designed into the fuel injector.

The HEUI system is comprised of six main components: (1) a high pressure oil pump, (2) a rail pressure control valve (RPCV), (3) the hydraulic unit injectors, (4) sensors (for speed/timing, oil temperature, inlet manifold air pressure, and rail oil pressure), (5) an electronic control module (ECM), and (6) a fuel transfer pump. These components are shown in Figure 4-5; a schematic of the system configuration is illustrated in Figure 4-6.

The injector itself consists of a solenoid-driven control valve, an intensifier plunger and barrel, and the fuel injector nozzle (see Figure 4-7). To initiate a fuel injection event, the solenoid is energized by the ECM, which moves the control valve (upward in the figure) and allows high pressure oil to enter the passageway above the intensifier. The high pressure oil (at pressures up to 3,000 psi) pushes the 7-to-1 intensifier plunger downward, forcing fuel past a ball check valve into the nozzle. The pressurized fuel (as high as 21,000 psi) unseats the nozzle needle from its seat, releasing the fuel into the combustion chamber. When the solenoid is de-energized, the oil pressure inside the injector drops, the intensifier plunger returns to its initial position, and fuel is replenished inside the plunger chamber (downstream of another ball check valve).

Both of the common rail systems described above utilize high pressure pumps that place an increased accessory load on the engine. However, it is believed that combustion improvements resulting from the implementation of higher fuel injection pressures will counter this effect and result in no net change in brake specific fuel consumption (BSFC).

4.1.2 Improved Injector Nozzles

The injector nozzle itself significantly affects the delivery of fuel into the combustion chamber and can have a major impact on air-fuel mixing and thus emissions. Nozzle hole diameters must be optimized to provide the proper spray and amount of fuel atomization. The number of nozzle holes should be matched with the fuel injection pressure and combustion chamber geometry to provide the best air utilization. Other optimization parameters include nozzle position and spray cone angle.

In sac type nozzles, minimizing the sac volume is critical to reduce leakage of fuel droplets into the combustion chamber, which contributes to HC emissions. In this regard, valve-closed orifice (VCO) tips are superior, although this design results in high stresses in the nozzle tip. A comparison of these two types of nozzles is shown in Figure 4-8.

4.1.3 Rate Shaping and Multiple Injections

Because peak combustion temperatures are determined largely by the pre-mixed or rapid combustion phase of diesel combustion, limiting the amount of fuel injected at the beginning of the injection duration (rate shaping) can significantly cut down on NO_x formation. Multiple or split injection can also be utilized to achieve the same result.

Rate shaping or multiple injection can be accomplished by designing the injector with a restrictive device, a retractive device, or a spill control device. Rate shaping is achieved with the HEUI system by means of a spill control port located in the intensifier plunger of the unit injector (the device is called PRIME, which stands for PRe-Injection MEtering). The device, shown in Figure 4-9, controls injection pressure as the intensifier plunger moves downward. Depending on the design of the injector and on the engine operating condition, rate shaping or split injection can be achieved. Similar design features can be used to provide rate shaping or split injection in other common rail systems.

Rate shaping in cam-driven electronic unit injectors can be accomplished through modification of the cam profile. For 2004, it is envisioned that technology advancements will allow full electronic control of rate shaping or multiple injections (e.g., by utilizing advanced fast-response solenoid valves), with parameters being fully controlled with the engine's electronic control module.

4.2 COMBUSTION CHAMBER MODIFICATIONS

Combustion chamber designs have already gone through a significant evolution, but further incremental improvements can still be achieved. Today, engine designers have at their disposal more powerful computers and better computer models to assist them in a design process which involves extensive testing, computer modeling, model validation, extension of predictions, and further testing. Although no breakthrough designs are anticipated, further combustion chamber design optimization, done in concert with modifications to air and fuel management components, can contribute to the emissions reductions required to meet the proposed 2004 standards.

4.2.1 Compression Ratio Increases

Increasing the compression ratio in a diesel engine reduces the ignition delay period, thereby reducing the amount of fuel burned in the premixed region and allowing more injection timing retard to control NO_x emissions. Since raising compression ratio also increases combustion temperature, cold start PM emissions and white smoke are reduced. High compression ratios offer the most emissions reductions at high speed, light load conditions when ignition delay is the longest, and under cold operating conditions. In both cases, major reductions in HC emissions are achieved.

Several methods can be employed to increase the compression ratio in an existing diesel engine. Redesign of the piston crown, increasing the length of the connecting rod, or increasing the distance between the piston pin and crown will raise the compression ratio of an engine. Higher compression rations can also be accomplished by modification to the cylinder head, although this would likely be done only in combination with a cylinder head redesign for other purposes (e.g., to accommodate unit injectors or four valves per cylinder).

4.2.2 Piston Bowl Shape

The shape of the piston bowl in direct-injected diesel engines is critical to air-fuel mixing. In recent years, engine manufacturers have employed so-called "reentrant" piston bowl designs that generate increased swirl to promote better mixing of air and fuel before the start of combustion (see Figure 4-10). Because higher pressure injection systems usually allow for proper air-fuel mixing without turbulent in-cylinder charge air motion, such piston bowls are most often used with lower pressure injection systems. Reentrant piston bowl designs can be further optimized by modifying the radius of the combustion bowl, the angle of the reentrant lip, and the ratio of the bowl diameter to bowl depth. The location of the center of the combustion bowl with respect to the center of the cylinder bore can also significantly affect combustion. Bowl design must be carefully matched with injector spray pattern and pressure for the optimal emissions behavior.

4.2.3 Four Valves Per Cylinder

All U.S. heavy-duty engine manufacturers already employ four valves per cylinder (2 inlet valves and 2 exhaust valves per cylinder) in their heavy heavy-duty and urban bus diesel engines. Many medium and some light heavy-duty engines also use four valves. The use of four valves can also be used with variable valve timing to improve engine breathing at high loads and increase swirl at low loads. Another advantage of using four valves is that the fuel injector can then be placed in the center of the cylinder bore. Moving to four valves per cylinder requires redesign of engine components such as the cylinder head, valve train (cams, rocker arms, etc.) and intake and exhaust ports. This change does provide emissions benefits, but even without tightening emission standards, it is likely that manufacturers will change additional engine lines to four valves per cylinder for fuel economy and performance reasons alone.

4.2.4 Reduced Oil Consumption

Engine oil left on the cylinder during the expansion stroke, or oil otherwise introduced into the combustion chamber can contribute significantly to engine-out PM emissions. For instance, prior to 1991, soluble oil accounted for about 30 percent of diesel engine PM emissions. Several methods have been utilized to lower oil consumption in diesel engines. Precise bore honing and enhanced ring pack design have been shown to reduce PM emissions, and improvements to other mechanical components such as valve guides and valve guide seals can also play an important role. Engine designers, however, must balance the need to control oil consumption with the need to avoid engine wear from too little oil remaining on cylinder walls.

4.3 EXHAUST GAS RECIRCULATION

Several manufacturers have shown interest in exhaust gas recirculation (EGR), as it provides good NO_x control without serious negative effects on fuel consumption. While there are current prototype EGR systems being tested on engines and in vehicles, some issues still need to be resolved. Depending on flow rate and temperature, EGR can increase PM emissions and BSFC to varying degrees. Cooling of the EGR charge can provide significant PM reductions and some reductions in BSFC over hot EGR. The reentrance of exhaust into the engine cylinder can also cause increased cylinder wear rates at high EGR flow rates, due to deposition of particulates and sulfuric acid on cylinder walls and in the lubricating oil. This latter trend can be reduced, however, through increased oil sump capacities or other approaches.

There are several ways to employ EGR. The simplest method, denoted "Internal EGR," is accomplished through reduction of valve overlap using variable valve timing. The amount of EGR which can be used with this method is limited and in-cylinder charge temperatures will tend to increase. Variable valve timing and control of the valve timing is required for optimum control of Internal EGR.

The second method, denoted "Hot EGR," introduces exhaust from the exhaust manifold upstream of the turbocharger turbine through an electronic EGR valve into the intake manifold downstream of the aftercooler. With this type of system, PM emissions tend to increase as the EGR flow rate increases. The additional exhaust particulates and sulfates recirculated back into the engine might tend to increase engine wear rates at higher EGR flow rates. Limiting EGR rates to not more than eight percent of air flow would keep the potential negative effects to a minimum. Use of cooling fins on the EGR tubing would provide some cooling of the EGR charge and further minimize particulate emissions increases by allowing more air to enter the engine cylinder. A schematic diagram of a system that uses this method is shown in Figure 4-11. By keeping EGR flow rates at less than eight percent of air flow and using it only on low and mid-range speeds and loads, the fuel economy penalty for using EGR is estimated to be 0.5 percent. However, future engines will most likely utilize split injection to minimize NO_x formation and engine noise. Since split injection has been shown to be quite tolerant of EGR, the fuel economy penalty should be nil if the EGR flowrates are kept low.

The third method, denoted "Cooled EGR," ports exhaust gas from the exhaust manifold upstream of the turbocharger turbine through an EGR cooler and back into the intake manifold downstream of the aftercooler. A filter can be used to remove particulates, but manufacturers believe they can overcome wear issues without using such a filter. The EGR cooler is essentially a tube-in-shell heat exchanger. Engine coolant from the engine block travels through the heat exchanger shell while the exhaust gas passes through the tubes within the heat exchanger shell.[5] Low flow EGR systems (estimated as eight percent of air flow at mid load and speed conditions) have heat exchangers that are approximately 6 cm in diameter and 30 to 40 cm in length. These tend to have approximately fifty-five 9 mm diameter tubes within the heat exchanger shell. High flow EGR systems (estimated as fifteen percent of air flow at mid load and speed conditions) tend to be approximately 8 cm in diameter and 30 to 45 cm in length. These heat exchangers can have approximately one hundred 9 mm diameter tubes within the shell. Heat exchanger cores will most likely be stainless steel to minimize corrosion and fouling. Also these coolers will need to be designed to minimize back pressure. By properly sizing the turbocharger and using a wastegate, enough exhaust back pressure can be generated to force enough exhaust gas through the EGR system into the turbo-boosted intake at mid loads and speeds. A schematic of a cooled EGR system is shown in Figure 4-12.

To minimize performance and fuel economy penalties, EGR systems will be designed to apply high EGR rates at idle (40 to 60 percent), medium rates at light loads (20 to 30 percent) and moderate rates at mid speeds and loads (15 percent) for the high flow case. No EGR will be used at high loads and speeds. To prevent condensing of water vapor in the exhaust gas, EGR systems will operate only after the coolant temperature reaches 65°C. If EGR flowrates are limited as

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[5] Assuming EGR is not used at high load and limiting its use at medium loads, the extra heat absorbed by the engine coolant can be removed by the vehicle's existing radiator.

described above, fuel economy penalties will approach an estimated 2 percent. About 1 percent can be saved through less severe injection retard, however, resulting in a net fuel economy penalty of approximately 1 percent. If EGR flow rates are limited to eight percent of air flow at mid speeds and loads and reduced proportionately at other speeds and loads, the fuel economy penalty could be reduced to zero.

At low and mid loads and speeds, the intake pressure is typically higher than the exhaust pressure thus making it virtually impossible for exhaust gases to flow into the intake manifold by itself. By proper sizing of the turbocharger and using a wastegate, exhaust pressures can be increased to allow EGR to flow.

The EGR valve will most likely be electronically controlled. Such a valve and control system is shown in Figure 4-13.

4.4 TURBOCHARGER IMPROVEMENTS

Improved turbochargers can provide significant improvements in fuel consumption and emissions. Variable geometry turbochargers provide leaner air/fuel ratios under full load conditions (thereby reducing emissions) and also improve transient response at lower loads and speeds. They are expected to be an important component for heavy-duty diesel engines meeting 2004 emissions standards. Other turbocharging advancements such as two-stage turbocharging can improve performance and increase brake horsepower without increasing fuel consumption or emissions. Turbochargers must be selected carefully so that their operating characteristics match well with specific engine models.

4.4.1 Variable Geometry Turbochargers

Variable geometry turbochargers (VGTs) have been developed in an effort to match turbocharger performance to engine operation over a wider speed-load range. VGTs also allow for quicker transient response by restricting the turbine nozzle during accelerations. Their ability to provide additional air to the engine over a wider range of operating conditions also allows for emissions reductions.

A common VGT design employs a ring of movable nozzle vanes around the turbine, as is shown in the turbine housing assembly of the Garrett VNT-45 turbocharger (Figure 4-14). A variant on this design, which was developed by Honda for passenger car applications, is the "wing turbo" shown in Figure 4-15. In either case, the vanes require an external (to the turbocharger) actuating mechanism. In the Garrett turbocharger, an actuator rod is connected to the crank assembly and rotates the union ring in either direction to move the vanes open or closed. This actuator rod is driven by an electro-mechanical actuation mechanism (a stepper motor controlled by the engine's electronic control module). The Honda wing turbo utilizes linkages driven by a pneumatic system to move the vanes. This particular VGT configuration is shown in Figure 4-16. The two-stage actuator in the figure is driven by a differential pressure system with high pressure from the compressor outlet and low pressure from the inlet manifold. Without external forces, a spring holds the vanes in the closed position. To position the vanes, signals from the electronic control unit (ECU) are sent to the two solenoid valves which in turn precisely control the differential pressure acting upon the two-stage actuator. In addition to these actuation systems, manufacturers are also pursuing the use of hydraulic actuators. These would be best matched with engines already equipped with a high pressure fluid as a part of their fuel injection systems (e.g., the HUEI system).

Holset Engineering has developed a different type of VGT that utilizes a moveable shroud to control the turbocharger boost (Figure 4-17). The nozzle vanes do not rotate, but rather a thin-walled shroud is moved in a direction parallel to the axis of the turbine wheel. As the shroud reduces the size of the turbine, the expansion ratio rises, leading to an increase in charge air pressure. The Holset VGT is presumably of simpler design than the movable vane VGTs, and provides comparable performance.

4.4.2 Other Turbocharger Improvements

Additional technology improvements are available with respect to turbochargers. Engine manufacturers will likely work with suppliers to better match turbocharger boost and operating range to specific engines. Moderate redesign such as implementation of lower inertia (perhaps ceramic) turbines may allow manufacturers to avoid moving to the more complicated VGTs described above. Use of two-stage turbocharging (i.e., two individual turbochargers, possibly with an expansion stage in between) is also being considered to increase the engine breathing.

4.5 AFTERCOOLER IMPROVEMENTS

Charge air cooling has long been used to increase the density of air entering the combustion chamber, thereby improving the specific power output of a given engine. Most engine manufacturers utilized jacket-water cooling prior to 1991, but the use of air-to-air aftercoolers (see Figure 4-18) is now preferred for HDDEs. Air-to-air aftercoolers provide improved charge air cooling, which allows for more power output, better fuel economy, and because the cooled charge limits peak in-cylinder combustion temperatures, lower NO_x emissions. Lower combustion temperatures also improve engine life by reducing thermal stresses. Aftercooling on diesel engines can be improved by sizing the aftercooler for optimal cooling and minimal pressure loss. Ducting to and from the aftercooler can also be refined to minimize pressure loss. Special care must be taken to avoid condensation in the aftercooler, which can result from overcooling of low temperature and humid intake air. Computer control of the electric fan and shutters on the aftercooler intake can regulate air temperatures within the aftercooler. It is doubtful that much improvement in air-to-air aftercoolers will be seen above those in heavy heavy-duty engines today.

4.6 OXIDATION CATALYSTS

Oxidation catalysts are very effective in reducing hydrocarbons (HC), carbon monoxide (CO) and soluble organic fraction (SOF) emissions from diesel exhaust. Catalyst design has been focussed on achieving high activity for desired reactions and low activity for undesired reactions. The largest problem is controlling sulfate formation resulting from sulfur in the diesel fuel. Oxidation catalysts also store sulfuric acid formed from sulfates and water vapor under low to moderate temperature conditions and release sulfates during a higher temperature condition. This storage and release of sulfates can result in bursts of particulate matter during speed/load changes and adversely affect the durability of the catalyst.

Current diesel oxidation catalysts use platinum (Pt) on an alumina (Al_2O_3) washcoat. Typical precious metal loading are on the order of 1.4 grams per liter (g/L) of catalyst volume. Pt/Al_2O_3 catalysts typically exhibit excellent CO, HC and SOF reductions under normal diesel exhaust temperatures but sulfate formation can be high. Use of Pt/Al_2O_3 catalysts will most likely require low sulfur fuels (50 to 100 ppm) to keep particulate levels low and catalyst life high.

Engelhard has developed an oxidation catalyst that uses a ceria/alumina washcoat to oxidize SOFs. Very low levels of platinum (0.02 g/L) are used to control odor but do very little conversion of HC or CO. Low platinum levels also make this catalyst sulfur tolerant. Typical catalyst volumes are equal to the displacement of the engine on which the catalyst is used.

Significant research is underway looking at other precious metals and washcoats. Palladium/alumina catalysts significantly lower sulfate formation but also reduce low temperature HC and CO conversion. Modification to the washcoats and addition of other base metals have shown some reduction in sulfate formation while keeping HC/CO conversion high. Johnson Matthey found that the use of high amounts of vanadium (7 g/L) together with Pt/Al_2O_3 has shown significant reductions in sulfate storage with relatively little loss of HC or CO performance.

Research is continuing on the manufacture of sulfur-tolerant catalysts, but the cost effectiveness of reducing fuel sulfur versus catalyst changes needs to be evaluated.

4.7 LEAN NO_x CATALYSTS

Lean NO_x catalysts provide a catalytic reduction of NO_x emissions in a fuel-lean environment. At the present time it is not envisioned that lean NO_x catalysts will be available by 2004. However, research continues on this technology and some manufacturers are holding out hope that this can prove viable in the near future. Previous work with copper zeolites (Cu-ZSM-5) showed feasibility of reducing NO_x emissions by using hydrocarbons in the diesel engine exhaust at higher temperatures (425°C to 550°C). The problem was that it required a significant amount of hydrocarbons to reduce the NO (approximately 4 to 1) and that the systems were very sensitive to poisoning by SO_2, and inhibition by water. Furthermore these catalysts were only effective at low space velocities. Platinum-based catalysts are quite active in reducing NO_x emissions in the 200° to 300°C range and need lower amounts of HCs to reduce NO_x (2 to 1). However, platinum produces sulfates from the fuel sulfur which increase particulate emissions.

Allied Signal has developed a non-zeolite noble metal catalyst which they have named LNX3. LNX3 has reached NO_x conversion efficiencies as high as 34 percent when HC/NO_x ratio is in excess of 2. The catalyst also demonstrates good control of HC, CO and SOFs making it a true 4-way catalyst. Unfortunately overall NO_x reductions for the catalyst system using real diesel exhaust under real engine operating conditions is only 5 to 6 percent. Other versions of this non-zeolite catalyst have shown NO_x conversion efficiencies of up to 35 percent over the engine operating range with peak efficiencies reaching as high as 60 percent using simulated diesel engine exhaust. Further research will be necessary to improve NO_x conversion efficiency in real diesel exhaust while removing sensitivities to space velocity and making it work at a broader temperature range and with lower HC/NO_x ratios.

The most significant problem with lean NO_x catalysts is the need for large amounts of hydrocarbons. Current lean NO_x catalysts also prefer lower molecular weight hydrocarbons such as propane. However, it is clear for such a system to be realistic on diesel engines, it must use diesel fuel to create the additional hydrocarbons needed.

To provide the additional hydrocarbons needed by such a catalyst system, three approaches have been suggested using diesel fuel. The first is to place an additional fuel injector in the exhaust pipe to inject diesel fuel into the exhaust stream prior to the catalyst. Such a system could encourage tampering, since removal of this injector would not result in any performance loss and would actually result in a fuel savings. The second method is to inject more fuel mixture into the cylinder during the injection process to create additional hydrocarbons. While this method is less liable to be tampered with, larger fuel penalties and higher HC emissions could result. The third method is to inject additional fuel during the exhaust stroke. A fuel injection system such as the HEUI could be used for this purpose. The third method is the most feasible method to date. Based upon current technology and assuming that the lean NO_x catalyst is responsible for reducing NO_x emissions from 4 g/bhp-hr to 2 g/bhp-hr, it is estimated that fuel consumption will increase approximately 5 percent. However, since these catalysts would replace other methods of NO_x control which are also associated with a fuel economy penalty, some of the increased fuel consumption attributed to these catalysts would be counteracted.

4.8 SELF-REGENERATING PARTICULATE TRAPS

Particulate traps showed some promise in 1991 as a method for engine manufacturers to meet the reduced particulate standard of 0.1 g/bhp-hr for urban buses. However, due to the complexity of regeneration and the development of engines that could meet the 0.1 g/bhp-hr PM standards without a trap, the use of traps on buses was discontinued. There has been some resurgence of passive particulate traps recently as a result of the EPA urban bus retrofit rule. While most manufacturers will probably opt to meet the 2004 standards without a trap of any kind, the significantly lower particulate standard applicable to UBEs together with the proposed 2004 standard of 2.4 g/bhp-hr NO_x plus NMHC may force some manufacturers to reconsider the use of traps for meeting the 2004 urban bus standards.

One of the most promising passive particulate traps is the continuous regenerative trap (CRT) from Johnson Matthey. This is a two stage trap which incorporates a platinum catalyst ahead of the trap, allowing combustion of soot below 300°C. Without such a catalyst, soot normally combusts at about 650°C, a temperature difficult to maintain at low load conditions.

The first stage of the system (the platinum oxidation catalyst) converts exhaust NO to NO_2. The oxidation catalyst is also very effective in reducing hydrocarbons, carbon monoxide and soluble organic fraction (SOF). The trap which follows captures the particulates. The NO_2 then reacts with the carbon particulate to form NO and carbon dioxide (CO_2). While there is no effective reduction in NO_x emissions, PM emissions are reduced by a factor of 10. The system requires no electronics or valving. It simply replaces the muffler. It is currently being used in Europe on buses, pickup and delivery (P&D) trucks, and refuse haulers with no apparent problems. Johnson Matthey believes the durability of the system will meet the requirements of the bus retrofit rule as well as the life cycle cost requirement incorporated into that rule. The system tends to work better on 4-stroke engines than 2-strokes as the 4-stroke engines have higher exhaust temperatures, but Johnson Matthey is also developing this system for 2-stroke buses in the United States for the EPA bus retrofit rule. A picture of the CRT is shown in Figure 4-19.

As with any particulate trap, increased exhaust back pressure results which can result in increased fuel consumption. While Johnson Matthey has not reported fuel consumption penalties with these catalysts, it is estimated that fuel consumption might increase up to 2 percent based on data from other trap systems.

Another passive regenerative trap method that is receiving much attention includes the blending of a small amount (< 50 ppm) of catalytic material with the fuel. Both Rhone-Poulenc and Lubrizol are developing such systems and engine manufacturers are reviewing them carefully for use in urban bus applications.

4.9 CLOSED CRANKCASE

Typical diesel engine crankcase emissions are in the order of 0.01 g/bhp-hr PM and there has been some interest in regulating these emissions as well. These emissions are mostly oil vapor. The systems to control crankcase emissions are similar to those which have been used to control crankcase emissions in gasoline engines for 20 to 30 years. The problem with crankcase emission controls on diesel engines is that the crankcase ventilation systems port the crankcase vapors through the turbocharger compressor and this can have a detrimental effect on aftercooler life. Crankcase vapors tend to clog the air-to-air aftercooler passages. Another option is to continue using open crankcases but to account for crankcase emissions during certification by venting crankcase emissions into the exhaust stream during certification testing. This would require correspondingly lower exhaust emissions from the engine to compensate for the crankcase emissions, which will most likely be more cost-effective than closed crankcase systems.

If closed crankcase systems are required on diesel engines, they will most likely include a positive crankcase ventilation valve, a small filter which would need to be changed at every other oil change interval and tubing from the crankcase to the air cleaner. If engine manufacturers are allowed to include crankcase emissions with exhaust emissions without a specific crankcase ventilation requirement, engine manufacturers would pursue methods discussed earlier to reduce exhaust particulate emissions to compensate for the small amount of crankcase emissions that would be added to the exhaust when certifying the engine.

SECTION 5
DIESEL ENGINE TECHNOLOGY COSTS

In this section, incremental engine manufacturer and consumer costs for various technology improvements needed to meet the proposed 2.4 g/bhp-hr NO_x plus NMHC standard with diesel engines are discussed. For each technology, incremental costs have been calculated from a "bottom up" analysis.

5.1 FUEL SYSTEM UPGRADES

Costs of fuel system upgrades are given in this analysis for two basic fuel system types: (1) cam-driven electronic unit injector (EUI) systems and (2) common rail injection systems. These two systems are representative of the fuel systems to be used on both 1998 and 2004 engines. Costs to modify these systems to meet the 2004 emission standards are the same or higher than costs for modifying other fuel systems that might be used in their place. Since modifications to fuel injection systems needed to meet the proposed 2004 standards will most likely encompass a combination of increased fuel injection pressure, improved spray patterns and rate shaping or split injection, we have not attempted to break out costs for each fuel system improvement, but rather have estimated the incremental hardware and fixed costs for fuel system upgrades that accomplish all of the above fuel system changes.

5.1.1 Cam-driven EUI

To increase injection pressure in a cam-driven EUI, various components and materials must be strengthened to handle higher pressure. Increased material costs to the engine manufacturer for injectors should be on the order of $3 to $5 each depending on the desired injection pressure. This would cover costs associated with strengthened injector tips to handle higher fuel delivery pressure and a stiffer plunger return spring. In addition, a stronger and quicker acting solenoid will be needed to handle the higher pressures and provide split injections. These improved solenoids should add another $8 to $10 to the engine manufacturer's cost per injector. Rate shaping will most likely be accomplished through cam lobe design. The material costs per injector were determined for a HHDDE or UBE and then scaled using economy of scale factors for LHDDEs and MHDDEs [3].

Since urban buses use HHDDEs, the cost per injector for HHDDEs and UBEs would be the same. Thus injector production volumes used in the analyses for HHDDEs and UBEs are the sum of the HHDDE production volume times six injectors per engine plus the UBE production volume times four injectors per engine. We assumed that manufacturers will be able to make improved injectors that are outwardly similar to current designs, so that no additional engine modification will be needed to accommodate the new injectors and no additional assembly time will be required for injector installation.

Typical research and development (R&D) costs for increased injection pressures and rate shaping or split injection run approximately $1,500,000 per engine line. In some cases, injectors for one engine line within a specific heavy-duty engine category can be used on other engines within that category. R&D costs given here include demonstrating the new technology on an engine dynamometer while final injection timing and duration electronic control unit programming will be part of the combustion chamber optimization R&D costs described in subsection 5.2.4. The supplier must also retool to make the new injectors, adding from $350,000 to $560,000 in tooling expenses depending on production volume.

Even though increased injection pressure increases parasitic losses on the engine, it is assumed that reduced ignition delay and more rapid diffusive burning resulting from finer droplet sprays will cancel out any increased fuel consumption due to increased parasitic losses. Thus no additional operating costs are expected.

Total incremental life-cycle costs per engine for improved cam-driven EUI fuel injection systems are estimated to be from $88 to $132 as shown in Table 5-1.

5.1.2 Common Rail Injection Systems

For common rail injection systems, incremental costs to meet the proposed 2004 standards were determined assuming a hydraulically-activated electronically-controlled unit injector (HEUI) system Although systems utilizing a common rail of high pressure fuel are also in use, the HEUI system is currently found on both Caterpillar and Navistar engine models, and the possibility exists that additional engine manufacturers will adopt this type of system in the future. It should also be noted that many similarities exist between both systems, and the incremental costs determined for a HEUI system would also provide a good estimate for a high pressure fuel common rail system. For example, upgrades to solenoid valves apply in both cases, and the oil pump upgrade for a HEUI system would parallel a fuel pump upgrade to provide higher common rail fuel pressure.

For a HEUI-type system, increased fuel injector pressures will likely be achieved by upgrading the high pressure oil pump. Pumps which currently supply oil to the unit injectors at 3,000 psi will need to pressurize oil to roughly 4,000 psi. This will result in an incremental hardware cost to the engine manufacturer of approximately $60 to $75 per engine. Improved solenoid valves to control multiple injections or rate shaping are estimated to have an incremental cost of $5 to $7 per electronic unit injector. Incremental material costs for enhancements such as stronger oil passageways and injector components are estimated at $5. No other engine redesign or increase in assembly costs are projected.

As with cam-driven unit injectors, R&D costs of $1,500,000 per engine line are used. Note that the R&D costs include the costs of demonstrating the redesigned unit injectors on an engine

Table 5-1 Incremental cost for improved cam-driven EUI fuel systems

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
Hardware Cost to Manufacturer (per Injector)				
Incremental Hardware Costs				
Incremental Material	$3	$4	$5	$5
Improved Solenoid	$8	$9	$10	$10
Total Hardware Cost	$11	$13	$15	$15
Total Assembly Costs	$0	$0	$0	$0
Variable Cost to Mfr.	$11	$13	$15	$15
Markup @ 29%	$3	$3	$4	$4
Hardware RPE (per injector)	**$14**	**$16**	**$19**	**$19**
Fixed Costs (per injector)				
R&D Costs	$1,500,000	$1,500,000	$1,500,000	$1,500,000
Tooling Costs	$560,000	$355,000	$350,000	$350,000
Injectors per year	600,000	180,000	172,000	172,000
Years to recover	5	5	5	5
Fixed cost (per injector)	**$1**	**$3**	**$3**	**$3**
Total Costs (per injector)	**$15**	**$19**	**$22**	**$22**
Number of Injectors	8	6	6	4
Total Fuel System Increment	**$120**	**$114**	**$132**	**$88**

Table 5-2 Incremental cost for HEUI systems

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
	Hardware Cost to Manufacturer			
Incremental Hardware Costs				
Injector Cost	$40	$36	$42	$28
Solenoid-Control Valve	$5	$6	$7	$7
Injectors per Engine	8	6	6	4
Higher Pressure Oil Pump	$60	$65	$75	$75
Material	$5	$5	$5	$5
Total Hardware Cost	$105	$106	$122	$108
Total Assembly Cost	$0	$0	$0	$0
Total Variable Cost to Mfr.	$105	$106	$122	$108
Markup @ 29%	$30	$31	$35	$31
Total Hardware RPE	**$135**	**$137**	**$157**	**$139**
	Fixed Costs			
R&D Costs	$1,500,000	$1,500,000	$1,500,000	$1,500,000
Tooling Costs	$640,000	$407,000	$400,000	$400,000
Injectors/yr.	600,000	180,000	172,000	172,000
Years to recover	5	5	5	5
Fixed cost/injector	$1	$3	$3	$3
Number of Injectors	8	6	6	4
Fixed cost/engine	**$8**	**$18**	**$18**	**$12**
Total Incremental Costs	**$143**	**$154**	**$176**	**$152**

dynamometer but not the final determination of optimal injector control. Modifications required to manufacturing equipment are estimated at between $400,000 and $640,000. While fuel economy may suffer from an increased accessory load on the engine (from the high pressure oil pump), it is believed that combustion improvements resulting from higher fuel injection pressures will counter this effect and result in no net fuel economy penalty.

As shown in Table 5-2, incremental life cycle costs per engine for upgraded common rail systems range from $143 for LHDDEs to $175 for HHDDEs.

5.2 COMBUSTION CHAMBER UPGRADES

Several combustion chamber modifications are envisioned in engines to meet the 2.4 g/bhp-hr NO_x plus NMHC standard. These might include use of 4 valves per cylinder, variable valve timing, improved oil control and combustion chamber optimization.

5.2.1 Two Valves to Four Valves

All U.S. heavy-duty engine manufacturers already employ four valves per cylinder in their HHDDEs and UBEs. Because changing from 2 valves per cylinder to 4 valves can be costly relative to engine cost in LHDDE, it is unlikely that LHDDE manufacturers will pursue this option. In this class, we have seen low emissions with 2-valve engines such as the Navistar T444, thus this option is only costed for MHDDEs.

Incremental costs for converting to a 4-valve system include approximately $12.50 per rocker arm that will actuate two valves instead of one, $8 per valve for the additional valves, guides, springs and other hardware resulting in an additional $171 per 6 cylinder engine. In addition to the hardware costs, it is expected that labor will increase by 40 minutes to provide for the additional machining of the head and manifolds and assembly of the additional valves and rocker arms.

R&D costs are estimated to be about $3,500,000 with retooling costs running around $1,000,000. Total incremental costs for a MHDDE will be $296 as shown in Table 5-3.

5.2.2 Variable Valve Timing

Most of the major manufacturers are reviewing variable valve timing as a possibility to improve engine efficiency and provide internal EGR. Hardware costs in the most likely scenario include electronic actuators to move the rocker arm to a different location on the cam lobe and special rocker arm assemblies. Total hardware costs to manufacturers will be from $135 to $155 depending upon production volumes. Additional labor to assemble and install the variable valve timing system will be approximately 1 hour.

R&D costs for variable valve timing systems will be approximately $3,000,000 per engine line and will require from $350,000 to $500,000 in retooling costs depending upon production volume. Total incremental costs per engine for variable valve timing will range from $238 to $282 per engine as shown in Table 5-4.

Table 5-3 Incremental cost for 4-valve medium heavy-duty engines

Heavy-Duty Category	**Medium**
Hardware Cost to Manufacturer	
Hardware Costs	
Rocker Arms	$75
Valves, Guides, Springs, etc.	$96
Total Hardware Cost	$171
Assembly	
Labor (min)	40
Labor Cost @ $28.00/hr	$19
Overhead @ 40%	$7
Total Assembly Cost	$26
Total Variable Cost to Mfr.	$197
Markup @ 29%	$57
Total Hardware RPE	**$254**
Fixed Costs	
R&D Costs	$3,500,000
Tooling Costs	$1,000,000
Engines/yr.	30,000
Years to recover	5
Fixed cost/engine	**$41**
Total Costs	**$296**

Table 5-4 Incremental cost for variable valve timing

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
		Hardware Cost to Manufacturer		
Hardware Costs				
Electronic Actuators	$25	$25	$25	$25
V.V.T. Rocker Arms	$110	$130	$120	$120
Total Hardware Cost	$135	$155	$145	$145
Assembly				
Labor (min)	60	60	60	60
Labor Cost @ $28.00/hr	$28	$28	$28	$28
Overhead @ 40%	$11	$11	$11	$11
Total Assembly Cost	$39	$39	$39	$39
Variable Cost to Mfr.	$174	$194	$184	$184
Markup @ 29%	$51	$57	$54	$54
Total Hardware RPE	**$225**	**$251**	**$238**	**$238**
		Fixed Costs		
R&D Costs	$3,000,000	$3,000,000	$3,000,000	$3,000,000
Tooling Costs	$500,000	$350,000	$350,000	$350,000
Units/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/unit	**$13**	**$31**	**$31**	**$31**
Total Variable Valve Timing Increment	**$238**	**$282**	**$269**	**$269**

5.2.3 Improved Oil Control

Most HHDDEs and UBEs currently have excellent oil control and therefore have low soluble organic fraction (SOF) emissions. LHDDEs and MHDDEs, however, have higher SOF emissions resulting from engine oil blowby and some improvement in oil control could be applied to reduce particulate emissions from these engines. Better ring packs and valve guide seals are generally used to achieve these effects, however, oil control measures must still ensure proper lubrication of cylinder walls while reducing in-cylinder oil. Material costs include improved valve guide seals at approximately 50 cents per valve and improved rings at $2 per cylinder. It is reasonable to believe that there will be no increased labor costs to install the new rings and valve guide seals. R&D efforts are estimated at approximately $1,000,000 per engine line with retooling costs ranging from $100,000 to $140,000 depending upon sales volume. Total incremental costs for improved oil control will range from $33 to $35 per engine as shown in Table 5-5.

Table 5-5 Incremental cost for oil control

Heavy-Duty Category	**Light**	**Medium**
Hardware Cost to Manufacturer		
Improved Hardware Incremental Costs		
Valve Guides	$8	$6
Rings	$16	$12
Total Hardware Cost	$24	$18
Markup @ 29%	$7	$5
Total Hardware RPE	**$31**	**$23**
Fixed Costs		
R&D Costs	$1,000,000	$1,000,000
Tooling Costs	$140,000	$100,000
Units/yr.	75,000	30,000
Years to recover	5	5
Fixed cost	**$4**	**$10**
Total Incremental Cost	**$35**	**$33**

5.2.4 Combustion Chamber Optimization

Techniques for combustion chamber optimization include increasing compression ratio, modifying piston bowl shape, modifying injection timing and duration profiles, and programming the electronic control unit for all the control systems on the engine. The final engine line optimization includes significant testing of all horsepower ratings within an engine line. First the highest displacement volume and horsepower rating is tested, followed by the lowest. Setting are determined through additional testing of the other ratings. This effort takes approximately six months in two test cells with total R&D costs estimated at $5,000,000 per engine line. Additional tooling costs are estimated at $350,000 to $500,000 per engine line depending upon production volume.

Total incremental life-cycle costs per engine for combustion chamber optimization is estimated to be $20 per LHDDE and $50 per engine for all other HDDEs as shown in Table 5-6.

5.3 EXHAUST GAS RECIRCULATION

Three different types of exhaust gas recirculation (EGR) may be employed by engine manufacturers to meet the reduced NO_x standard: internal EGR systems, hot EGR systems and cooled EGR systems. The LHDDE and MHDDE classes will most likely use cooled EGR which provides the largest NO_x reduction of the three types of EGR. While HHDDEs might also need cooled EGR to meet the proposed NO_x standard in early years, it is likely that engine manufacturers of HHDDEs and UBEs will attempt to use other means of reducing NO_x to minimize wear and fuel consumption increases in these longer life engines.

Table 5-6 Incremental cost for combustion optimization

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
		Fixed Costs		
R&D Costs	$5,000,000	$5,000,000	$5,000,000	$5,000,000
Tooling Costs	$500,000	$350,000	$350,000	$350,000
Units/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost	**$20**	**$50**	**$50**	**$50**
Total Incremental Cost	**$20**	**$50**	**$50**	**$50**

5.3.1 Internal EGR

Internal EGR will be controlled solely by varying valve overlap. Thus the costs of this type of system are included in the costs of variable valve timing. Costs of variable valve timing can be found in Section 5.2.2.

5.3.2 Hot EGR

Hot EGR systems will have an electronically-controlled EGR valve and finned tubing to port the exhaust to the intake manifold. The EGR valve will be mounted on the intake manifold and controlled by the engine ECU. EGR will most likely be used only during part-load and mid-range conditions and limited to less than eight percent of air flow to minimize detrimental effects such as increased fuel consumption and cylinder wear.

Component costs to the engine manufacturer for a hot EGR system include an electronic EGR valve costing from $35 to $50, depending on flow rate, and stainless steel tubing for connecting the EGR valve to the exhaust manifold. The tubing will have fins to provide some air cooling and will cost from $51 to $66. Further details regarding the cost of the tubing is provided in Appendix Section A.1.1. Mounting the EGR valve on the intake manifold, connecting the tubing to the valve and exhaust manifold plus connecting the wiring harness to the valve might take up to five minutes of assembly time.

R&D costs will include significant testing to develop EGR flow-rate maps and ensure that neither the functionality or durability of the engine is affected. Estimated costs for this test and development program, including the development of the algorithm for EGR flow rate and valve opening height at various speeds and loads, are $7,500,000. In addition, tooling costs to redesign intake manifolds for mounting of the EGR valve and exhaust manifolds to connect the EGR tubing will range from $100,000 to $140,000 per engine line depending on production volume. Since HHDDEs and UBEs will most likely use the same systems and the engines are very similar, fixed costs for these two engine categories are spread over the total production of both HHDDEs and UBEs.

While low flow rates of EGR are not expected to significantly affect engine durability or fuel economy, there is some penalty associated with EGR use. If EGR is used only in the low and mid range loads and speeds and is cooled slightly, fuel economy penalties can range from zero to 0.5 percent. In addition, some oil degradation might occur. To avoid increased wear rates, manufacturers will most likely increase oil sump volumes to compensate. A ten percent increase in oil sump volumes was used in this analysis. While not costed as part of this analysis, it is possible that the EGR valve and tubing might need cleaning and/or replacement once during the lifetime of a HHDDE or UBE.

Total incremental life-cycle costs for hot EGR will range from $213 to $755 per engine as shown in Table 5-7.

5.3.3 Cooled EGR

Two forms of cooled EGR are discussed under this subsection. Low-flow cooled EGR is described as a cooled system that limits EGR flow rate to approximately eight percent of air flow at mid loads and speeds, with higher flow rates at lower speeds and loads and no EGR at higher loads and speeds. High-flow cooled EGR, on the other hand, is assumed to use approximately 15 percent EGR at mid loads and speed, up to 60 percent at idle, and no EGR at high loads and speeds.

5.3.3.1 Low-Flow Cooled EGR

Low-flow cooled EGR systems will contain an electronic EGR valve, an EGR cooler and stainless steel tubing to connect the EGR system to the valve and cooler.

Component costs to the manufacturer will include an electronic EGR valve costing from $35 to $50 depending on flow rate, EGR tubing at $9 to $26, and an EGR cooler at approximately $48 to $70. Details on tubing costs can be found in Appendix Section A.1.2. Cooler cost details can be found in Appendix Section A.2.1.

Fixed costs will include extensive testing for a cooled EGR system to ensure proper flow rates of EGR at each load and speed range. R&D efforts are estimated to be $10,000,000. Additional tooling costs will vary from $100,000 to $140,000 per engine family depending on production volume. Since HHDDEs and UBEs will most likely use the same systems and the engines are very similar, fixed costs for these two engine categories are spread over the total production of both HHDDEs and UBEs.

Table 5-7. Incremental life-cycle cost for hot EGR systems

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
		Hardware Cost to Manufacturer		
Hardware Costs				
Electronic EGR Valve	$35	$35	$50	$50
Finned EGR Tubing	$51	$54	$66	$55
Total Hardware Cost	$86	$89	$116	$105
Assembly				
Labor (min)	5	5	5	5
Labor Cost @ $28.00/hr	$2	$2	$2	$2
Overhead @ 40%	$1	$1	$1	$1
Total Assembly Cost	$3	$3	$3	$3
Total Variable Cost to Mfr.	$89	$92	$119	$108
Markup @ 29%	$26	$27	$35	$31
Total Hardware RPE	**$115**	**$119**	**$154**	**$139**
		Fixed Costs		
R&D Costs	$7,500,000	$7,500,000	$7,500,000	$7,500,000
Tooling Costs	$140,000	$100,000	$100,000	$100,000
Units/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/unit	**$28**	**$71**	**$71**	**$71**
		Operating Costs		
Vehicle Lifetime (mi)	145,000	280,000	560,000	513,000
Vehicle Lifetime (yr)	10	13	12	15
Fuel Consumption				
Base fuel economy	14	10	6	4
Reduction due to EGR	0.5%	0.5%	0.5%	0.5%
Cost of fuel ($/gal)	$1.11	$1.11	$1.11	$1.11
Life-cycle Fuel Cost	$44	$107	$371	$449
Oil Changes				
Frequency (mi)	8,000	8,000	14,000	14,000
Incremental oil per change (gal)	0.4	0.5	1.1	0.9
Cost of Oil ($/gal)	$4.70	$4.70	$4.70	$4.70
Life-cycle Oil Cost	$25	$56	$146	$95
Life-cycle Operating Costs	**$69**	**$163**	**$517**	**$544**
Total Life-cycle Costs	**$213**	**$353**	**$742**	**$755**

Since the EGR is cooled and introduced at low flow rates, it is expected that there will be no increase in fuel consumption. However, oil sump capacities may need to be increased about five percent to minimize possible negative durability effects of EGR. While not included in this analysis, the EGR valve, tubing and cooler might need cleaning or replacement once during the lifetime of a HHDDE and UBE.

As shown in Table 5-8 , total incremental life-cycle costs per engine for low-flow cooled EGR will range from $178 to $362.

5.3.3.2 High-Flow Cooled EGR

High-flow cooled EGR systems will also need an electronic EGR valve, a larger water jacket EGR cooler to accommodate the higher flow rates and stainless steel tubing to connect the EGR system to the cooler and valve.

Component costs to the manufacturer will include an electronic EGR valve costing from $35 to $50 depending on flow rate, EGR tubing at $12 to $30, and an EGR cooler at approximately $85 to $129. Details on tubing costs can be found in Appendix Section A.1.3 and cooler costs can be found in Appendix Section A.2.2.

Fixed costs will include extensive testing for a cooled EGR system to ensure proper flow rates of EGR at each load and speed range. R&D efforts are estimated to cost $10,000,000. Additional tooling costs will vary from $100,000 to $140,000 per engine family depending on production volume. Since HHDDEs and UBEs will most likely use the same systems and the engines are very similar, fixed costs for these two engine categories are spread over the total production of both HHDDEs and UBEs.

Due to the higher EGR flow rates at mid and low loads and speeds, it is estimated that fuel economy will decrease approximately two percent due to slower combustion and intake-charge dilution effects. Manufacturers, however, will be able to reduce the amount of injection timing retard to low NO_x by using EGR, the net fuel consumption reduction will be approximately one percent. In addition, oil sump capacities will need to be increased about 10 percent to minimize possible negative durability effects of EGR. While not included in this analysis, the EGR valve, tubing and cooler might need cleaning or replacement once during the lifetime of a HHDDE and UBE.

Table 5-8. Incremental life-cycle cost for low-flow cooled EGR systems

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
Hardware Cost to Manufacturer				
Hardware Costs				
Electronic EGR Valve	$35	$35	$50	$50
EGR Tubing	$9	$14	$26	$17
EGR Cooler	$48	$53	$70	$49
Total Hardware Cost	$92	$102	$146	$116
Assembly				
Labor (min)	10	10	10	10
Labor Cost @ $28.00/hr	$5	$5	$5	$5
Overhead @ 40%	$2	$2	$2	$2
Total Assembly Cost	$7	$7	$7	$7
Total Variable Cost to Mfr.	$99	$109	$153	$123
Markup @ 29%	$29	$31	$44	$36
Total Hardware RPE	**$128**	**$140**	**$197**	**$159**
Fixed Costs				
R&D Costs	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Tooling Costs	$140,000	$100,000	$100,000	$100,000
Units/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/unit	**$38**	**$94**	**$94**	**$94**
Operating Costs				
Vehicle Lifetime (mi)	145,000	280,000	560,000	513,000
Vehicle Lifetime (yr)	10	13	12	15
Fuel Consumption				
Reduction due to EGR	0%	0%	0%	0%
Life-cycle Fuel Cost	$0	$0	$0	$0
Oil Changes				
Frequency (mi)	8,000	8,000	14,000	14,000
Oil Change Amount (gal)	0.2	0.3	0.6	0.5
Cost of Oil ($/gal)	$4.70	$4.70	$4.70	$4.70
Life-cycle Oil Cost	$12	$27	$71	$46
Life-cycle Operating Costs	**$12**	**$27**	**$71**	**$46**
Total Life-cycle Costs	**$178**	**$261**	**$362**	**$299**

Total incremental life-cycle costs for high-flow cooled EGR will range from $328 to $1,272 per engine as shown in Table 5-9.

5.4 TURBOCHARGER UPGRADES

Two kinds of turbocharger upgrades are costed in this report: variable geometry turbochargers and improved wastegate control. It is envisioned that by 2004, all heavy-duty engines might use variable geometry turbochargers (VGTs) which provide better response than conventional turbochargers and also provide enough air when operating with EGR. In addition, VGTs might be used to increase exhaust manifold back pressure to allow EGR to flow into the intake manifold under light and medium load conditions. In many cases, VGTs may be used for increased performance even if EGR is not used.

5.4.1 Variable Geometry Turbochargers

VGTs represent a substantial increase in complexity over conventional free-flowing or even wastegated turbochargers. For instance, an assembly of movable or rotating vanes and mechanisms must be incorporated into the turbocharger housing as the variable geometry element, compared to a one-piece nozzle ring and fixed vanes found in present turbochargers. Because of the increased part count and machining effort, the variable geometry nozzle ring assembly is expected to be the largest contributor to the incremental cost of a VGT. This cost to a supplier (or to the turbocharger division of an engine manufacturer) is estimated at between $40 to $85, depending on engine category.

Movable vanes in a VGT must be positioned by an actuator connected to linkages and/or crank arms. Actuators can be electric (stepper motor), pneumatic (driven from compressed air of the braking system or by differential pressure), or hydraulic (using pressurized engine oil). It is unclear what actuation method will eventually be utilized, and the method may in fact vary depending on engine manufacturer. Engines using a HEUI fuel system, for example, might be better matched with hydraulic actuators due to the availability of high pressure oil. The best estimate at this time for actuator and linkage costs are between $40 and $50, and between $10 and $15, respectively. A turbine speed sensor and exhaust back pressure sensor will likely be required, adding approximately $25 to the supplier's cost. Additional material costs for components such as spring disks and larger turbocharger housings are estimated at between $25 and $55.

Table 5-9. Incremental life-cycle cost for high-flow cooled EGR systems

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
	Hardware Cost to Manufacturer			
Hardware Costs				
Electronic EGR Valve	$35	$35	$50	$50
EGR Tubing	$12	$17	$30	$19
EGR Cooler	$85	$97	$129	$89
Total Hardware Cost	$132	$149	$209	$158
Assembly				
Labor (min)	10	10	10	10
Labor Cost @ $28.00/hr	$5	$5	$5	$5
Overhead @ 40%	$2	$2	$2	$2
Total Assembly Cost	$7	$7	$7	$7
Total Variable Cost to Mfr.	$139	$156	$216	$165
Markup @ 29%	$40	$45	$63	$48
Total Hardware RPE	**$179**	**$201**	**$279**	**$213**
	Fixed Costs			
R&D Costs	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Tooling Costs	$140,000	$100,000	$100,000	$100,000
Units/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/unit	**$38**	**$94**	**$94**	**$94**
	Operating Costs			
Vehicle Lifetime (mi)	145,000	280,000	560,000	513,000
Vehicle Lifetime (yr)	10	13	12	15
Fuel Consumption				
Base fuel economy	14	10	6	4
Reduction due to EGR	1%	1%	1%	1%
Cost of fuel ($/gal)	$1.11	$1.11	$1.11	$1.11
Life-cycle Fuel Cost	$86	$208	$721	$873
Oil Changes				
Frequency (mi)	8,000	8,000	14,000	14,000
Oil Change Amount (gal)	0.4	0.5	1.1	0.9
Cost of Oil ($/gal)	$4.70	$4.70	$4.70	$4.70
Life-cycle Oil Cost	$25	$54	$141	$92
Life-cycle Operating Costs	**$111**	**$262**	**$862**	**$965**
Total Life-cycle Costs	**$328**	**$557**	**$1,235**	**$1,272**

Because of the larger number of parts, assembly labor is projected to increase approximately 20 minutes per unit, which translates into about $13 per turbocharger. R&D and tooling costs are estimated at $2,500,000 and between $1,000,000 and $1,400,000, respectively. Estimates for R&D costs include the costs of developing computer control algorithms for the VGT.

As shown in Table 5-10 , total incremental life-cycle costs for a VGT are estimated at between $269 and $436 per engine.

5.4.2 Improved Wastegate Control

Computer controlled wastegated turbochargers can be developed with less effort than that required for the development of VGTs. Turbochargers with improved wastegates might be implemented in applications where the move to a VGT is less desirable, most likely in the smaller heavy-duty diesel engines. Incremental costs to improve a turbocharger wastegate have been estimated to be between $20 and $30, and other materials costs associated with the wastegate redesign are assumed to be $10. Assembly times are projected to increase by 15 minutes due to component complexity, and R&D and tooling costs are estimated at $1,000,000 and $75,000 to $105,000, respectively. No fuel economy penalties are expected. As shown in Table 5-11, these inputs result in a total incremental cost of between $76 and $100 per engine for an improved wastegated turbocharger.

5.5 ADVANCED OXIDATION CATALYSTS

Advanced oxidation catalysts that would be used to meet the proposed 2004 standards will be more costly than the oxidation catalysts that might be used on engines meeting the 1998 standards. Almost all engine lines in 1998 will have electronically-controlled fuel injection systems and manufacturers will strive not to use oxidation catalysts. It is expected that oxidation catalysts will still be employed on urban buses in 1998 due to the lower particulate matter (PM) standard. The cost per engine of both 1998 oxidation catalysts and advanced oxidation catalysts are estimated here. For engine lines that use no catalyst in 1998 but employ an advanced oxidation catalyst to meet the proposed 2004 standards, the entire cost of the advanced oxidation catalyst would be attributable to the proposed 2004 standards. For those engine lines that use oxidation catalysts in 1998, and more advanced oxidation catalysts to meet the proposed 2004 standards, the incremental cost of the advanced oxidation catalyst compared with the 1998 oxidation catalyst would apply. This incremental cost is calculated as well.

Table 5-10 Incremental life-cycle costs for variable geometry turbocharger upgrades

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
		Hardware Cost to Supplier		
Hardware Costs				
Nozzle Ring Assembly	$40	$60	$85	$85
Actuator (Stepper Motor)	$40	$45	$50	$50
Actuator linkages	$10	$10	$15	$15
Sensors	$25	$25	$25	$25
Other Material	$25	$35	$55	$55
Total Hardware Cost	$140	$175	$230	$230
Assembly				
Labor (min)	20	20	20	20
Labor Cost @ $28.00/hr	$9	$9	$9	$9
Overhead @ 40%	$4	$4	$4	$4
Total Assembly Cost	$13	$13	$13	$13
Total Variable Cost to Supplier	$153	$188	$243	$243
Supplier Markup	$44	$55	$70	$70
Markup @ 29%	$58	$70	$91	$91
Total Hardware RPE	**$255**	**$313**	**$404**	**$404**
		Fixed Costs		
R&D Costs	$2,500,000	$2,500,000	$2,500,000	$2,500,000
Tooling Costs	$1,400,000	$1,000,000	$1,000,000	$1,000,000
Engines/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/engine	**$14**	**$32**	**$32**	**$32**
Total Life-Cycle Costs	**$269**	**$345**	**$436**	**$436**

Table 5-11 Incremental life-cycle costs for improved wastegate control

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
Hardware Cost to Supplier				
Hardware Costs				
Wastegate Assembly	$20	$25	$30	$30
Other Materials	$10	$10	$10	$10
Total Hardware Cost	$30	$35	$40	$40
Assembly				
Labor (min)	15	15	15	15
Labor Cost @ $28.00/hr	$7	$7	$7	$7
Overhead @ 40%	$3	$3	$3	$3
Total Assembly Cost	$10	$10	$10	$10
Total Variable Cost to Supplier	$40	$45	$50	$50
Supplier Markup	$16	$18	$20	$20
Markup @ 29%	$16	$18	$20	$20
Total Hardware RPE	**$72**	**$81**	**$90**	**$90**
Fixed Costs				
R&D Costs	$1,000,000	$1,000,000	$1,000,000	$1,000,000
Tooling Costs	$105,000	$75,000	$75,000	$75,000
Engines/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/engine	**$4**	**$10**	**$10**	**$10**
Total Incremental Costs	**$76**	**$91**	**$100**	**$100**

Advanced oxidation catalysts are envisioned to be an even mix of platinum and palladium with a precious metal loading of 1.4 g/L. Catalyst washcoat is estimated to be an even mix of ceria and alumina loaded at 450 g/L plus 7.0 g/L of vanadium to minimize fuel sulfur to sulfate reactions. Diesel oxidation catalysts are sized to the engine with flow-through volumes equal to engine displacement. Catalyst assembly includes deposition of precious metals, vanadium, and washcoat slurry on the ceramic substrate and placement in a stainless steel can. Can costs were calculated by determining the stainless steel required to cover the substrate plus an additional length of 2.8 cm for the end caps. Steel quantities include an additional 20 percent for scrap.

To minimize the effect of price fluctuations of precious metals, it is envisioned that most engine manufacturers will purchase their own precious metals and supply them to the catalyst manufacturers. Therefore precious metals are marked up only for engine manufacturer and dealer overhead and profit, while all other components also include a supplier mark-up.

Substrates costs are estimated at $10 per catalyst volume liter, precious metals at $11 per catalyst volume liter and vanadium at approximately $5 per catalyst volume liter. Can costs range from $11 to $18. The amount of labor to dip the substrate in the precious metal/washcoat slurry, assemble the can and mount the substrate within the can is estimated at from 8 to 12 minutes, depending upon catalyst size. Total RPE for advanced diesel oxidation catalysts range from $294 to $620 per engine as shown in Table 5-12. Catalysts on 1998 engines are estimated to cost between $171 and $354 per engine, giving incremental costs for those engines using catalysts in 1998 of $123 to $266 per engine.

5.6 LEAN NO_x CATALYSTS

Lean NO_x catalysts reduce NO_x emissions in a fuel lean environment. While it is possible that these catalysts will be a viable alternative to other methods of emissions control by 2004, they are at the present time not leading candidates. Nonetheless, we have provided estimated costs based on the state of the technology as it exists today. There is considerable on-going research on these four-way catalysts that reduce NO_x emissions while oxidizing CO, hydrocarbons and soluble organic fraction (SOF). While optimal catalyst formulations are still under investigation, a gallium and platinum zeolite lean NO_x catalyst has been costed for this report. Gallium and platinum are mixed with alumina and silica and deposited on a ceramic substrate Lean NO_x catalyst volumes are approximately 120 percent of engine displacement. A stainless steel can covers the substrate, and includes an additional 2.8 cm of length for the end caps. A 20 percent scrap factor is assumed in can

Table 5-12 **Incremental cost for advanced oxidation catalysts**

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
Catalyst Volume (l)	**6.0**	**8.0**	**13.0**	**9.0**
Supplier Costs				
Substrate	$60	$80	$130	$90
Ceria/Alumina	$24	$32	$52	$36
Can	$11	$13	$17	$14
Material Cost	$95	$125	$199	$140
Assembly Time (min)	8	9	12	11
Labor Cost	$4	$4	$6	$5
Labor Overhead @ 40%	$1	$1	$2	$2
Total Supplier Costs	$100	$130	$207	$147
Supplier Markup @ 29%	$29	$38	$60	$42
Cost to Mfg. from Supplier	**$129**	**$168**	**$267**	**$189**
Manufacturer Costs				
Cost to Mfg. from Supplier	$129	$168	$267	$189
Pt/Pd/Rd *	$66	$88	$144	$99
Vanadium *	$33	$44	$70	$49
Total Manufacturer Costs	$228	$300	$481	$337
Markup @ 29%	$66	$87	$139	$98
Total Hardware Costs	**$294**	**$387**	**$620**	**$435**
1998 Technology Costs	**$171**	**$223**	**$354**	**$251**
Total Incremental Costs	**$123**	**$164**	**$266**	**$184**

* It is assumed that engine manufacturers purchase their own precious metals and provide them to the supplier to install into the catalysts

manufacturing. Material costs to catalyst suppliers including precious metals range from $488 to $1,052 per catalyst with 24 to 40 minutes of assembly time assumed to prepare and deposit the platinum and gallium zeolite on the substrate, assemble the can and mount the substrate in the can. Since lean NO_x catalysts will be supplied by a catalyst manufacturer, all hardware costs are marked up with supplier, engine manufacturer and dealer profit and overhead.

For conversion efficiencies close to 50 percent, additional hydrocarbons need to be added to the diesel exhaust. It is assumed in this analysis that the additional hydrocarbons will be injected through the main in-cylinder injector during the exhaust stroke and will require no additional hardware beyond a system which allows split injections as described in Section 5.1. Therefore no additional cost is added here for that capability.

Estimated R&D efforts for this technology are estimated to be $10,000,000 to derive catalyst formulations and to develop the late injection methodology. Since this unit will replace the vehicle muffler, no additional on-vehicle assembly is assumed. As UBEs and HHDDEs would use the same technology and the engines are similar, the fixed costs for the two categories can be spread over the sum of the production of HHDDEs and UBEs.

The additional fuel injected during the exhaust stroke is estimated to increase fuel consumption by approximately 5 percent, but 1 percent can be recovered since this technology should allow less severely retarded injection timing.

Life-cycle costs for lean NO_x catalysts range from $1,229 for light heavy-duty engines to $4,950 for UBEs as shown in Table 5-13. Since these catalysts will replace the muffler, muffler costs need to be subtracted from the above amounts. In addition, the lean NO_x catalyst will replace any oxidation catalyst that might have been used on a 1998 engine, so the cost of the replaced oxidation catalyst should also be subtracted.

5.7 CONTINUOUSLY REGENERATING TRAPS

While most manufacturers believe that they can meet the proposed 2.4 g/bhp-hr NO_x plus NMHC standard without a trap, the lower PM standard (0.05 g/bhp-hr) for buses may require the use of particulate traps. Some of the most promising designs currently are continuously regenerating traps such as that developed by Johnson Matthey for EPA's Urban Bus Retrofit Rule.

This system uses a diesel oxidation catalyst in front of a diesel particulate trap to cause regeneration. No burner or control mechanism is needed. Since this trap has already been developed for the retrofit market, no additional R&D is assumed.

Material costs include a ceramic catalyst substrate and a ceramic trap element mounted in a stamped steel can. The catalyst is assumed to be loaded with 1.4 g/L platinum and 7.0 g/L vanadium slurried in an alumina/ceria washcoat. Material costs are $709 per catalyst with 20 minutes assumed for assembly time of the trap system. Material costs and assembly labor are assumed to occur on a supplier level and thus are marked up for supplier, manufacturer and dealer overhead and profit. No additional on-vehicle assembly is assumed since this unit would replace the muffler and catalyst.

Table 5-13 Incremental life-cycle costs for lean NO_x catalysts

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
Catalyst Volume (l)	**7.2**	**9.6**	**15.6**	**10.8**
Material Costs				
Substrate	$72	$96	$156	$108
Alumina	$12	$16	$26	$18
Gallium	$272	$362	$589	$407
Platinum	$120	$161	$261	$182
Can	$12	$14	$20	$17
Material Cost	$488	$649	$1,052	$732
Assembly Time (min)	24	29	40	35
Labor Cost	$11	$14	$19	$16
Labor Overhead @ 40%	$5	$5	$7	$6
Total Supplier Costs	$504	$668	$1,078	$754
Supplier Markup @ 29%	$146	$194	$313	$219
Cost to Mfg. from Supplier	$650	$862	$1,391	$973
Markup @ 29%	$188	$249	$403	$282
Total Material Costs	**$838**	**$1,111**	**$1,794**	**$1,255**
Fixed Costs				
R&D Costs	$10,000,000	$10,000,000	$10,000,000	$10,000,000
Units/yr.	75,000	30,000	30,000	30,000
Years to recover	5	5	5	5
Fixed cost/unit	**$37**	**$93**	**$93**	**$93**
Operating Costs				
Vehicle Lifetime (mi)	145,000	280,000	560,000	513,000
Vehicle Lifetime (yr)	10	13	12	15
Fuel Consumption				
Base fuel economy	14	10	6	4
Reduction due to Control	4%	4%	4%	4%
Cost of fuel ($/gal)	$1.11	$1.11	$1.11	$1.11
Life-cycle Operating Costs	**$354**	**$857**	**$2,974**	**$3,602**
Total Life-cycle Costs	**$1,229**	**$2,061**	**$4,861**	**$4,950**

Since particulate traps add some flow resistance to the exhaust, an increase in fuel consumption of 2 percent is estimated. Total life-cycle cost for a continuously regenerating trap is estimated to be $2,739 as shown in Table 5-14. Since these traps will replace the muffler, muffler costs need to be subtracted from the above amounts. In addition, the continuously regenerating trap will replace any oxidation catalyst that might have been used on a 1998 engine, so the cost of the replaced oxidation catalyst should also be subtracted.

5.8 CLOSED CRANKCASE SYSTEMS

While it is not envisioned that engine manufacturers will use closed crankcase systems on engines that are turbocharged and aftercooled, we have costed the option here. If there is ever a need for crankcase emission control, manufacturers may opt to include crankcase emissions with tailpipe emissions during certification, rather than contend with required filter replacements and increased aftercooler durability issues related to closed crankcase systems. Although it is not included in the cost estimate here, cleaning an aftercooler can cost approximately $200 in labor to remove, steam clean and replace, should it become clogged with oil residue.

Material costs for a closed crankcase system would include a positive crankcase ventilation valve, tubing that connects to the air cleaner and a replaceable filter. Total hardware costs are approximately $9 per engine. Assembly times to install a closed crankcase system are estimated to be 2 minutes.

Operating costs to consumers will include replacement of the filter at every other oil change interval with filters costing 3 times manufacturer cost. Since filter replacements will occur at oil changes and the time to replace a filter will be negligible, no labor for replacement of the filter is costed in the analysis.

Total life-cycle costs for closed crankcase systems range from $51 to $94 per engine as shown in Table 5-15.

Table 5-14 Incremental life-cycle costs for particulate trap catalyst

Heavy-Duty Category	Urban Bus
Engine Volume (l)	**9.0**
Material Costs	
Trap	$350
Substrate	$90
Ceria/Alumina	$36
Platinum	$151
Vanadium	$49
Can	$33
Total Material Cost	$709
Assembly Labor (min)	20
Labor Cost @ $28/hr	$9
Labor Overhead @ 40%	$4
Supplier Markup @ 29%	$209
Cost to Mfg. from Supplier	$931
Mfg./Dealer Markup @ 29%	$270
Total Variable Costs	**$1,201**
Operating Costs	
Vehicle Lifetime (mi)	513,000
Vehicle Lifetime (yr)	15
Fuel Consumption	
Base fuel economy	4
Reduction due to Trap	2%
Cost of fuel ($/gal)	$1.11
Total Annual Operating Costs	$194
Life-cycle Operating Costs	**$1,538**
Total Life-cycle Costs	**$2,739**

Table 5-15 Incremental life-cycle costs for crankcase systems

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
Hardware Cost to Manufacturer				
Hardware Costs				
PCV Valve	$5	$5	$5	$5
Filter	$2	$2	$2	$2
Tubing	$2	$2	$2	$2
Total Hardware Cost	$9	$9	$9	$9
Assembly				
Labor (min)	2	2	2	2
Labor Cost @ $28.00/hr	$1	$1	$1	$1
Overhead @ 40%	$0	$0	$0	$0
Total Assembly Cost	$1	$1	$1	$1
Total Variable Cost to Mfr.	$10	$10	$10	$10
Markup @ 29%	$3	$3	$3	$3
Total Hardware RPE	**$13**	**$13**	**$13**	**$13**
Operating Costs				
Vehicle Lifetime (mi)	145,000	280,000	560,000	513,000
Vehicle Lifetime (yr)	10	13	12	15
Filter Replacement				
Frequency (mi)	16,000	16,000	28,000	28,000
Cost (per filter)	$6	$6	$6	$6
Life-cycle Operating Costs	**$38**	**$67**	**$81**	**$64**
Total Life-cycle Costs	**$51**	**$80**	**$94**	**$77**

SECTION 6
GASOLINE ENGINE TECHNOLOGY PROJECTIONS

Strategies for reducing emissions from heavy-duty gasoline engines certified on an engine dynamometer differ from those used to reduce emissions from light-duty gasoline trucks certified on a chassis dynamometer due to differences in the weighting of the cold start portion of the respective federal test procedures. Chassis dynamometer-certified light-duty trucks weight the cold start portion at one-quarter of the total emissions weighting, while heavy-duty engines certified on an engine dynamometer weight the cold start portion at only one-seventh of the total emissions weighting. This is because heavy-duty engines are generally used for commercial applications, which tend to have continuous operation and a lower ratio of cold start driving. This reduced emphasis on cold start emissions for heavy-duty engines tends to focus emissions control technologies less on cold start emissions and more on improved catalysts which have high conversion efficiencies when fully warmed-up and good resistance to thermal deterioration.

Heavy-duty gasoline engine emission control has lagged behind light-duty gasoline truck emission control primarily due to less stringent heavy-duty gasoline emission standards. On the other hand, heavy-duty gasoline engine emissions are well below current standards partly because manufacturers can transfer technology from high-sales light-duty truck lines and the newer technology provides significant fuel economy benefits. As permissible emission levels are decreased in new regulations, lessons learned from light-duty trucks will be adapted to heavy-duty gasoline engines to provide significantly reduced tailpipe emissions.

Likely technologies to meet the proposed 2.4 g/bhp-hr NO_x plus NMHC emissions standard for heavy-duty gasoline engines are discussed below. Costs of these technologies are discussed in Section 7.

6.1 COMBUSTION CHAMBER IMPROVEMENTS

Heavy-duty gasoline engine manufacturers have learned from their light-duty engine lines how to reduce emissions while increasing performance. One of the most significant changes in combustion chamber design is proper design of in-cylinder squish and swirl to promote faster combustion. With more controlled turbulence, flame burning rates are faster and spark timing can be set so that a larger portion of the charge burning can occur on the down stroke of the piston. This design technique, which keeps combustion temperatures lower and reduces NO_x emissions without affecting performance or fuel economy, has been used on light-duty gasoline engines to reduce emissions to current levels.

Port and manifold design is also integral to low emissions and good performance. Better tuning of the intake manifolds gives more even air and EGR distribution between cylinders and results in more stoichiometric operation. This is of utmost importance when three-way catalysts are used for emission control.

Another trend in gasoline combustion chamber design is to minimize crevice volume. As shown in Figure 6-1, crevice volumes are located at the piston top-land, the head gasket, the spark plug threads, and the valve seat. The most significant of these crevices is that at the piston-ring-liner region. Crevices are considerably more important with regards to emissions in heavy-duty gasoline engines than they are in diesel engines. This is because: (1) crevices contribute to HC emissions, which are more important to control in gasoline engines (whereas NO_x and PM control is more important in diesel engines); (2) because a fuel-air mixture is inducted into the combustion chamber, hydrocarbons are present in the unburned air-fuel mixture prior to combustion in a gasoline engine; and (3) the nature of spark-ignition combustion (with a flame front propagating from the spark plug) forces unburned gas to the outer areas of the combustion chamber, which are precisely where the crevice regions exist. Gases trapped in these crevices remain unburned because of quenching of the flame as it reaches the crevice entrance.

Although crevice volumes in the combustion chamber make up only about 1 to 2 percent of the clearance volume, substantial amounts of fuel can be stored in the crevices since the unburned gases in these regions are at high pressures and have been cooled to near wall temperatures. The gas densities in the crevices are thus several times higher than the gas density of the bulk gases.

Engine manufacturers will need to continue to design gasoline engines with minimum crevice volumes. Redesigning the ring-pack, moving the piston rings higher on the piston, and chamfering the outer circumference of the piston crown are among the methods of reducing the important piston top-land crevice. Of course, such design changes must be made with due consideration to several factors such as heat transfer to the piston crown, oil control, and engine wear.

6.2 FUEL INJECTION IMPROVEMENTS

As of 1998, all heavy-duty gasoline engines will use multi-port fuel injection systems with feedback control for emissions control. Almost all of the light heavy-duty engines will use sequential multi-port injection. This allows for better control of air/fuel ratio during transients. The main improvements in fuel injection systems will result from improved nozzle spray patterns and better spray targeting. If gasoline pools on the port walls, which would occur if the injection began before the intake valve opened or if the spray was injected at too high a pressure, the result would be higher levels of hydrocarbon emissions. Minimizing pooling results in better mixing and more complete combustion.

Under normal operating conditions, the fuel injection system is closed-loop controlled. There are a few instances however, when the system runs open-loop. In cold starts, the fuel system runs open-loop until the engine coolant and the oxygen sensor reach their operating temperatures. Under wide-open throttle, the system also goes open-loop. Manufacturers program fuel injection to be fuel rich under wide-open throttle conditions so that maximum accelerations are possible and so exhaust temperatures remain cooler to prevent damage to valves and exhaust ports. By using higher temperature materials for exhaust valves and ports, manufacturers have been able to maintain mixtures at only a few percent richer than stoichiometric under these conditions. More precise control of air-fuel ratio at wide-open throttle will reduce the amount of hydrocarbon emissions that the catalyst must oxidize, resulting in lower catalyst temperatures and increased catalyst durability.

Closed-loop control of fuel injection will also improve over the coming years due to more powerful computer control systems. By decreasing off-stoichiometric operation, emissions can be greatly improved. More details on computer control system improvements are given in Section 6.5. A schematic of an electronic fuel injection system is shown in Figure 6-2.

6.3 IGNITION (SPARK) TIMING IMPROVEMENTS

Precise control of spark timing is necessary to ensure low emissions from spark ignition engines. Distributorless Ignition Systems (DIS) eliminate many of the mechanical losses associated with traditional distributor systems. Some of these losses include rotor to tower losses and losses resulting from aging of gears which decrease timing precision as the engine ages.

In current DIS systems, one coil is used to fire two cylinders 180 degrees out of phase from one another. Thus one coil is used for every two cylinders of the engine. When the controller unit energizes the two cylinder coil, both spark plugs are fired simultaneously, one in the cylinder where it is needed to start combustion and the other in the cylinder that is currently in its exhaust stroke. Since gas temperature is higher and the gas is already ionized in the out-of-phase cylinder, most of the energy is diverted to the cylinder where the spark is needed to start combustion. A schematic of this system is shown in Figure 6-3.

The next generation of this system is the "coil-on-plug". In this system, each spark plug has its own coil attached to the top of the spark plug. This system eliminates losses in high tension wires and provides higher energy to the plug. Furthermore, more precise ignition timing can result from complete computer control of spark timing. Optimum spark timing for lowest emissions and best performance can be accomplished with this system.

6.4 EXHAUST GAS RECIRCULATION IMPROVEMENTS

EGR is an effective way to reduce NO_x emissions in gasoline engines. On current heavy-duty gasoline vehicles, EGR is controlled with an EGR valve connecting the intake and exhaust manifolds. The EGR valve opening is controlled by a solenoid which in turn is controlled by the intake manifold vacuum. Under start-up (when the engine is cool), idle, and wide-open throttle conditions, a solenoid keeps the EGR valve closed. When the engine is cool, more dilution of the air/fuel mixture is undesirable since it makes the engine run rougher. Under full-throttle, there is insufficient vacuum to pull exhaust into the intake manifold. Under part-throttle conditions, the solenoid allows the valve to open so that appropriate amounts of exhaust gas recirculates into the intake manifold and combustion chamber. EGR valve control can be improved with the use of a small computer-controlled linear solenoid to control the valve opening. The EGR control valve operation signal would come from the engine electronic control module. The amount of EGR flow (via the valve opening height) would be determined by a complex algorithm using engine coolant temperature, throttle position, intake manifold pressure and engine load. This would allow for more precise positioning of the valve, more controlled recirculation rates and faster response time to changes in engine conditions. Thus, the recirculation rates can be more closely tailored to engine conditions. By increasing charge turbulence through modifications to the combustion chamber, good combustion with high dilution can be achieved. An electronically controlled system would also decrease the number of mechanical components, creating a more reliable system. No maintenance is required for such a system over the life of the vehicle. A schematic of an electronic EGR system is shown in Figure 6-4.

There are some concerns associated with an electronically-controlled system. Some durability problems associated with the vibration of the valve position feedback sensor could exist. This sensor is component located furthest from the mounting location. Deterioration of electrical components exposed to hot temperatures must also be addressed. Mounting the valve on the intake manifold, which has lower temperatures under normal operating conditions, and placing the valve in a natural air flow stream in the engine compartment may aid in the removal of heat from the component. In general, engine operating temperatures in heavy-duty vehicles are higher than those in light-duty vehicles, so heat resistant materials, such as stainless steel, should be used in some of the valve components.

6.5 ELECTRONIC CONTROL WITH ADAPTIVE LEARNING

Electronic control of engine systems has revolutionized emissions control and engine development. As computer technology improves, more precise control of all engine systems is possible. With 32-bit addressing in data transfer and faster microprocessors, changes in engine parameters can be processed more quickly and precisely. These faster and more powerful control units allow for better feedback control and more detailed control algorithms which allow the fuel system to be optimized. This ultimately leads to decreased emissions over the life of the engine. In fact, American Honda Motor Co., Inc., in a recent press release, stated that they were able to reduce off-stoichiometric operation from 53 percent of the time to 15 percent of the time using a 32-bit reduced instruction set computer (RISC) system in a light-duty vehicle. More powerful computers also allow more complex control algorithms to be utilized for control of engine systems. Additional sensors can be added and processed to provide more information on present engine conditions. This provides quicker response to transient conditions and results in improved performance and lower emissions. A sample schematic diagram of an electronic control unit and its sensors is shown in Figure 6-5.

Emissions control will also benefit from the improvement of some of electronic sensors such as oxygen sensors. A cross-section view of an oxygen sensor is shown in Figure 6-6. Oxygen sensors are crucial feedback devices which maintain stoichiometry in closed-loop fuel systems. They provide no feedback control when they are cold (below 600°F). Since minimum exhaust emissions are only possible in closed-loop operation, it is desirable for the sensor to achieve its designed operating temperature as quickly as possible. This can be done by heating the sensor with a battery-operated electrical heating element.

Most heavy-duty gasoline engines are built in a ‘V’ configuration. Some current engines have an oxygen sensor on only one of the two banks. This provides adequate information for fuel control for the one bank but with an oxygen sensor on the other bank, additional fine control of fuel injection can be achieved. Placing an oxygen sensor downstream of the catalyst, mandated in light-duty vehicles in California's on-board diagnostics (OBD-II) requirements, would also help in optimizing fuel control in gasoline heavy-duty vehicles. This would be especially beneficial during transient conditions. This sensor would also be a good diagnostic tool to monitor the health of the catalyst. If for some reason the oxygen sensor upstream of the catalyst were to malfunction, the downstream catalyst would continue to control the air/fuel mixture. Some possible configurations for oxygen sensor placement are shown in Figure 6-7.

Manufacturers are also utilizing knock sensors to provide input regarding the optimum spark timing for maximum performance while keeping emissions low. In conjunction with knock sensors, higher compression ratios can be used to increase performance while minimizing potentially damaging spark knock conditions.

Adaptive learning can also be incorporated into computer systems to automatically compensate for component wear, changing environmental conditions, varying fuel composition, etc. This allows the engine to maintain a proper air/fuel mixture under more varied driving conditions for lower emissions performance. The trend is to develop adaptive learning algorithms for not only steady-state operation, but for transient driving conditions as well.

6.6 CATALYTIC CONVERTER IMPROVEMENTS

Catalyst development has provided the largest reductions in gasoline engine emissions. Catalytic converters for heavy-duty engines are similar to those for light-duty engines, except that they must be able to handle larger mass flow rates and withstand higher operating temperatures for extended periods of time. Since there are no direct temperature control devices for catalysts, positioning and material selection are the most important design criteria.

Material selection is the key to improving catalytic converter efficiencies. Because heavy-duty gasoline engines have higher and more prolonged exhaust temperatures than light-duty vehicles, special attention must be paid to catalyst placement to prevent thermal deterioration. In some 1994 heavy heavy-duty gasoline vehicles, the three-way catalyst is placed behind the oxidation catalyst for thermal protection. This limits NO_x emissions reduction in the rear three-way catalyst due to oxygen storage and release occurring in the oxidation catalyst. However, with recent advances in catalyst technology, manufacturers now have several options to prevent thermal deterioration in heavy-duty vehicle catalysts.

Three-way catalysts traditionally use platinum and rhodium for simultaneous control of HC, CO and NO_x. Although this type of catalyst is very effective in reducing emissions, rhodium, which is primarily used to reduce NO_x emissions, tends to thermally deteriorate at temperatures significantly lower than platinum. Recent advances in palladium-only three-way catalyst technology and tri-metal (platinum, rhodium and palladium) catalysts have improved the high temperature durability of three-way catalysts.

Palladium-only and tri-metal catalysts have several advantages over platinum-rhodium three-way catalysts. First, palladium-only and tri-metal catalysts operate at lower temperatures than rhodium catalysts (light-off temperatures are approximately 70 °F lower than conventional three-way catalysts), so they can be positioned further back from the engine. This allows better temperature protection while still not dropping below light-off temperatures during low load operation. Second, palladium-only and tri-metal catalysts can tolerate higher temperatures (approximately 100 °F hotter than conventional three-way catalysts) before thermal degradation begins. Furthermore, palladium is significantly less expensive than either rhodium or platinum.

Catalyst washcoats are also undergoing improvements. The washcoat stores and releases oxygen during three-way catalyst operation allowing higher simultaneous HC, CO and NO_x conversion efficiencies. The two most widely used materials in washcoats are alumina and ceria. Recent studies have shown that increasing the levels of ceria in the washcoat can improve the oxygen storage capacity. Ceria is more effective than alumina for oxygen storage and will withstand higher exhaust temperatures.

Better control of air-fuel ratio, particularly during transients and wide-open throttle operation, will significantly improve catalyst durability. By having to process fewer unburned fuel bursts, catalyst overheating will be greatly reduced resulting in longer catalyst life.

SECTION 7
GASOLINE ENGINE TECHNOLOGY COSTS

Several 1996 LHDGEs currently meet the proposed 2.4 g/bhp-hr NO_x plus NMHC standard and several of the 1996 HHDGEs have significantly lower emissions as compared with their 1994 models. While it is possible that existing engine lines will be discontinued by 2004 and new lines will be in production by then, this analysis is concerned only with costs of compliance for 1998 engines to meet the proposed 2004 standard. Based upon current certification data, it is possible that heavy-duty gasoline engine manufacturers could meet an even lower NMHC plus NO_x values than 2.4 g/bhp-hr using the technology costed out below.

Various technology improvements and their relative incremental costs are discussed in this section. Life-cycle technology costs are not detailed in tables in this section as there are few additional costs beyond increased hardware costs that are explained in the following subsections. The one exception is advanced three-way catalysts, for which costs have been estimated in a bottom-up analysis.

7.1 IMPROVED COMBUSTION CHAMBER AND FUEL INJECTION

All combustion chamber, fuel injection and manifold changes generally occur when an engine line is developed and are accounted for in the R&D costs for a particular engine. Engine combustion chambers are generally not redesigned after an engine line is setup and in production. Slight changes may be made after a line is in production but usually these changes have to do with the improvement of hardware components, such as the valve train, and would not necessarily to improve the combustion process to achieve lower engine-out emission levels. If an engine cannot meet upcoming emissions standards, it is either upgraded to comply or discontinued and new lines are developed. Since most modifications in combustion chamber shape and fuel injection will be for performance and fuel economy reasons, no incremental costs are described in this analysis for these technology changes.

7.2 IMPROVED ELECTRONIC CONTROL

Because manufacturers are leaning toward faster microprocessors and more memory, prices of electronic control units are increasing. Currently, cost to manufacturers for control units run from $150 to $200. This price reflects hardware improvements to allow for more computer memory and software changes made to the system. According to manufacturers, this price is expected to increase by 20 percent by 1998. Since another similar increase will likely occur from 1998 to 2004, we have assumed an increase in hardware costs of $30 to $40 for electronic control units. Assembly times are not expected to increase. It is expected that more sensors will be used on future heavy-duty engines. Specifically, most manufacturers are expecting to add an additional oxygen sensor downstream of the catalytic converter by the 1998 model year to comply with California OBD requirements on LHDGEs. Since this change will most likely be in place by the 1998 model year, no increased sensor costs or increases in assembly times are expected between 1998 and 2004.

7.3 ELECTRONIC EGR

Since EGR system components are purchased by the original equipment manufacturers (OEMs) from outside suppliers, it is the increase in costs of the parts supplied to the OEMs that is important. R&D and assembly costs incurred by suppliers of this technology are therefore included in the estimated price paid by the manufacturer for those parts described in this subsection.

The use of electronically actuated EGR valves eliminates the need for some parts found on conventional EGR systems. For example, the vacuum valve is replaced by an electronic sensor in the intake manifold. In general, costs of EGR valves are very dependent on the complexity of the mounting base and the production volume. EGR valves in heavy-duty engines must be able to withstand higher operating temperatures. This may require using materials that are more corrosion resistant at higher temperatures, such as stainless steel, which costs more than the materials generally used in current valves. Another difficulty with calculating incremental costs is that some OEMs are currently using more sophisticated EGR valves than others. For some, replacement of their conventional EGR systems with electronically controlled ones would not result in an increase in cost. Others are currently using lower-cost, less sophisticated systems, and their incremental cost will thus be higher. Still others will not be using EGR at all on their 1998 model engines and might have to incur the cost of adding this unit to meet the proposed 2004 standards. In larger engines, space for the placement of the EGR valve is sometimes an issue. If the valve has to be placed in an unconventional position, the cost of a complex mounting base might drive up the cost of the valve assembly considerably.

The tubing and duct work would be identical for both systems. Vacuum actuated valves currently run between $20 and $30 for a conventional mounting base design. An electronic EGR valve with a simple mounting base cost between $30 and $40. These costs could vary significantly if high temperature resistant materials are used, if the mounting configuration is unconventional, or if production numbers are low. Incremental costs for electronic EGR systems could thus vary from $10 to $50.

EGR assembly costs would not be greatly affected by the change from a conventional EGR system to an electronically-controlled one. Because the valve opening would be electronically controlled, there would be one less connection to make; the vacuum connection would be eliminated. The remainder of the installation procedure would be the same, so installation costs would be unchanged.

7.4 IMPROVED SPARK TIMING

Heavy-duty engines in 1998 will use both distributorless and conventional distributor ignition systems. By 2004, it is expected that all heavy-duty engines in production will use coil-on-plug ignition systems. Although there are fewer parts in the distributorless and coil-on-plug systems than there are in conventional systems, the costs of the parts are expected to increase slightly. The cost increase to improve from a conventional distributor system to a distributorless ignition system is expected to be $8 to $15. The cost to improve from a distributorless ignition system to a coil-on-plug is expected to be $20 to $25. Distributorless ignition systems will not be used by all OEMs in either light heavy-duty or heavy heavy-duty engines, so the costs to improve ignition systems will be dependent on the components used in the 1998 engines. We have estimated that one-third of engine lines will have distributorless ignition systems by 1998, while the other two-thirds will use conventional systems. Thus the incremental costs for upgrading to coil-on-plug ignition systems from the average 1998 engine will range from $25 to $35.

Ignition system assembly times vary depending on the ignition system. The assembly time for conventional distributor systems, including testing time, is approximately four minutes. Distributorless ignition systems eliminate the need for the installation of a distributor; since the coil packs are mounted on the engine block on brackets. Although there are fewer parts to assemble, the assembly is slightly more difficult to perform, so the overall assembly and testing time is approximately one minute longer per engine than a conventional system. Assembly of a coil-on-plug system is significantly simpler than the other two systems. Because the coils are positioned on the spark plug, there are no cables. There is only an electrical connection which needs to be made between each coil and the control unit. Assembly times for coil-on-plug systems would be dependent on the number of cylinders in the engine. It is expected that 15 seconds is needed per plug, so a six cylinder engine would take about 1.5 minutes and an eight cylinder engine two minutes including testing time. Thus, assembly time would be only half that required for conventional systems.

7.5 IMPROVED CATALYSTS

Current 1996 engines use three-way catalysts coupled with an oxidation catalyst. Only slight changes in catalysts will need to occur from 1998 to 2004 for engines to meet the standards. We have assumed that tri-metallic three-way catalysts with increased precious metal loading will be used instead of the current two-metal catalysts. We have also assumed that current catalysts are one-third platinum and two-thirds palladium with a loading of 1.4 g/L. The total "bottom up" estimated catalyst cost for a LHDGE with a dual catalyst system is approximately $206 which is consistent with prices quoted by parts suppliers.

The improved three-way catalysts in this analysis contain 30 percent by weight platinum, 55 percent palladium and 15 percent rhodium with a precious metal loading of 1.8 g/L. Incremental catalyst costs for this scenario run $77 for the LHDGE and $96 for the HHDGE as shown in Table 7-1.

Assembly times for the OEMs are not expected to increase with improvements to catalytic converters. The improvements in catalytic converters will come mainly from the improvements in the materials and manufacturing processes of the converters themselves. Assembly of a catalytic converter on a heavy-duty vehicle is estimated to be between two to three minutes. Three-way catalysts are expected to last the useful life of the vehicle.

7.6 SYSTEM CALIBRATION

Most of the research and development efforts needed to meet the proposed 2004 standards will be spent in system calibration. Engines are generally recalibrated every three years. While light heavy-duty engines are already emitting at the levels of the proposed 2004 standards due to California's medium-duty regulations, heavy heavy-duty gasoline engines will require more

Table 7-1 Incremental costs for three-way catalysts

	CURRENT		FUTURE	
Heavy-Duty Category	**Light**	**Heavy**	**Light**	**Heavy**
Catalyst Volume (l)	**3.0**	**3.8**	**3.0**	**3.8**
2 CATALYSTS REQUIRED				
Supplier Costs				
Substrate	$25	$32	$25	$32
Ceria/Alumina	$9	$11	$9	$11
Can	$1	$2	$1	$12
Total Material Cost	$35	$45	$35	$45
Assembly Time (min)	8	9	8	9
Labor Cost	$4	$4	$4	$4
Labor Overhead @ 40%	$2	$2	$2	$2
Total Supplier Costs	$41	$51	$41	$51
Supplier Markup @ 29%	$12	$15	$12	$15
Cost to Man. from Supplier	$53	$66	$53	$66
Pt/Pd/Rd*	$27	$34	$57	$71
Total Manufacturer Costs	**$80**	**$100**	**$110**	**$137**
Total Manufacturer Cost (per engine)	**$160**	**$200**	**$220**	**$274**
Incremental Cost to Manufacturer			**$60**	**$74**
Manufacturer & Dealer Markup @ 29%	$23	$29	$32	$40
Total RPE (per catalyst)	**$103**	**$129**	**$142**	**$177**
Total RPE (per engine)	**$206**	**$258**	**$283**	**$354**
Incremental RPE			**$77**	**$96**

* It is assumed that the engine manufacturers purchase their own precious metals and give them to the supplier to install into the catalysts.

sophisticated system calibration which can cost up to $2,000,000 per engine line. Significant testing is need to develop the fuel injection and spark timing algorithms and map. Since system calibration is defined by software, no additional hardware costs are incurred.

SECTION 8
ADVANCED 2004 TECHNOLOGY TRENDS

With eight years remaining, diesel engine manufacturers are pursuing all options possible for reaching the proposed 2.4 g/bhp-hr NO_x plus NMHC standard. Some manufacturers believe that they will be able to reach this standard with improved fuel, air and combustion systems only. High pressure electronic unit injection will be commonplace on most diesel engines with sophisticated electronic control of all systems. Some manufacturers plan to use limited EGR in some of their engine lines while others believe that they will reach the standards without it. Others still believe that lean NO_x catalysts may be available to meet the standards sometime after 2004. While at this point it is difficult to provide firm strategies for meeting the standards, we have provided likely scenarios that manufacturers might use. Likely technologies that might be used on diesel engines are shown in Table 8-1 while likely technologies for gasoline engines are shown in Table 8-2.

Engineering design goals for the proposed 2.4 g/bhp-hr NO_x plus NMHC engines (with the PM standard remaining at 0.1 g/bhp-hr) will most likely require 2.0 g/bhp-hr NO_x, 0.1 g/bhp-hr HC and 0.07 g/bhp-hr PM[6]. Regulation of crankcase emissions could add even more complexity to emission control systems as discussed in Section 4.9.

8.1 LIGHT HEAVY-DUTY DIESEL ENGINES

LHDDEs will most likely be able to meet the proposed standards with both DI and IDI technology. Light-duty vehicles that use IDI diesel engines have shown very low emissions. IDI engines can use geometry-dependent air motion to achieve optimum air-fuel mixing and are therefore less dependent on injection pressure. IDI engines are also much more tolerant of EGR than DI engines for NO_x reductions. The disadvantages of IDI engines are a comparatively large reduction (10 to 15 percent) in fuel economy, higher HC emissions and increased heat loss to the radiator. However, IDI engines will still provide better fuel economy than gasoline engines of the

[6] Urban buses, which have a PM standard of 0.05 g/bhp-hr, will have PM engineering design goals of 0.035 g/bhp-hr.

Table 8-1 Likely technologies for diesel engine control

NO_x Control	PM Control
• Split injection or rate shaping • Exhaust gas recirculation • Optimized combustion • Advanced electronics	• Higher pressure injection • Improved spray pattern • Better oil control • Variable geometry turbocharger

Table 8-2 Likely technologies for gasoline engine control

NO_x and HC Control
• Electronic EGR • Optimized ignition timing • Improved closed-loop control with adaptive learning • Optimized three-way catalyst

same power and emissions rating.

The light heavy-duty DI diesel engine will most likely use high pressure electronic unit injection. Several manufacturers have developed common rail injection systems which provide more flexibility with injection timing and duration and rate shaping. Fuel injection systems will be improved to provide higher injection pressures, improved spray patterns, and split or rate shaped injection. Variable geometry turbochargers might be used in this class to provide better transient response and optimum conditions for EGR to flow at low speeds and loads as well as provide better PM control. Combustion chambers will also be reoptimized for the improved fuel injection and air systems. Combustion chamber improvements might include optimization of combustion through piston bowl shape modifications, optimum injection timing and duration, and better oil control. Hot EGR most likely will be used on these engines for additional NO_x control.

8.2 MEDIUM HEAVY-DUTY DIESEL ENGINES

The MHDDE will also use high pressure electronic unit injectors. Common rail injection systems, developed by some manufacturers, will provide significant emissions improvements. The

Caterpillar and Navistar HEUI system provides common rail injection capabilities fairly independent of speed. In addition, this system can be used for rate shaping. Other manufacturers will upgrade their cam-driven electronic unit injectors to allow split injection or rate shaping. High pressure injection (25,000 psi and higher) will most likely be used. Manufacturers will also work to improve spray patterns to reduce wall wetting and improve mixing, modify the combustion chamber to work with fuel and air improvements, and use better oil control strategies. Variable geometry turbochargers might also be used for better transient response and lower PM emissions. Manufacturers agree at this point that only limited Hot EGR will be used, with most of the emission improvements coming from fuel, air and combustion chamber shape modifications.

8.3 HEAVY HEAVY-DUTY DIESEL ENGINES

HHDDE manufacturers plan to meet the proposed 2004 standards through basic improvements in fuel system, air system and combustion system. Most manufacturers state that they will try to avoid the use of EGR. Currently heavy heavy-duty engines are running close to one million miles between rebuilds and significant use of EGR may raise durability issues. Research and development will most likely resolve the complexity and potential problems associated with extensive EGR usage, but EGR still may be less desirable than other methods which can be employed to reduce HHDDE emissions.

Fuel system improvements will probably include higher pressure injection, rate shaping and improved spray patterns. Those currently using high pressure electronic unit injectors will most likely modify them to provide rate shaping or split injection. Those with common rail systems will optimize injection pressures and provide rate shaping.

Manufacturers will most likely consider variable geometry turbochargers to provide quicker response and more precise control over boost pressure. Combustion chambers will also be optimized for the new air and fuel system modifications.

One of the greatest boons to emissions control technology is electronic control. With more powerful computer systems, the control algorithms can be more sophisticated and able to provide optimum control over fuel and air systems. By being able to inject the precise amount of fuel at a rate and time that is optimum for both combustion and emissions, engines can provide good performance with significantly lower emissions.

Most manufacturers will try to meet the proposed 2004 standards without an oxidation catalyst. Because heavy heavy-duty engines are low in SOF emissions, oxidation catalysts will not provide much PM reduction. However, some manufacturers may try to use oxidation catalysts to eliminate hydrocarbon emissions to allow slightly higher NO_x emissions.

Lean NO_x catalysts are still in the development stage. Much development effort will need to be done before any significant NO_x reduction efficiency is possible. If lean NO_x catalysts become available in the 2004 time frame and are 20 percent effective over the federal test procedure with the promise that in a few years they may be 50 percent effective, manufacturers would begin integrating these catalysts into their engine designs. At this point, however, no heavy-duty engine manufacturer is predicting that this technology will be viable in the 2004 time frame.

8.4 URBAN BUSES

UBEs will follow the development path of the HHDDE. However, UBEs will need to meet a lower particulate standard which most likely will require the use of a particulate trap or oxidation catalyst. Manufacturers have a variety of options here, such as early introduction of alternative fuel buses to offset diesel bus emissions after 2004. Alternative fuels provide the fewest challenges in this centrally-fueled market and several low NO_x alternative fuel engines have already demonstrated 2004 emission levels.

While manufacturers currently resist the use of particulate traps, they are watching carefully the development of passive regenerative traps and those that use fuel additives to regenerate. Passive regenerative traps do not require the extensive burner and control mechanisms that early trap technology required. Much research is being undertaken by both engine manufacturers and trap technology manufacturers to perfect this form of aftertreatment.

Oxidation catalysts will most likely be used in this market as they provide cost effective reduction of SOFs, HC and CO emissions. Most manufacturers are more comfortable with proven catalyst technologies than they are with the less-proven trap technologies.

8.5 LIGHT HEAVY-DUTY GASOLINE ENGINES

Due to extensive improvements in electronic control, sequential multi-port fuel injection, and catalyst formulations, 1996/1997 gasoline engines of this category are being certified at emission levels well below the proposed 2004 emission standards. In fact, Ford has certified several of its 1997 LHDGE lines at levels below 0.4 g/bhp-hr NO_x + NMHC. This has been accomplished by utilizing emissions improvement technologies on light-duty vehicles and trucks, such as optimized ignition timing for best emissions and performance, optimized three-way catalyst formulations and catalyst location, and improved closed loop control with adaptive learning. While EGR will continue to be used in some engines, it use will be limited where possible to improve fuel economy while still maintaining low emissions.

8.6 HEAVY HEAVY-DUTY GASOLINE ENGINES

While much improvement has been shown in this class in the 1996 models, further improvements will be necessary to meet the SOP requirements. Most likely to meet 1998 emission standards, all engines of this class will also be multi-port fuel injected with three-way catalysts and closed-loop control. Closer control of wide-open throttle operation will also be part of the 1998 strategy.

Technology on these engines will most likely follow the development of the LHDGEs. This will include more precise fuel injection control especially during transient and wide-open throttle operation and optimized three-way catalysts. Optimized spark timing for best fuel economy and emissions together with EGR will continue to be strategies for low emissions.

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APPENDIX A
COST ANALYSIS DETAILS

A.1 EXHAUST GAS RECIRCULATION TUBING COSTS

Tubing costs for three EGR systems are detailed in this section. The three types of tubing detailed here are hot EGR finned tubing, low-flow cooled EGR tubing and high-flow cooled EGR tubing. It is assumed that all tubing is made of stainless steel to minimize corrosion. Stainless steel properties and costs used in these calculations are given in Table A-1.

A.1.2 Low-Flow Hot EGR Tubing Costs

EGR flow rates were calculated to handle eight percent of air flow passing through the engine at a mid-speed condition. Engine speeds used for calculating tubing sizes were 2080 rpm for LHDDEs, 1900 rpm for MHDDEs and 1560 rpm for HHDDEs and UBEs. One engine volume of air flow moves through an engine every other crank shaft revolution. Assuming eight percent of air flow at these conditions, tubing diameters were estimated to be 3.3 cm for the LHDDE, 3.6 cm for the MHDDE, 4.1 for a HHDDE and 3.5 for an UBE. Cooling fins were assumed to be square and two times the tubing diameter in length and width. Based upon heat rejection of 2.2 to 3.7 kW at a mid load and speed condition to provide a 110°C to 120°C temperature drop in the EGR stream, cooling fin surface areas were calculated for each engine using a gas to gas heat transfer rate of 25 W/m^2-°C. This resulted in 53 to 55 fins depending on fin size. Assuming the fins are spaced at 1 cm intervals and that the tubing needed to be long enough for the finned section to be at the front of the engine compartment, tubing lengths were then calculated. Based upon these assumptions, material costs varied from $13 for the LHDDE to $23 for the HHDDE. Fabrication and assembly

Table A-1. Stainless steel costs and density

Cost per pound	$1.72
Cost per gram	$0.004
Density (g/cm^3)	7.7

time was assumed at 2 seconds per 10 cm of tubing length to extrude the tubing, 2 seconds to stamp each fin, and another 2 seconds to attach each fin to the tubing. Using these assumptions, labor costs plus supplier overhead varied from $26 to $28. With a supplier markup of 29 percent, total finned tubing costs for the hot EGR system ranged from $51 to $66, as shown in Table A-2.

A.1.2 Low-Flow Cooled EGR Tubing Costs

EGR flow rates were calculated to handle eight percent of air flow passing through the engine at a mid-speed condition. As in the Hot EGR case, engine speeds used for the calculation were 2080 rpm for LHDDEs, 1900 rpm for MHDDEs and 1560 rpm for HHDDEs and UBEs. One engine volume of air flows through an engine every other crank shaft revolution. Based upon these assumptions, tubing diameters were estimated to be 3.3 cm for the LHDDE, 3.6 cm for the MHDDE, 4.1 for the HHDDE and 3.5 for the UBE. The tubing needed to be long enough to connect a EGR cooler between the exhaust manifold and the EGR valve. Tubing lengths were estimated to from 91 cm to 198 cm depending on engine size. Material costs varied from $3 for the LHDDE to $10 for the HHDDE. Tubing fabrication time was estimated to be 2 seconds per 10 cm of tubing length. Using these assumptions, labor costs plus supplier overhead varied from $3 to $7. Tubing to connect the EGR cooler to the engine block for coolant flow and hose clamps were estimated cost another $1 to $3 depending on engine size. With a supplier markup of 29 percent, total tubing costs for the low-flow cooled EGR system ranged from $9 to $26 as shown in Table A-3.

A.1.3 High-Flow Cooled EGR Tubing Costs

EGR flow rates were calculated to accommodate fifteen percent of air flow passing through the engine at a mid-speed condition. Engine speeds used for the calculation were 2080 rpm for LHDDEs, 1900 rpm for MHDDEs and 1560 rpm for HHDDEs and UBEs. One engine volume of air flows through an engine every other crank shaft revolution. Tubing diameters were estimated to be 4.5 cm for the LHDDE, 4.9 cm for the MHDDE, 5.7 for the HHDDE and 4.7 for the UBE. The tubing needed to be long enough to connect the EGR cooler between the exhaust manifold and the EGR valve. Tubing lengths were estimated to from 91 cm to 198 cm depending on engine size. Material costs varied from $5 for the LHDDE to $13 for the HHDDE. Tubing fabrication time was estimated to be 2 seconds per 10 cm of tubing length. Using these assumptions, labor costs with supplier overhead varied from $3 to $7. Tubing to connect the water jacket cooler to the engine block for coolant flow and hose clamps were estimated to be another $1 to $3 depending on engine size. With a supplier markup of 29 percent, total tubing costs for the high flow cooled EGR system ranged from

Table A-2 Low-flow hot EGR tubing costs

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
Engine Volume (l)	6.0	8.0	13.0	9.0
Engine Speed (rpm)	2080	1900	1560	1560
EGR Flow Rate (l/sec)	8.3	10.1	13.5	9.4
EGR Flow Rate (g/sec)	18.4	20.9	27.7	19.2
Cooling (°C)	110	115	120	120
Heat Rejected (kW)	2.2	2.6	3.7	2.5
Tubing Dimensions				
Diameter (cm)	*3.3*	*3.6*	*4.1*	*3.5*
Length (cm)	*116*	*135*	*187*	*147*
Surface Area (cm^2)	*1184*	*1519*	*2443*	*1592*
Fin Size (cm^2)	*42*	*52*	*69*	*48*
Number of Fins	*55*	*53*	*55*	*55*
Cooling Surface Area (cm^2)	*2323*	*2751*	*3809*	*2637*
Thickness of steel (cm)	*0.127*	*0.127*	*0.127*	*0.127*
Volume of steel (cm^3)	*264*	*454*	*1311*	*537*
Weight of steel (g)	*3429*	*4175*	*6114*	*4135*
Material Costs	$13	$16	$23	$16
Labor @ $28.00 per hour	$19	$19	$20	$19
Overhead @ 40%	$8	$7	$8	$8
Supplier Markup @ 29%	$11	$12	$15	$12
Total Tubing Costs	**$51**	**$54**	**$66**	**$55**

Table A-3 Low-flow cooled EGR tubing costs

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
Engine Volume (l)	6.0	8.0	13.0	9.0
Engine Speed (rpm)	2080	1900	1560	1560
EGR Flow Rate (l/sec)	8.3	10.1	13.5	9.4
Tubing Dimensions				
Diameter (cm)	*3.3*	*3.6*	*4.1*	*3.5*
Length (cm)	*91*	*122*	*198*	*137*
Surface Area (cm^2)	*935*	*1376*	*2582*	*1488*
Thickness of steel (cm)	*0.127*	*0.127*	*0.127*	*0.127*
Volume of steel (cm^3)	*119*	*175*	*328*	*189*
Weight of steel (g)	*914*	*1345*	*2525*	*1455*
Material Costs	$3	$5	$10	$6
Labor @ $28.00 per hour	$2	$3	$5	$3
Overhead @ 40%	$1	$1	$2	$1
Water Jacket Tubing	$1	$2	$3	$3
Supplier Markup @ 29%	$2	$3	$6	$4
Total Tubing Costs	**$9**	**$14**	**$26**	**$17**

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$12 to $30 as shown in Table A-4.

A.2 EGR COOLER COSTS

Costs for two types of EGR coolers are detailed in this section. The two types of coolers described here are for a low-flow system (eight percent EGR at mid load and speed ranges) and a high-flow system (fifteen percent EGR at mid load and speed ranges). All coolers are assumed to be made of stainless steel to minimize corrosion.

A.2.1 Low-Flow EGR Cooler Costs

EGR flow rates were calculated to accommodate eight percent of air flow passing through the engine at a mid-speed condition. Estimated mid engine speeds and loads used for the calculation were 2080 rpm and 7.0 bar for LHDDEs, 1900 rpm and 8.2 bar for MHDDEs, 1560 rpm and 9.0 bar for HHDDEs, and 1560 rpm and 8.5 bar for UBEs. Assuming one engine volume of air moves through an engine every other crank shaft revolution and cooling the EGR flow from 300°C to 325°C depending on engine size, heat rejection rates were calculated. These calculated heat rejection rates

Table A-4 High-flow cooled EGR tubing costs

Heavy-Duty Category	**Light**	**Medium**	**Heavy**	**Urban Bus**
Engine Volume (l)	6.0	8.0	13.0	9.0
Engine Speed (rpm)	2080	1900	1560	1560
EGR Flow Rate (l/sec)	15.6	19.0	25.4	17.6
Tubing Dimensions				
Diameter (cm)	*4.5*	*4.9*	*5.7*	*4.7*
Length (cm)	*91*	*122*	*198*	*137*
Surface Area (cm^2)	*1280*	*1884*	*3536*	*2037*
Thickness of steel (cm)	*0.127*	*0.127*	*0.127*	*0.127*
Volume of steel (cm^3)	*163*	*239*	*449*	*259*
Weight of steel (g)	*1252*	*1842*	*3458*	*1992*
Material Costs	$5	$7	$13	$8
Labor @ $28.00 per hour	$2	$3	$5	$3
Overhead @ 40%	$1	$1	$2	$1
Water Jacket Tubing	$1	$2	$3	$3
Supplier Markup @ 29%	$3	$4	$7	$4
Total Tubing Costs	**$12**	**$17**	**$30**	**$19**

varied from 6.1 kW for the LHDDE to 9.9 kW for the HHDDE. Based upon these heat rejection requirements and a gas to liquid heat transfer rate of 40 W/m^2-°C, cooler sizes were calculated.

Coolers were assumed to be stainless steel tube-in-shell heat exchangers. The outside diameter of the cooler varied from 5.6 cm to 6.0 cm depending on engine size. Cooler lengths varied from 30.5 to 40.5 cm plus another 5 cm for the end caps. Based upon the assumption that the tubes would occupy 65 percent of the internal cross-sectional area of the shell and the tubes were 9.3 mm in diameter, from 51 to 59 tubes would be inside the shell depending on cooler size. With 20 percent scrap allowance, the total material cost for the tube-in-shell heat exchangers varied from $24 for the LHDDE to $36 for the HHDDE. Labor costs to assemble the heat exchanger plus supplier overhead varied between $13 to $18. With a supplier markup of 29 percent, total low-flow cooler costs ranged from $48 to $70 as shown in Table A-5.

A.2.2 High-Flow EGR Cooler Costs

EGR flow rates were calculated to accommodate fifteen percent of air flow passing through the engine at a mid-speed condition. Engine speeds and loads used for the calculation were 2080 rpm and 7.0 bar for LHDDEs, 1900 rpm and 8.2 bar for MHDDEs, 1560 rpm and 9.0 bar for HHDDEs, and 1560 rpm and 8.5 bar for UBEs. Assuming one engine volume of air flows through an engine every other crank shaft revolution and cooling the EGR stream from 325°C to 350°C depending on engine size, heat rejection rates were calculated. These heat rejection rates varied from 12.4 kW for the LHDDE to 20.1 kW for the HHDDE. Based upon this heat rejection requirements and a gas to liquid heat transfer rate of 40 W/m^2-°C, cooler sizes were calculated.

Coolers were assumed to be stainless steel tube-in-shell heat exchangers. The outside diameter of the cooler varied from 7.6 cm to 7.9 cm depending on engine size. Cooler lengths varied from 30.5 to 45.7 cm plus another 5 cm for the end caps. Based upon the assumption that the tubes would occupy 65 percent of the internal cross-sectional area of the shell and the tubes were 9.3 mm in diameter, from 94 to 101 tubes would be inside the shell depending on cooler size. With 20 percent scrap allowance, the total material cost for the tube-in-shell heat exchangers varied from $43 for the LHDDE to $65 for the HHDDE. Labor costs to assemble the heat exchanger plus supplier overhead varied between $23 to $35. With a supplier markup of 29 percent, total high-flow cooler costs ranged from $85 to $129 as shown in Table A-6.

Table A-5 Low-flow EGR cooler costs

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
Engine Volume (l)	6.0	8.0	13.0	9.0
Engine Speed (rpm)	2080	1900	1560	1560
Engine Power (bar)	7.0	8.2	9.0	8.5
Turbo Boost (bar gauge)	1.00	0.86	0.85	0.85
EGR Flow Rate (l/sec)	8.3	10.1	13.5	9.4
EGR Flow Rate (g/sec)	18.4	20.9	27.7	19.2
Cooling (°C)	300	320	325	325
Heat Rejection (kW)	6.1	7.4	9.9	6.9
Cooler Dimensions				
Diameter (cm)	*5.6*	*6.0*	*6.0*	*5.8*
Length (cm)	*30.5*	*30.5*	*40.6*	*30.5*
Working Length (cm)	*35.5*	*35.5*	*45.6*	*35.5*
Surface Area of Can (cm^2)	*680*	*729*	*919*	*697*
Number of Tubes	*51*	*59*	*58*	*54*
Surface Area of Tubes (cm^2)	*4691*	*5339*	*7093*	*4910*
Total Area (w/20% scrap)	*6445*	*7281*	*9615*	*6729*
Thickness of steel (cm)	*0.127*	*0.127*	*0.127*	*0.127*
Volume of steel (cm^3)	*818*	*925*	*1221*	*855*
Weight of steel (g)	*6302*	*7120*	*9402*	*6580*
Material Costs	$24	$27	$36	$25
Labor @ $28.00 per hour	$9	$10	$13	$9
Overhead @ 40%	$4	$4	$5	$4
Supplier Markup @ 29%	$11	$12	$16	$11
Total Cooler Costs	**$48**	**$53**	**$70**	**$49**

Table A-6 High-flow EGR cooler costs

Heavy-Duty Category	Light	Medium	Heavy	Urban Bus
Engine Volume (l)	6.0	8.0	13.0	9.0
Engine Speed (rpm)	2080	1900	1560	1560
Engine Power (bar)	7.0	8.2	9.0	8.5
Turbo Boost (bar gauge)	1.00	0.86	0.85	0.85
EGR Flow Rate (l/sec)	15.6	19.0	25.4	17.6
EGR Flow Rate (g/sec)	34.6	39.2	52.0	36.0
Cooling (°C)	300	320	325	325
Heat Rejection (kW)	11.4	13.8	18.6	12.9
Cooler Dimensions				
Diameter (cm)	*7.7*	*7.6*	*7.8*	*7.9*
Length (cm)	*30.5*	*35.6*	*45.7*	*30.5*
Working Length (cm)	*35.5*	*40.6*	*50.7*	*35.5*
Surface Area of Can (cm^2)	*956*	*1065*	*1332*	*980*
Number of Tubes	*96*	*94*	*97*	*101*
Surface Area of Tubes (cm^2)	*8795*	*10,011*	*13,299*	*9207*
Total Area (w/20% scrap)	*11,702*	*13,291*	*17,558*	*12,225*
Thickness of steel (cm)	*0.127*	*0.127*	*0.127*	*0.127*
Volume of steel (cm^3)	*1486*	*1688*	*2230*	*1553*
Weight of steel (g)	*11,443*	*12,997*	*17,170*	*11,955*
Material Costs	$43	$49	$65	$45
Labor @ $28.00 per hour	$16	$19	$25	$17
Overhead @ 40%	$7	$7	$10	$7
Supplier Markup @ 29%	$19	$22	$29	$20
Total Cooler Costs	**$85**	**$97**	**$129**	**$89**