ECONOMIC ANALYSIS OF DIESEL AFTERTREATMENT SYSTEM CHANGES MADE POSSIBLE BY REDUCTION OF DIESEL FUEL SULFUR CONTENT

REVISED FINAL REPORT

December 3, 1999

EPA Contract No. 68-C-98-170
Work Assignment No. 9
Task 1

Engine, Fuel, and Emissions
Engineering, Incorporated

9812 Old Winery Place, Suite 22 ph. (916) 368-4770
Sacramento, CA 95827-1732 USA fax (916) 362-2579

Economic Analysis of Diesel Aftertreatment System Changes Made Possible By Reduction Of Diesel Fuel Sulfur Content

Revised Final Report

Prepared Under EPA Contract No. 68-C-98-170
Work Assignment No. 9

December 3, 1999

Prepared by
Christopher S. Weaver, P.E.
Lit-Mian Chan
Engine, Fuel, and Emissions Engineering, Inc.
9812 Old Winery Place, Suite 22
Sacramento, CA 95827 USA
(916) 368-4770

CONTENTS

LIST OF TABLES

1. INTRODUCTION

On May 13th, 1999, the U.S. Environmental Protection Agency (EPA) published an Advanced Notice of Proposed Rulemaking concerning new requirements for diesel fuel[1]. While EPA solicited comments on all aspects of diesel fuel quality, the focus of EPA's interest is on the establishment of new and much stricter limits on the fuel's sulfur content. According to the ANPRM, EPA's principal motivation for proposing to tighten fuel sulfur limits was to enable the deployment of advanced diesel emission control technologies. These technologies are estimated to have the potential to reduce diesel NOx emissions by 75% and emissions of particulate matter (PM) by 80% or more compared to present emission standards. Such technologies would be required in order for diesel light-duty vehicles to meet EPA's proposed Tier 2 emission standards, and for heavy-duty diesel engines to meet the new emission standards now being considered for 2007 and later model years.

Promising diesel emission control technologies identified by EPA in its ANPRM include:

- Cooled exhaust gas recirculation (EGR);
- Oxidation catalytic converters;
- Particulate filters;
- Lean NOx catalysts;
- Selective catalytic reduction; and
- NOx storage catalyst systems.

Of the technologies on this list, one – cooled EGR – would reduce the amount of NOx formed in the diesel engine. The other five are aftertreatment technologies. These are intended to eliminate NOx and PM after they are produced by the engine, but before they are emitted from the exhaust pipe. It is these latter technologies that are the subjects of this report.

1.1 DIESEL AFTERTREATMENT TECHNOLOGIES

Aftertreatment technologies to reduce diesel NOx and PM emissions have been the subjects of intense research and development efforts for more than two decades, but have seen only limited application on vehicles up to the present time. Because diesel engines typically operate with very lean air-fuel ratios, the three-way catalytic converter systems used to control NOx emissions from spark-ignition engines are ineffective. Lean NOx catalysts work to reduce NOx despite the overall oxidizing nature of diesel exhaust by reacting the NOx with unburned hydrocarbons (HC), which serve as the reductant. NOx adsorbers capture NOx chemically under lean conditions, and must be regenerated periodically under rich conditions to remove and reduce the trapped NOx. Selective catalytic reduction (SCR) systems react NOx with ammonia to produce nitrogen and water.

Aftertreatment technologies intended for control of diesel PM emissions include oxidation catalytic converters and diesel particulate filters or "traps". Oxidation catalysts work primarily by burning part of the organic vapors that would otherwise condense and add to the particulate matter. Because they have little effect on the carbon component of the PM, they are typically only about 20 to 30% effective in reducing PM emissions. The catalysts used in SCR systems also function as oxidation catalysts for this purpose.

Particulate filters or "traps" do collect carbon PM and other solid particles in the exhaust, and can achieve PM control efficiencies of 90% or more. The carbon PM quickly plugs the filter, however, requiring that some system be put in place to clean the filter by burning or otherwise removing the carbon PM - a process known as "regeneration". Most regeneration systems include a catalyst to promote carbon PM oxidation. One of the most promising regeneration technologies uses an oxidation catalyst to convert NO in the exhaust to NO_2, which then reacts with and oxidizes the collected particulate matter.

Oxidation catalytic converters and aftertreatment devices that include oxidation catalysts (such as traps and SCR systems) are also effective in reducing HC, CO, and toxic emissions from diesel engines.

1.2 EFFECTS OF FUEL SULFUR LEVEL ON AFTERTREATMENT SYSTEMS

The levels of sulfur found in diesel fuel pose a substantial barrier to aftertreatment technologies. Sulfur binds to and poisons NOx adsorbers, and temporarily reduces the efficiency of platinum group metal (PGM) catalysts used in oxidation catalyst systems. Even worse, the presence of SO_2 limits the amount and activity of PGM catalysts that can be used in diesel systems. This is because the PGM catalysts also oxidize SO_2 to SO_3, which can then react with water in the exhaust to form sulfuric acid - H_2SO_4. The resulting acid droplets are a health hazard, and also contribute to measured particulate emissions.

Because of these effects, the Manufacturers of Emission Controls Association (MECA) has urged EPA to reduce the levels of sulfur permitted in diesel fuel from the present 500 parts per million (already a 10-fold reduction from uncontrolled levels) to no more than 30 ppm[2]. Some analysts believe that sulfur levels as low as 10 ppm may be required for NOx aftertreatment systems to be practical.

EPA is now in the process of developing a "Notice of Proposed Rulemaking" (NPRM) on diesel fuel sulfur, based on information received in response to its ANPRM. As part of this development, EPA assigned ICF Consulting and its subcontractor, Engine, Fuel, and Emissions Engineering, Inc. to study the effects of greatly-reduced fuel sulfur levels on engine durability and maintenance costs and on the costs and efficiency of diesel aftertreatment systems. This latter issue was assigned to EF&EE, and the results are presented in this report. A separate report on engine durability and maintenance costs has also been prepared.

1.3 GUIDE TO THE REMAINDER OF THE REPORT

The remainder of this report comprises seven chapters. Chapter 2 presents the assumptions and analytical methodology used in the study. Chapters 3 through 7 each deal with one diesel aftertreatment technology: Chapter 3 with oxidation catalysts, Chapter 4 with diesel particulate filters, Chapter 5 with lean NOx catalysts, Chapter 6 with NOx storage catalyst systems, and Chapter 7 with selective catalytic reduction systems. Chapter 8 summarizes the study results.

2. METHODOLOGY AND ASSUMPTIONS

2.1 METHODOLOGY FOR COST ESTIMATION

To bring some order and reproducibility to cost estimates of emission control systems, EPA has developed a standard retail price equivalent (RPE) technique[3]. We applied this technique, along with available cost data and estimates, to estimate the incremental cost of an EHC in a typical vehicle. EPA's RPE methods were first outlined by Lindgren[4] in a study done for EPA in 1978, and refined by Putnam, Hayes, and Bartlett (PHB)[5]. The present study utilizes an adapted version of PHB's method that eliminates the use of assumed "markup" percentages in favor of specific estimates of the effects of each technology on indirect costs. This modified approach was adopted on the basis of industry comments, and is considered to better reflect actual pricing practices in the industry than the Lindgren method.

Cost estimation for heavy-duty diesel emission control systems is complicated by the fact the number of manufacturers involved. Catalytic substrates and traps are produced by one set of suppliers, and are washcoated and canned by another set. The engine manufacturer certifies its engines with a specific aftertreatment system in place, but generally does not sell the aftertreatment system as part of the engine. Instead, the vehicle manufacturer orders the aftertreatment system directly. This commonly involves separate price negotiations with the substrate supplier and washcoater/canner, and some vehicle manufacturers go so far as to purchase their own PGM metal supplies.

The basic equation used in this study for the retail price equivalent (RPE) of an aftertreatment system in a heavy-duty vehicle reflects this structure. The RPE is given by

$$RPE = ((DM + DL + LO) \times (1 + MC) + MW) \times (1 + DC)$$

where: RPE is the retail price equivalent;

DM is the direct cost of materials and components to the vehicle manufacturer

DL is the direct cost of assembly labor to the vehicle manufacturer

LO is the manufacturer's labor overhead

MW is the present value of the projected future cost of warranty repairs to the emission control system

MC is the incremental change in the vehicle manufacturer's indirect costs due to the emission control system, expressed as a percentage of the direct costs. This includes capital charges and insurance for increased inventory and work-in-progress, as well as storage and handling

DC is the incremental change in the truck or bus dealer's indirect costs, expressed as a percentage of the direct costs.

Direct component costs are technology-specific, and are discussed in the sections on each technology. Direct labor costs were estimated at 17.50 per hour, consistent with past studies. The number of labor hours required to assemble and install each system was estiametd based on engineering judgement, and ranged from 0.5 to about 2.5 hours. For the labor overhead, PHB estimated roughly 40% of direct labor costs. This percentage appears reasonable, and is used in the present report.

Future warranty costs were calculated by multiplying an estimated failure rate (from 2 to 10%, depending on the system) by an estimate of the parts and labor cost per incident. Labor costs were calculated assuming that the manufacturer would reimburse the dealer at a rate of $50 per hour for mechanic labor. Parts costs were calculated by multiplying the OEM component cost by 2.5 to reflect typical markups on retail parts sold to the dealer.

The manufacturer's carrying cost was estimated at 4% of the direct costs. This reflects primarily the costs of capital tied up in extra inventory, and secondarily the incremental costs of insurance, handling, and storage. The dealer's carrying cost was estimated at 3% of the incremental cost, again reflecting primarily the cost of capital tied up in extra inventory.

A major problem in estimating the costs of emission control systems is that the true costs of automotive components and systems are difficult to determine for anyone not directly involved in automobile production. For competitive reasons, auto manufacturers do not normally disclose their internal costs and overhead rates, and suppliers do not normally publish the prices at which they sell their components. While it would theoretically be possible to estimate these costs from first principles (bills of materials, manufacturing operations, etc.), this approach is far too time-consuming and uncertain to be practical. The estimates shown here reflect a mix of approaches, combining cost information from engine and emission control system manufacturers with "best estimates" based on engineering judgement and analogy to similar systems already in production.

2.2 DATA SOURCES

Data sources used in this analysis included a review of the applicable technical literature, together with industry submissions to EPA. Submissions by the Manufacturers of Emission Controls Association[2,16] were particularly valuable. A statement by the Engine Manufacturers Association[6] supported and incorporated the MECA statement, lending it additional credibility.

In addition to the technical literature, EF&EE engineers participated along with EPA and ICF Consulting personnel in conference calls with diesel engine manufacturers, and initiated separate telephone conversations with catalyst suppliers. Prior to initiating the conference calls, the project team developed a list of questions to be addressed. A copy of this questionnaire is given in Appendix A. ICF then contacted the Engine Manufacturers Association, which provided contacts with individual manufacturer members. Through these contacts, it was possible to arrange conference calls with two engine manufacturers, and to receive written answers to the questionnaire from a third. Unfortunately, as of the time of preparation of this draft, it had not been possible to arrange conference calls with several of the leading engine manufacturers in the U.S. – companies that account for virtually 100% of the markets for heavy-heavy duty and transit bus engines. It is hoped to incorporate information from these companies in the final report.

2.3 ASSUMPTIONS USED IN THE ANALYSIS

In developing our cost estimates, it was necessary to make a number of assumptions. The most important set of assumptions concerned the possible range of fuel sulfur levels to be permitted in diesel fuel. Based on discussions with EPA staff, we decided to examine three different regulatory limits for fuel sulfur content: 500 ppm, 30 ppm, and 10 ppm. The first of these corresponds to the existing regulation for on-highway diesel fuels, while the 30 and 10 PPM levels are considered representative of the likely range of future sulfur limits. For comparison, most Swedish diesel fuel and a substantial fraction of diesel fuel sold in California already contains 10 ppm sulfur or less. The European Union has adopted regulations that will limit diesel fuel sulfur content to 50 ppm beginning in 2005, and Japan is also considering a 50 ppm limit. The Manufacturers of Emission Controls Association (MECA) has recommended a diesel fuel sulfur limit "below" 30 ppm[2], but note that it is presently uncertain how far below 30 ppm will be necessary. The Engine Manufacturer's Association has stated[6] that fuel sulfur content of 5 ppm or less is required for light-duty vehicles with diesel engines to meet EPA's proposed Tier 2 emission standards.

We were also requested to develop cost estimates for different heavy-duty vehicle classes. In this study, we developed cost estimates for three heavy-duty vehicle classes: namely light heavy-duty vehicles (L-HDVs), medium heavy-duty vehicles (M-HDVs) and heavy heavy-duty vehicles (H-HDVs). Estimates of average engine displacement and annual production volume for these vehicle classes are shown in Table 1. These estimates were the same ones used by MECA in a survey of aftertreatment system costs among its members. Average vehicle life estimates were taken as equal to the engine's "useful life" for compliance purposes, as defined by EPA regulations.

Table 1: Estimated engine displacement and annual production

	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)[7]	6	8	13
Annual Production Volume per Engine Model[7]	75,000	30,000	26,000
Total Industry Wide Production Volume[7]	280,000	140,000	220,000
Average Vehicle Life (miles)	110,000	185,000	400,000
Average Fuel Economy (mpg)[8]	12.6	8.1	6.4

Assumptions and estimates for the technical characteristics of the aftertreatment technologies (such as catalyst and trap sizes, catalyst and washcoat materials, catalyst and carrier loadings, material costs etc.) were developed based on responses and confidential submissions from engine and aftertreatment system manufacturers, as well as from data found in the public literature. Estimated catalyst and trap sizes, as well as catalyst and carrier loadings for each aftertreatment technology are discussed separately for each technology. Estimated material costs are common to all technologies, and are tabulated in Table 2.

Table 2: Estimated material costs for diesel aftertreatment systems

	Material Costs				
	$/liter	$/gal	$/lb.	$/troy oz	$/g
Ceramic Substrate[a]	10				

Washcoat Materials[b]	5.5				
Platinum [d]				371.82	11.96
Rhodium [d]				553.67	17.80
Diesel Fuel Cost[e]		0.85			
Urea Wholesale Cost[f]		0.85			
16 gauge stainless steel[b]			0.98		0.002

[a] Estimated based on data provided by engine manufacturers and Browning, 1997[9]

[b] Extracted from data found in Browning, 1999[10]

[c] Estimated based on data found in Browning, 1997[9]

[d] 1998 average prices[11]

[e] Average resource cost of diesel fuel in October, 1999, based on retail price of $1.22, less federal fuel tax of 22 and state fuel tax of 15 cents per gallon. Taxes represent transfer payments, not actual resource costs to society, and are therefore excluded from cost-effectiveness calculations

[f] Urea cost ranges from $0.75 to $0.95 per gallon at wholesale.

3. OXIDATION CATALYTIC CONVERTERS

3.1 TECHNOLOGY DESCRIPTION

Recent progress on in-cylinder diesel particulate control has greatly reduced particulate emission levels, especially the soluble organic fraction (SOF), much of which is derived from the lubricating oil. Widespread use of exhaust gas recirculation (EGR) in future engines is likely to increase the solid carbonaceous component of the PM, making further SOF reductions necessary. Depending on engine and operating conditions, the SOF will likely account for 20 to 40 percent of PM emissions from future engines. A diesel oxidation catalytic converter (DOC) can reduce PM emissions by oxidizing a large portion of the hydrocarbons present in the SOF. The reduction in SOF emissions is typically of the order of 60 to 70%[12], and this may translate into a reduction of 10 to 30 percent in overall PM emissions. DOCs can also destroy most emissions of gaseous HC (including toxic air contaminants) and carbon monoxide (CO).

Platinum and palladium oxidation catalysts have been used extensively on light-heavy, medium-heavy, and transit bus engines in the U.S. In the 1994 and 1995 model years, most diesel L-HDVs, M-HDVs, and transit buses sold in the U.S. were equipped with DOCs in order to meet the 1994 PM standard of 0.1 g/BHP-hr[13]. Their use has since declined, as engine manufacturers improved their ability to meet 1994 and 1998 emission standards without aftertreatment. They may come into increasing use again, however, in 2004, as engine manufacturers seek to meet the combined NOx+NMHC emission standard of 2.5 g/BHP-hr while still maintaining PM emissions less than 0.1 g/BHP-hr. The catalytic converter will provide a double benefit in this case – reducing both PM and NMHC.

Diesel oxidation catalysts have been shown to exhibit good durability in certification testing, lasting the regulatory life of the engine. Data on their durability under real-world in-use conditions are not available. Since the major cause of in-use catalyst failure is overheating, which is very unlikely in a diesel engine, in-use catalyst durability is expected to be good.

3.2 EFFECTS OF FUEL SULFUR CONTENT

At temperatures higher than about 350 °C, the platinum and palladium used in diesel oxidation catalysts also catalyze the oxidation of SO_2 in the exhaust to SO_3. This then combines with water to form sulfuric acid and other sulfate species, which condense to form particulate matter. The percentage of fuel sulfur that is converted to sulfates depends on the catalyst loading and the substrate material, but can approach 100% at temperatures above 500 °C[14]. If fuel sulfur levels are significant, these compounds can add considerably to particulate mass – more than offsetting the reduction in PM due to oxidation of the SOF. For this reason, catalyst formulators must limit the PGM loading (and thus the efficiency of the catalyst) if significant amounts of sulfur will be present. The use of zeolites in combination with reduced levels of platinum catalyst can reportedly achieve similar activity levels to a platinum-only catalyst while producing much less sulfate[15].

Sulfur in fuel also binds to the active sites on PGM catalysts, blocking access by other molecules and reducing catalyst efficiency. In preliminary results from the ongoing DECSE study[16], tests performed on a heavy-heavy duty engine with an oxidation catalyst showed that the green catalyst was virtually 100% efficient for THC emissions on the Heavy Duty Federal Test Procedure using fuel with 3 or 30 ppm sulfur, but only about 90% efficient using fuel with 150 or 350 ppm sulfur. CO efficiency also declined slightly with increasing sulfur. PM reduction efficiency was low with at all sulfur levels, and became sharply negative under high temperature conditions due to sulfate formation with the higher-sulfur fuels.

3.3 SYSTEM COST ESTIMATES VS FUEL SULFUR LEVEL

Retail price equivalent - Table 3, Table 4, and Table 5 show our estimates of the retail price equivalent cost for diesel oxidation catalyst systems at different fuel sulfur levels. In developing these estimates, we assumed that engine manufacturers would seek the best possible catalyst efficiency to help them comply with stringent NMHC+NOx and PM emission standards. Thus, we assumed that the PGM loading in the catalyst would be limited primarily by sulfate production.

In developing these estimates, we first established the technical characteristics of the catalysts based on the information provided by OEMs and technical data found in the literature. The major technical characteristics and specification of DOCs were the catalyst sizes, catalyst and carrier materials, and PGM and carrier loading.

Based on information received from the engine manufacturers and data in the technical literature, we estimate that precious-metal type DOCs used with future diesel engines will have the following characteristics:

- The volume of the DOC will be roughly equal to the engine displacement;
- Typical catalyst diameter will range from 7 to 10 inches, and typical catalyst length will range from 5 to 7 inches[9];
- Catalyst materials will be platinum on an alumina carrier;
- Vanadium will be used to suppress the activity of the platinum for the SO_2 conversion reaction without diminishing the rate of the SOF oxidation reaction for high sulfur diesel fuel[18];
- Alumina loading will be about 2 g/in^3 (122 g/liter);
- Platinum loading will range from 0.5 to 60 g/ft^3 (0.02 to 2.65 g/liter) depending on the sulfur level in the fuel[17]; lower precious metal is used with high sulfur fuel to reduce sulfate made;
- Vanadium loading will be about 0.12 g/in^3 (7 g/liter)[18];

The canning material for the DOC system was assumed to be 16 gauge stainless steel sheet. For the L-HDVs, we estimated the DOC catalyst dimensions to be seven inches in diameter by five inches in length. For the M-HDVs, the DOC catalyst dimensions were estimated to be 8.5 inches diameter by 7.2 inches long; and for the H-HDVs they were estimated to be 10 inches in diameter by 8.4 inches long. These values gave catalyst volumes equal to the engine displacement.

To estimate the size of the catalyst housing, we added 20 percent to the catalyst length to allow for entry and exit to the catalyst, and another 20 percent to account for scrap materials. Using the estimated catalyst dimensions, we determined that the total volume of stainless steel sheet required were 16, 23 and 32 in^3 for DOC systems used in L-HDVs, M-HDVs, and H-HDVs, respectively. Using the density of the stainless steel, the amount of stainless steel required (in grams) was then calculated for each system.

For the catalyst loading, we estimated that a DOC system designed for 500 ppm sulfur fuel would have a loading of 5 g/ft^3 platinum, together with 207 g/ft^3 of vanadium. The platinum loading was based on industry responses to our questionnaire and comments from catalyst suppliers. For 30 and 10 ppm sulfur in the fuel, the estimated platinum loadings were 30 and 50 g/ft^3, respectively. These estimates were also based on industry responses. Vanadium would not be required to suppress sulfate formation in these latter cases.

The projected costs of washcoating and canning were estimated by "scaling down" estimates of washcoating costs for DPF systems. The latter estimates were provided by MECA members in comments on our draft report, and ranged from 150 to 250 dollars per substrate, depending on size. For DOC systems, we estimated that the costs would be 125 to 175 dollars – reflecting the smaller substrate and simpler performance requirements.

We estimated that it would require about 30 minutes to prepare the catalyst and assemble and install the DOC system, on a mass production scale.

Warranty costs for DOCs were estimated to be low, as these systems are simple and offer few opportunities for failure. We estimated the rate of warranty incidents at 2% of production, and that each incident would require three hours of labor to diagnose, remove the old catalytic converter, and install a new one.

<u>Operating Costs</u> – Based on information from engine manufacturers and experience with the present generation of DOCs, we do not expect that these units would have a measurable impact on fuel economy or other operating costs. Thus, the lifecycle cost would be equal to the initial cost to the buyer.

Table 3: Cost estimate for diesel oxidation catalysts with estimated 10% PM reduction and 50% HC reduction using 500 ppm sulfur in fuel

Diesel Oxidation Catalysts 500 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Litre)	6	8	13
Substrate	$ 52	$ 70	$ 113
Washcoating and Canning	$ 125	$ 150	$ 175
Platinum	$ 13	$ 17	$ 27
Catalyst Can Housing	$ 4	$ 6	$ 9
Direct Labor Costs			
Estimated Labor hours	0.5	0.5	0.5
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 9	$ 9	$ 9
Labor Overhead @ 40%	$ 4	$ 4	$ 4
Total Direct Costs to Mfr.	$ 207	$ 263	$ 350
Warranty Cost (2% fail)	12	14	18
Mfr. Carrying Cost	8	$ 11	$ 14
Total Cost to Dealer	$ 227	$ 288	$ 382
Dealer Carrying Cost	7	9	11
Total Cost to Buyer	$ 233	$ 297	$ 393
Lifecycle Cost	$ 233	$ 297	$ 393

Table 4: Cost estimate for diesel oxidation catalysts with estimated 25% PM reduction and 80% HC reduction using 30 ppm sulfur in fuel

Diesel Oxidation Catalysts 30 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Litre)	6	8	13
Substrate	$ 52	$ 70	$ 113
Washcoating and Canning	$ 125	$ 150	$ 175
Platinum	$ 76	$ 101	$ 165
Catalyst Can Housing	$ 4	$ 6	$ 9
Direct Labor Costs			
Estimated Labor hours	0.5	0.5	0.5
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 9	$ 9	$ 9
Labor Overhead @ 40%	$ 4	$ 4	$ 4
Total Direct Costs to Mfr.	$ 270	$ 348	$ 487
Warranty Cost (2% fail)	15	18	25
Mfr. Carrying Cost	11	$ 14	$ 19
Total Cost to Dealer	$ 296	$ 380	$ 532
Dealer Carrying Cost	9	11	16
Total Cost to Buyer	$ 304	$ 391	$ 548
Lifecycle Cost	$ 304	$ 391	$ 548

Table 5: Cost estimate for diesel oxidation catalysts with estimated 30% PM reduction and 85% HC reduction using 10 ppm sulfur in fuel

Diesel Oxidation Catalysts 10 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Litre)	6	8	13
Substrate	$ 52	$ 70	$ 113
Washcoating and Canning	$ 125	$ 150	$ 175
Platinum	$ 127	$ 169	$ 274
Catalyst Can Housing	$ 4	$ 6	$ 9
Direct Labor Costs			
Estimated Labor hours	0.5	0.5	0.5
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 9	$ 9	$ 9
Labor Overhead @ 40%	$ 4	$ 4	$ 4
Total Direct Costs to Mfr.	$ 321	$ 415	$ 597
Warranty Cost (2% fail)	17	22	31
Mfr. Carrying Cost	13	$ 17	$ 24
Total Cost to Dealer	$ 351	$ 454	$ 651
Dealer Carrying Cost	11	14	20
Total Cost to Buyer	$ 361	$ 467	$ 671
Lifecycle Cost	$ 361	$ 467	$ 671

3.4 CONCLUSIONS

Diesel oxidation catalytic converters can help to reduce PM and HC emissions, including emissions toxic air contaminants. At high exhaust temperatures, however, PGM-based DOCs can increase PM emissions due to "sulfate make" - the conversion of SO_2 in the exhaust to sulfuric acid and other sulfates. To reduce sulfate make under high loads, manufacturers will have to reduce catalyst loading and/or position the catalytic converter further downstream in the exhaust. Both of these measures would reduce its efficiency. Sulfur also inhibits the activity of the PGM catalyst itself. With 500 ppm sulfur in the fuel, we estimate that the efficiency for PM reduction would be limited to around 10%, and that for HC reduction around 50%.

If fuel sulfur levels were limited to 30 or 10 ppm, engine manufacturers could use higher catalyst loading, and the catalyst would suffer less from sulfur poisoning. DOCs would therefore be much more effective in reducing PM SOF and HC, including toxic emissions. Based on very limited data, we estimate that a DOC designed for 30 ppm fuel could attain 25% efficiency for PM and 80% efficiency for HC, while one designed for 10 ppm fuel could attain 30% efficiency for PM and 85% for HC. Since the platinum catalyst accounts for a large fraction of the total cost, these more-efficient converters would also be more expensive – about 12% more expensive for catalytic converters designed for 30 ppm fuel, and about 48% more expensive for those designed for 10 ppm fuel.

The diesel oxidation catalyst is estimated to have no measurable effect on fuel economy or operating costs, and this would not be affected by the fuel sulfur level.

4. DIESEL PARTICULATE FILTERS

4.1 TECHNOLOGY DESCRIPTION

A diesel particulate filter (DPF) system comprises a particulate filter to remove the PM from the engine exhaust stream, together with some means for regenerating the filter by removing the particulate matter. Regeneration is accomplished by burning or otherwise oxidizing the collected material. Manufacturing a filter capable of collecting soot and other particulate matter from the exhaust stream is straightforward, and effective trapping media have been developed and demonstrated. The problem of DPF system development is in effectively removing the soot and regenerating the filter. Diesel PM consists of solid carbon coated with heavy hydrocarbons. This mixture ignites at 500 to 600 °C, which is well above the normal range of diesel engine exhaust temperatures. Special means are therefore needed to ensure ignition. Once ignited, however, the PM burns at temperatures that can melt or crack the particulate filter unless designed against. Initiating and controlling regeneration without damaging the filter is the central problem of DPF system development.

A number of filtration media have been tested successfully, including cellular ceramic monoliths, woven ceramic-fiber coils, ceramic foams, corrugated multi-fiber felts, and catalyst-coated stainless-steel wire mesh. Cellular ceramic monoliths are the type most commonly used. These are similar in construction to the cellular ceramic monoliths used in catalytic converters, except that the ends of alternate cells are blocked, forcing the exhaust gases to flow through the porous ceramic walls of the cells. The PM is filtered out on the upstream wall of the cell.

Many regeneration systems have been proposed for DPFs, and much development effort has been invested. Regeneration techniques can be divided into passive and active approaches. Passive systems attain the conditions required for regeneration as a result of normal vehicle operation. Given the range of vehicle operating patterns, is it difficult to assure that regeneration can be achieved under all conditions. Passive regeneration systems generally rely on a catalyst (as either a coating on the trap or a fuel additive) to reduce the ignition temperature of the collected particulate matter. A novel passive regeneration system that is now seeing much application is the "continuously regenerating" DPF system[19]. In this system, a platinum catalyst located upstream from the DPF is used to oxidize nitric oxide (NO) to nitrogen dioxide (NO_2). The NO_2 then reacts with the PM in the DPF, oxidizing it to CO and CO_2. This occurs even at low exhaust temperatures, thus preventing the accumulation of significant amounts of soot in the filter.

Other types of passive regeneration systems rely on catalytic coatings applied to the particulate filter itself, or catalytic additives in the fuel. By applying a platinum catalyst to the filter, it is possible to lower the PM ignition temperature and increase the oxidation rate by means of the same NO to NO_2 reaction used in continuously regenerating DPFs. With current fuel sulfur levels, however, the usable PGM loading and activity are limited by the potential for sulfate production at high temperatures. The resulting sulfuric acid passes through the trap in vapor form, then condenses downstream into particles – thus offsetting the PM reduction due to the filter.

Active DPF regeneration systems monitor particulate matter in the trap and trigger specific actions to regenerate it when needed. A variety of approaches to trigger regeneration have been developed, including diesel-fuel burners, electric heaters, and catalyst injection systems. Catalytic coatings have a number of advantages in active systems as well, and are often included. The reduced ignition temperature and increased combustion rate resulting from the catalyst imply that less energy is needed from the regeneration system. Regeneration will also occur spontaneously under most duty cycles - greatly reducing the number of times the regeneration system must operate. Spontaneous regeneration also provides insurance against regeneration system failure. The catalyst helps to increase the efficiency of the system by destroying SOF compounds that would otherwise pass through the filter as vapors, then condense downstream into particles again. Finally, the catalysts used may also help by reducing HC and toxic emissions.

4.2 EFFECTS OF FUEL SULFUR CONTENT

The effects of fuel sulfur content on DPF systems are similar to those on oxidation catalysts. The problem of sulfate production from SO_2 in the exhaust limits the amount and activity of the precious-metal catalysts that can be used. Sulfur also binds to and inhibits the activity of PGM catalysts, reducing their effectiveness in promoting particulate regeneration. Sulfur is especially effective in inhibiting the NO to NO_2 reaction. Because of this limitation, it has not been possible to develop a purely passive trap regeneration system that will work reliably in most types of vehicles with fuel sulfur levels of 500 ppm. We believe that such a system would be viable, however, at fuel sulfur levels in the 10 to 30 ppm range. At these sulfur levels, the PGM catalyst is effective in promoting the oxidation of NO to NO_2, which then oxidizes the carbonaceous material – facilitating regeneration. This is also the basis for the continuously regenerating trap system. Sulfate formation at high temperatures is also a problem with this system.

4.3 SYSTEM COST ESTIMATES VS. FUEL SULFUR LEVEL

Retail price equivalent - We estimated the RPE of two different DPF systems. The first system was a conventional "catalyzed" DPF, with the platinum catalyst applied on the trap substrate. Table 6, Table 7, and Table 8 show the estimated RPE for this type of system at fuel sulfur levels of 500, 30, and 10 ppm, respectively. The second type of system considered was a "continuously regenerating" DPF, which uses NO_2 produced from NO on a platinum catalyst upstream to oxidize the soot collected on the filter. Continuously regenerating DPF systems require low-sulfur fuel for the NO to NO_2 oxidation, so we did not estimate the costs of this system with 500 ppm fuel. Table 9 shows the estimated costs of continuously regenerating DPF systems with 30 ppm sulfur in the fuel, while Table 10 shows the estimated costs with sulfur at 10 ppm.

Catalyzed DPF Systems – We assumed a ceramic monolith type DPF. Responses from the engine manufacturers to our questionnaire indicated that typical DPF volume would range from 150 to 250% of engine displacement. We estimated that the DPF volume required to limit backpressure to acceptable levels would be twice the engine displacement. We assumed that the proportions of the DPF would be similar to those of a diesel oxidation catalyst, with all dimensions being increased more-or-less in proportion to provide the additional volume. We therefore multiplied our estimates of the diameters and lengths for the DOC system by the cube root of two to obtain comparable estimates for the DPF. This yielded dimensions of about 9 inches in diameter by 8 inches in length for L-HDVs, 11 inches in diameter by 9 inches in length for M-HDVs, and 13 inches in diameter and 11 inches in length for H-HDVs. With these dimensions, the total volume of stainless steel required for the containment systems on the catalyzed DPF systems were calculated as 25, 36 and 50 in^3 for L-HDVs, M-HDVs, and H-HDVs, respectively. For comparison, the catalyzed DPF used in the DECSE study has a dimension of 10.5 inches in diameter and 12 inches in length for a 8.5 liter engine.[16]

Based on industry responses to our questionnaire, the typical PGM loading for a catalyzed DPF system ranges from 0.5 to 50 g/ft^3, depending on the sulfur content in the fuel. We estimated that a catalyzed DPF system designed for 500 ppm sulfur fuel would have a loading of 0.5 g/ft^3 platinum, together with 207 g/ft^3 of vanadium. We also assumed that it would require an active trap regeneration system, with an estimated cost of $300[20].

For 30 and 10 ppm sulfur in the fuel, the estimated platinum loadings were 20 and 30 g/ft^3, respectively. These estimates were based on the middle of the range that the industry provided in response to our questionnaire, as well as subequent comments from MECA members on our draft analysis. In these cases, we assumed that the catalyst would be active enough to eliminate the need for an active regeneration system, thus saving the associated costs and complexity.

The projected costs of washcoating and canning were based on estimates provided by MECA members in comments on our draft report. These ranged from 150 to 250 dollars per substrate, depending on size.

We estimated that it would require about 1.5 minutes to prepare, assemble, and install a catalyzed DPF system on a mass production scale.

<u>Continuously Regenerating DPF Systems</u> - As indicated earlier, a continuously regenerating DPF system consists of an upstream catalytic converter and a DPF. We estimated that the volume of the DPF would be the same as that required for a catalyzed DPF system. The upstream catalyst for NO to NO_2 conversion was estimated to have volume similar to that of a diesel oxidation catalyst. The total volumes of stainless steel required for the complete containment system were calculated as 37, 55 and 75 in^3 for L-HDVs, M-HDVs, and H-HDVs, respectively. For comparison, the continuously regenerating DPF system used in the DECSE study has the similar arrangement but slightly different in configuration; it has a upstream catalyst with a dimension of 10.5 inches in diameter and 6 inches in length, and a DPF with a dimension of 10.5 inches in diameter and 12 inches in length for a 8.5 liter engine.[16]

We assumed the same precious metal loading in the continuously regenerating DPF systems as in the catalyzed DPF system discussed earlier. Washcoating costs for the upstream catalyst were assumed to be equal to those for DOCs, which would have the same volume.

We estimated that it would require about 1.5 hours to assemble and install a continuously regenerating DPF system.

Table 6: Cost estimate for catalytic DPF with estimated 70% PM reduction and 50% HC reduction using 500 PPM sulfur in fuel

Catalyzed DPFs	Vehicle Classes		
500 ppm Sulfur Content	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Filter Volume (Liter)	12	16	26
Filter Trap	$ 250	$ 350	$ 510
Washcoating and Canning	$ 150	$ 200	$ 250
Platinum	$ 3	$ 3	$ 5
Filter Can Housing	$ 7	$ 10	$ 14
Differential Pressure Sensor	$ 45	$ 45	$ 45
Active Regeneration System	$ 300	$ 300	$ 350
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	$ 791	$ 945	$ 1,223
Warranty Cost (10% fail)	209	247	314
Mfr. Carrying Cost	32	$ 38	$ 49
Total Cost to Dealer	$ 1,031	$ 1,230	$ 1,586
Dealer Carrying Cost	31	37	48
Total Cost to Buyer	$ 1,062	$ 1,267	$ 1,633
Lifecycle Cost	$ 1,228	$ 1,700	$ 2,822

Table 7: Cost estimate for catalytic DPF with estimated 80% PM reduction and 80% HC reduction using 30 PPM sulfur in fuel

Catalyzed DPFs 30 ppm Sulfur Content	Vehicle Classes L-HDVs	 M-HDVs	 H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Filter Volume (Liter)	12	16	26
Filter Trap	$ 250	$ 350	$ 510
Washcoating and Canning	$ 150	$ 200	$ 250
Platinum	$ 101	$ 135	$ 220
Filter Can Housing	$ 7	$ 10	$ 14
Differential Pressure Sensor	$ 45	$ 45	$ 45
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	602	$ 793	$ 1,113
Warranty Cost (5% fail)	74	98	135
Mfr. Carrying Cost	$ 24	$ 32	$ 45
Total Cost to Dealer	$ 700	$ 922	$ 1,293
Dealer Carrying Cost	21	28	39
Total Cost to Buyer	$ 721	$ 950	$ 1,331
Lifecycle Cost	$ 775	$ 1,091	$ 1,720

Table 8: Cost estimate for catalytic DPF with estimated 95% PM reduction and 85% HC reduction using 10 PPM sulfur in fuel

Catalyzed DPFs 10 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Filter Volume (Liter)	12	16	26
Filter Trap	$ 250	$ 350	$ 510
Washcoating and Canning	$ 150	$ 200	$ 250
Platinum	$ 152	$ 203	$ 329
Filter Can Housing	$ 7	$ 10	$ 14
Differential Pressure Sensor	$ 45	$ 45	$ 45
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	653	$ 860	$ 1,223
Warranty Cost (5% fail)	80	106	149
Mfr. Carrying Cost	$ 26	$ 34	$ 49
Total Cost to Dealer	$ 759	$ 1,001	$ 1,421
Dealer Carrying Cost	23	30	43
Total Cost to Buyer	$ 782	$ 1,031	$ 1,463
Lifecycle Cost	$ 836	$ 1,172	$ 1,851

Table 9: Cost estimate for continuously regenerating DPF with estimated 80% PM reduction and 80% HC reduction using 30 PPM sulfur in fuel

Continuously Regenerating DPFs	Vehicle Classes		
30 ppm Sulfur Content	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Filter Volume (Liter)	12	16	26
Catalyst Volume (Liter)	6	8	13
Substrate	$ 52	$ 70	$ 113
Filter Trap	$ 250	$ 350	$ 510
Washcoating and Canning	$ 125	$ 150	$ 175
Platinum	$ 76	$ 101	$ 165
Filter Can Housing	$ 10	$ 15	$ 21
Differential Pressure Sensor	$ 45	$ 45	$ 45
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	$ 595	$ 768	$ 1,078
Warranty Cost (5% fail)	80	101	139
Mfr. Carrying Cost	24	$ 31	$ 43
Total Cost to Dealer	$ 699	$ 900	$ 1,259
Dealer Carrying Cost	21	27	38
Total Cost to Buyer	$ 720	$ 927	$ 1,297
Lifecycle Cost	$ 774	$ 1,069	$ 1,685

Table 10: Cost estimate for continuously-regenerating DPF with estimated 95% PM reduction and 85% HC reduction using 10 PPM sulfur in fuel

Continuously Regenerating DPFs	Vehicle Classes		
10 ppm Sulfur Content	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Filter Volume (Liter)	12	16	26
Catalyst Volume (Liter)	6	8	13
Substrate	$ 52	$ 70	$ 113
Filter Trap	$ 250	$ 350	$ 510
Washcoating and Canning	$ 125	$ 150	$ 175
Platinum	$ 127	$ 169	$ 274
Filter Can Housing	$ 10	$ 15	$ 21
Differential Pressure Sensor	$ 45	$ 45	$ 45
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	$ 646	$ 835	$ 1,188
Warranty Cost (5% fail)	86	110	152
Mfr. Carrying Cost	26	$ 33	$ 48
Total Cost to Dealer	$ 758	$ 979	$ 1,387
Dealer Carrying Cost	23	29	42
Total Cost to Buyer	$ 781	$ 1,008	$ 1,429
Lifecycle Cost	$ 835	$ 1,150	$ 1,817

<u>Operating Costs</u> – Table 11 shows the estimated operating cost increase due to the DPF. The presence of a loaded DPF in the exhaust line would increase fuel consumption, due to the increase in engine backpressure. Based on information from engine manufacturers, we estimate that this increase would be only about 1% for DPFs used with low-sulfur fuel, as the NO_2 produced by the catalyst would keep the soot loadings low at all times. With high-sulfur fuel, this mechanism would be ineffective, and average soot loading would be considerably higher. In this case, we estimate that the fuel consumption penalty would be about 3%[20].

4.4 CONCLUSIONS

Diesel particulate filter systems with PGM catalysts can drastically reduce PM and HC emissions (including toxic air contaminants), and may slightly reduce NOx. The efficiency and cost of these systems would be strongly affected by the sulfur content of the fuel. Like diesel oxidation catalysts, catalytic DPF systems used with 500 ppm sulfur fuel could increase PM emissions at high exhaust temperatures due to sulfate make. To reduce sulfate make under high loads, manufacturers have had reduce catalyst loading and/or position the DPF system further downstream in the exhaust. Both of these measures also reduce its ability to regenerate unaided. Sulfur also inhibits the activity of the catalyst itself, especially affecting the production of NO_2 from nitric oxide.

Table 11: Estimated fuel consumption penalty due to C-DPFs and CR-DPFs.

DPFs	Vehicle Classes		
Operating Costs	L-HDVs	M-HDVs	H-HDVs
Vehicle Lifetime (mi.)	110,000	185,000	400,000
Baseline Fuel Economy (mpg)	12.6	8.1	6.4
Average Diesel Fuel Cost ($/gal)	0.85	0.85	0.85
Diesel Fuel Sulfur 500 ppm			
Fuel Penalty Due to DPF	3%	3%	3%
Lifetime Fuel Cost ($)	$ 230	$ 600	$ 1,646
Net Present Value of Fuel Cost ($)	$ 166	$ 433	$ 1,189
Diesel Fuel Sulfur 10 - 30 ppm			
Fuel Penalty Due to DPF ($)	1%	1%	1%
Lifetime Fuel Cost ($)	$ 75	$ 196	$ 538
Net Present Value of Fuel Cost ($)	$ 54	$ 142	$ 388

If fuel sulfur levels were limited to 30 or 10 ppm, engine manufacturers could use higher catalyst loading, and the catalyst would suffer less from sulfur inhibition. SOF and sulfate emissions would thus be reduced, and backpressure would be lowered. We estimate that a DOC designed for 30 ppm fuel could attain 80% efficiency for both PM and HC, while one designed for 10 ppm fuel could attain 95% efficiency for PM and 85% for HC. NOx emissions would also be reduced slightly. Lowered backpressure and the elimination of the active regeneration system would reduce the fuel penalty due to the trap to around 1%.

With 500 ppm sulfur in the fuel, we estimate that a DPF system would require active regeneration to for reliable regeneration. Catalyst loading would have to be limited, so that a significant amount of SOF would escape through the filter in vapor form. This, plus produced sulfates would limit the PM reduction efficiency of the trap to around 70%, and the HC reduction to around 50%. The extra backpressure and fuel required for regeneration would result increase fuel consumption by about 3%.

5. LEAN NO_X CATALYSTS

5.1 TECHNOLOGY DESCRIPTION

Lean NOx catalysts for diesel and lean-burn gasoline engines have been one of the main subjects of research and development in emission control systems during the last decade. The three-way catalytic converters used in gasoline engines use PGM catalysts to promote the reduction of NOx by reacting it with CO and unburned HC in the exhaust. These catalysts are ineffective in the presence of significant excess oxygen, since the oxygen and NOx compete for the reductant species available. Since diesel engines always operate with air-fuel ratios much leaner than stoichiometric, three-way catalytic converters are ineffective with such engines.

Catalysts have been developed that can promote the reduction of NOx by HC even in the presence of excess oxygen. These catalysts are generally based on zeolites. The crystal structure of the zeolite provides a large number of small enclosed spaces into which HC and NOx can diffuse while being mostly shielded from the excess oxygen present.[2] Even with zeolite catalysts, however, about six times as much HC is required as NOx in order to achieve good NOx reductions. Since HC emissions from modern heavy-duty diesel engines are generally less than one-tenth the NOx emissions this requires that hydrocarbons be added to the exhaust.

Two lean NOx catalyst types have been developed: a platinum-based system effective between about 200 and 300 °C, and systems using base-metal catalysts effective between about 350 and 500 °C. A commercial production system would likely combine these two types in order to achieve the best possible efficiency across a wide range of temperatures. Even in this case, however, typical efficiencies with 30 ppm sulfur diesel fuel are in the range of 20 to 30%.

Possible measures to increase the HC content of the exhaust include injecting additional diesel fuel into the cylinder during the exhaust stroke, or injecting fuel into the exhaust pipe. The former would be relatively easy to arrange in electrohydraulic or common-rail type fuel injection systems, which are expected to be used extensively in light-heavy and medium-heavy duty engines in coming years. In discussions with engine manufacturers, however, they indicated that such post-injection was unlikely to be implemented in production, due to concerns about effects on engine durability due oil dilution. Post-injection would also be difficult to arrange with the types of electronic unit injector systems common in heavy-heavy duty engines.

For these reasons, we assumed that post-injection systems would not be used to provide the extra HC flow required. Instead, we assumed that a separate exhaust fuel injection system would be used. This system would comprise a fuel booster pump, pressure regulator, and electronically-controlled fuel injector – similar to those used in throttle-body fuel injection systems for gasoline engines. To prevent coking and deposit formation in the injector nozzle from the heat of the exhaust, it would be necessary to provide cooling from the engine cooling jacket. Thus, coolant hoses and connections would also be required.

5.2 EFFECTS OF FUEL SULFUR CONTENT

Platinum is a key element of the low-temperature lean NOx catalyst system. As with platinum catalysts in other aftertreatment technologies, the efficiency of the deNOx catalyst is adversely affected by sulfur in the exhaust – reducing the already low efficiency of the system. The platinum catalyst also tends to convert SO_2 to sulfates at high temperatures, thus increasing PM emissions. In preliminary results from the DECSE program, converter-out PM emissions increased as much as 54% in the high-temperature OICA mode 2 using fuel with 150 ppm sulfur. The amount of increase at 350 ppm sulfur was less than at 150 ppm, but still substantial at 33%. For fuel with 3 ppm sulfur, the PM increase in OICA mode 2 was only 6%, and the catalyst actually gave a PM reduction under lighter loads[16].

5.3 SYSTEM COST ESTIMATES VS FUEL SULFUR LEVEL

Retail Price Equivalent - Table 12 and Table 13 show the estimated RPE costs for lean-NOx catalyst systems with 30 and 10 ppm sulfur in the fuel, respectively. Current lean NOx technology requires low sulfur fuel, and will not work with fuel containing significant sulfur. For this reason, we did not estimate a cost for these systems with fuel meeting the present 500 ppm sulfur limit.

Responses to our questionnaire from the engine manufacturers indicated that the catalyst size for a lean-NOx catalyst system should be about twice the engine displacement. We used this assumption in the cost analysis. Thus, the dimensions assumed for a lean-NOx catalyst system were the same as for the DPF system.

Based on industry responses to our questionnaire, the typical platinum loading for a lean-NOx catalyst system ranges from 50 to 90 g/ft^3. For 30 and 10 ppm sulfur in the fuel, the estimated platinum loadings were 50 and 90 g/ft^3, respectively. These estimates were based on the low end and high end of the range that the industry provided. Specific estimates of washcoating costs for lean NOx catalysts were not available from industry. We therefore assumed that these costs would be similar to those for catalytic trap-oxidizers, for which such estimates were available.

The cost for the fuel supply and injection system was estimated at $100 to $150, depending on the vehicle class. This estimate was based on comments from the engine manufacturers in our conference calls[10], as well as a previous cost analysis for a throttle-body fuel injection system for a utility engine[21]. We estimated that it would require about one hour to assemble and install the lean-NOx catalyst system.

Operating Costs – The extra fuel injected into the exhaust to serve as a reductant would add to vehicle fuel consumption. Based on information from the engine manufacturers, we estimate the incremental fuel consumption at about 2% of total fuel use. The effects of this added consumption on life-cycle costs are shown in Table 14.

Table 12: Cost estimate for lean NOx catalyst system with estimated 25% NOx reduction using 30 ppm sulfur in fuel

Lean NOx Catalysts 30 ppm Sulfur Content	Vehicle Classes L-HDVs	 M-HDVs	 H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Litre)	12	16	26
Substrate	$ 105	$ 140	$ 227
Washcoating and Canning	$ 250	$ 300	$ 350
Platinum	$ 253	$ 338	$ 549
Catalyst Can Housing	$ 7	$ 10	$ 14
Fuel Supply and Injection Assy	$ 100	$ 110	$ 150
Direct Labor Costs			
Estimated Labor hours	1	1	1
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 18	$ 18	$ 18
Labor Overhead @ 40%	$ 7	$ 7	$ 7
Total Direct Costs to Mfr.	$ 739	$ 922	$ 1,314
Warranty Cost (5% fail)	94	117	166
Mfr. Carrying Cost	30	$ 37	$ 53
Total Cost to Dealer	$ 863	$ 1,076	$ 1,533
Dealer Carrying Cost	26	32	46
Total Cost to Buyer	$ 889	$ 1,108	$ 1,579
Lifecycle Cost	$ 999	$ 1,394	$ 2,363

Table 13: Cost estimate for lean NOx catalyst system with estimated 30% NOx reduction using 10 ppm sulfur in fuel

Lean NOx Catalysts 10 ppm Sulfur Content	Vehicle Classes L-HDVs	 M-HDVs	 H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Litre)	12	16	26
Substrate	$ 105	$ 140	$ 227
Washcoating and Canning	$ 250	$ 300	$ 350
Platinum	$ 456	$ 608	$ 988
Catalyst Can Housing	$ 7	$ 10	$ 14
Fuel Injection Assembly	$ 100	$ 110	$ 150
Direct Labor Costs			
Estimated Labor hours	1	1	1
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 18	$ 18	$ 18
Labor Overhead @ 40%	$ 7	$ 7	$ 7
Total Direct Costs to Mfr.	$ 942	$ 1,192	$ 1,753
Warranty Cost (5% fail)	120	151	221
Mfr. Carrying Cost	38	$ 48	$ 70
Total Cost to Dealer	$ 1,099	$ 1,391	$ 2,044
Dealer Carrying Cost	33	42	61
Total Cost to Buyer	$ 1,132	$ 1,432	$ 2,106
Lifecycle Cost	$ 1,242	$ 1,718	$ 2,890

Table 14: Estimated lifetime reductant cost for lean-NOx catalyst systems

Lean NOx Catalysts	Vehicle Classes		
Operating Costs	L-HDVs	M-HDVs	H-HDVs
Vehicle Lifetime (mi.)	110,000	185,000	400,000
Fuel Consumption			
Baseline Fuel Economy (mpg)	12.6	8.1	6.4
Extra Fuel Needed as Reductant	2%	2%	2%
Average Diesel Fuel Cost ($/gal)	0.85	0.85	0.85
Lifetime Reductant Cost ($)	$ 152	$ 396	$ 1,086
Net Present Value of Reductant Cost ($)	110	286	784

5.4 CONCLUSIONS

Lean NOx catalyst systems can reduce can reduce NOx emissions by 20 to 30%, but will have little effect on PM. HC emissions are likely to increase, due to the effect of adding extra fuel to the exhaust (this was demonstrated in the DECSE study). The effectiveness of lean NOx catalyst systems would be strongly affected by the sulfur content of the fuel. As with other PGM catalytic systems, these catalysts would increase PM emissions if operated on 500 PPM sulfur fuel at high exhaust temperatures. Sulfur also interferes with the operation of the catalyst itself, especially affecting the NOx reduction reaction. For this reason, practical lean NOx catalyst systems would only be possible with fuel sulfur levels less than 50 ppm.

If fuel sulfur levels were limited to 30 or 10 ppm, engine manufacturers could use higher catalyst loading, and the catalyst would suffer less from sulfur poisoning. NOx efficiency would thus be increased, and sulfate emissions would be reduced. We estimate that a lean NOx catalyst system designed for 30 ppm fuel could attain 25% efficiency for NOx, while one designed for 10 ppm fuel could attain 30% efficiency. The need to add fuel to the exhaust to serve as a reductant for the NOx would add about 2% to fuel consumption. Based on results of the DECSE study[16], HC emissions would increase about three times.

6. NO_X STORAGE CATALYST SYSTEMS

6.1 TECHNOLOGY DESCRIPTION

NOx storage catalyst systems or "NOx traps" use a cyclic process to capture and reduce NOx in lean exhaust streams. As discussed in Chapter 5, the presence of excess oxygen interferes with NOx reduction under lean conditions. In this technology, the NOx is catalytically oxidized to NO_2 under lean conditions, then chemically captured by reaction with an alkaline earth metal such as barium. The resulting barium nitrate is stable under lean conditions, "trapping" the NOx.

Once the NOx storage medium nears saturation, the system must be regenerated by subjecting it to a short period of rich operation. Under rich conditions, the barium nitrate reacts to form barium carbonate and release the NO_2, which is then reduced to nitrogen using a catalyst such as rhodium.

To achieve rich conditions in a diesel engine is difficult, as the engines are designed to operate always with substantial excess air. While it would be possible to do so under most operating conditions by throttling the air intake or introducing an extremely high rate of exhaust gas recirculation, this probably would not suffice at idle or very light loads. In addition, the presence of inadequate oxygen in the cylinder would greatly increase emissions of soot and particulate matter.

To achieve rich conditions for NOx trap regeneration, we assumed that the NOx trap system would be temporarily bypassed, allowing the use of a separate diesel fuel burner system to produce the hot, rich mixture needed for regeneration. The costs of this diesel fuel burner system would be similar to those of an active regeneration system for a diesel particulate filter.

6.2 EFFECTS OF FUEL SULFUR CONTENT

Sulfur in diesel fuel has an extremely detrimental effect on NOx storage catalyst systems. SO_2 is chemically similar to NO_2, and binds strongly to the barium NOx storage medium, forming stable barium sulfate. Unlike NO_2, the sulfur is not desorbed during regeneration at temperatures typical of diesel operation, so it gradually accumulates, reducing the NOx storage capacity. To remove the sulfur and recover trap efficiency, it is necessary to heat the catalyst to around 700 ^{o}C for about 90 seconds in the presence of a rich air-fuel mixture. We assumed that this catalyst desulfation step would also be performed by the diesel fuel burner with the catalyst bypassed. For fuel with sulfur levels as high as 500 ppm, this desulfation would have to be performed so often as to be impractical. We therefore considered only the 30 and 10 ppm sulfur cases for this technology.

6.3 SYSTEM COST ESTIMATES VS FUEL SULFUR LEVEL

Retail Price Equivalent - A NOx storage catalyst system would have precious metal catalysts to oxidize NO to NO_2, alkaline earth oxide to store the NOx, and precious metal catalysts to reduce the stored NOx after a rich mixture is introduced. Based on industry responses and technical literature, one of the promising NOx storage catalyst systems uses platinum to perform the oxidation process, barium (Ba) as the storage medium, and rhodium (Rh) to perform the reduction process. Our cost estimates were developed for this type of NOx storage catalyst system.

Responses to our questionnaire from the engine manufacturers indicated that the catalyst size for a NOx storage system would range from 150 to 250% of the engine displacement. We assumed a total volume equal to 200% of engine displacement, divided between two separate catalytic converters. This would allow one to be regenerated or desulfated while the other was collecting NOx. Thus, the dimensions and substrate cost for each of the NOx storage catalyst units were assumed to be the same as those of a diesel oxidation catalyst. Table 15 and Table 16 show the RPE cost estimates for NOx storage catalyst systems for the 30 ppm and 10 ppm fuel sulfur levels.

Table 15: Cost estimate for NOx storage catalyst system with estimated 70% NOx reduction using 30 ppm sulfur in fuel

NOx Storage Catalyst 30 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Liter)	12	16	26
Substrates	$ 105	$ 140	$ 227
Washcoating and Canning	$ 250	$ 300	$ 350
Platinum	$ 137	$ 182	$ 296
Rhodium	$ 23	$ 30	$ 49
Alkaline Earth Oxide, Barium	$ 1	$ 1	$ 1
Catalyst Can Housing	$ 9	$ 13	$ 17
Regeneration System	$ 300	$ 300	$ 350
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	$ 861	$ 1,003	$1,340
Warranty Cost (5% fail)	113	131	171
Mfr. Carrying Cost	$ 26	$ 30	$ 40
Total Cost to Dealer	$ 999	$ 1,163	$1,551
Dealer Carrying Cost	30	35	47
Total Cost to Buyer	$ 1,029	$ 1,198	$1,598
Lifecycle Cost	$ 1,167	$ 1,557	$2,583

Table 16: Cost estimate for NOx storage catalyst system with estimated 80% NOx reduction using 10 ppm sulfur in fuel

NOx Storage Catalyst 10 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Liter)	12	16	26
Substrate	$ 105	$ 140	$ 227
Washcoating and Canning	$ 250	$ 300	$ 350
Platinum	$ 228	$ 304	$ 494
Rhodium	$ 38	$ 50	$ 82
Alkaline Earth Oxide, Barium	$ 1	$ 1	$ 1
Catalyst Can Housing	$ 9	$ 13	$ 17
Regeneration System	$ 300	$ 300	$ 350
Direct Labor Costs			
Estimated Labor hours	1.5	1.5	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 26	$ 26	$ 35
Labor Overhead @ 40%	$ 11	$ 11	$ 14
Total Direct Costs to Mfr.	$ 967	$ 1,144	$1,570
Warranty Cost (5% fail)	126	148	200
Mfr. Carrying Cost	$ 29	$ 34	$ 47
Total Cost to Dealer	$ 1,122	$ 1,327	$1,817
Dealer Carrying Cost	34	40	55
Total Cost to Buyer	$ 1,156	$ 1,367	$1,872
Lifecycle Cost	$ 1,293	$ 1,726	$2,857

As for catalyst loading, the typical platinum loading for a NOx storage catalyst system was stated by engine manufacturers as being from 50 to 90 g/ft^3, and the Pt/Rh ratio is typically 10 to 1. In subsequent comments, however, MECA members stated that these loadings were too high, and that only part of the catalyst volume would be loaded with PGM. We therefore used an average PGM loading of 30 g/ft^3 for the 30 ppm fuel case and 50 g/ft^3 for the 10 ppm sulfur level. The PGM were assumed to be 90% Pt and 10% Rh.

We estimated the cost for a regeneration system for the NOx storage system to be $300 to $350, depending on the vehicle class. These estimates were the same as those for the active DPF regeneration system, which was assumed to use a similar burner technology. We estimated that it would require about 1.5 to 2 hour of labor to assemble and install a NOx storage catalyst system in mass production.

Operating Costs – The NOx storage catalyst system would require diesel fuel to be burned to provide the rich mixture needed for regeneration, as well as the high temperature rich mixture needed for desulfation of the catalyst. For regeneration, we estimated that the burner would operate about three seconds every 45 seconds (regenerating each catalyst once every 90 seconds), with total air flow about one tenth that of the average for the engine, and total fuel flow about three tenths that of the engine. Thus, fuel consumption for regeneration would add up to 2% of the total. The higher temperatures and longer burner run times required for desulfation were estimated to add another 0.5% to the fuel use, for a total of 2.5%.

Table 17: Estimated diesel fuel consumption for NOx storage systems.

NOx Storage Catalyst	Vehicle Classes		
Operating Costs	L-HDVs	M-HDVs	H-HDVs
Vehicle Lifetime (mi.)	110,000	185,000	400,000
Fuel Consumption			
Baseline Fuel Economy (mpg)	12.6	8.1	6.4
Reductant Required for Regeneration & Desulfation	2.5%	2.5%	2.5%
Average Diesel Fuel Cost ($/gal)	0.85	0.85	0.85
Lifetime Reductant Cost ($)	$ 191	$ 498	$ 1,365
Net Present Value of Reductant Cost ($)	138	359	985

6.4 CONCLUSIONS

NOx storage catalyst systems could potentially reduce NOx emissions by 70 to 90%. CO and HC emissions would be likely to increase, however, due to emissions from the regeneration and desulfation processes. PM emissions would be little affected, except for the possibility of sulfate make at high temperatures and fuel sulfur levels.

The practicality of NOx storage catalyst systems would be strongly affected by the sulfur content of the fuel. As with other precious-metal catalytic systems, the rhodium catalysts used for NOx reduction would increase PM emissions at high exhaust temperatures due to sulfate make. Sulfur also inhibits the activity of the catalyst itself (especially affecting the NOx reduction reaction) and the NOx storage medium. For this reason, practical NOx storage catalyst systems would only be possible with fuel sulfur levels less than about 50 ppm.

If fuel sulfur levels were limited to 30 or 10 ppm, engine manufacturers could use higher catalyst loading, the catalyst would suffer less from sulfur inhibition, and would require desulfation less often. NOx efficiency would thus be increased, sulfate emissions would be reduced, and the energy consumed in the burner would be reduced. We estimate that a NOx storage catalyst system designed for 30 ppm fuel could attain 70% efficiency for NOx, while one designed for 10 ppm fuel could attain 80% efficiency. The need to for a diesel fuel burner to regenerate and desulfate the catalyst would add about 2.5% to fuel consumption.

7. SELECTIVE CATALYTIC REDUCTION SYSTEMS

7.1 TECHNOLOGY DESCRIPTION

Selective catalytic reduction (SCR) is another technique for reducing NOx to nitrogen and water by catalytic means. In this approach, the required chemical reduction potential is supplied by ammonia (NH_3) in the exhaust. The ammonia can be injected directly into the exhaust, but for mobile applications it is more practical to inject a related compound, urea (H_2NCONH_2) in water solution. In the heat of the exhaust, the urea hydrolyzes to produce two ammonia molecules, which then proceed to react with the NOx.

SCR has been the most effective method of controlling NOx emissions from stationary installations since the mid-1970's, with demonstrated effectiveness in excess of 95%. SCR systems based on platinum, on non-precious metal-oxide (base metal) catalysts, and on zeolite catalysts are now being offered commercially for stationary diesel engines, and a number have been installed - mostly in Europe. Production SCR units using ammonia and urea are operating successfully on offshore oil platforms, stationary reciprocating and turbine power plants, diesel motorships and boats, and in rail vehicles. A substantial number of heavy duty diesel trucks are also operating with SCR systems as part of a large-scale demonstration program.

The PGM and Ti-Vn catalysts used in SCR systems also function as oxidation catalysts, and can therefore help to reduce PM, HC, CO, and toxic emissions as well as NOx. Platinum SCR systems function at lower temperatures than most competing types (important for automotive applications, since average loads and exhaust temperatures tend to be low). Platinum catalysts have the disadvantages that they are sensitive to sulfur in the fuel, and that they have a narrow temperature range. Recent demonstrations have focused on the use of Ti-Vn catalysts, which are more efficient than Pt at temperatures typical of loaded diesel operation. These systems are also competitive with Pt at lower temperatures.

Efficient operation of SCR systems requires that the exhaust temperature be within the normal SCR operating range. For Ti-Vn catalysts, this range is 200 to 550 ^{o}C. Zeolite catalysts can tolerate higher temperatures than those using metals. At lower temperatures, the presence of sulfur in the fuel can result in ammonium sulfate formation – increasing PM and plugging catalyst pores. Platinum catalysts are effective at temperatures below 200 ^{o}C, but lose effectiveness at higher temperatures.

The urea injection rate in an SCR system must be controlled to match the NOx production rate. Too little reductant means that some NOx escapes unreacted, and too much results in significant ammonia emission in the exhaust, called "slip". As the catalyst efficiency increases or decreases due to temperature changes, reductant injection must be trimmed accordingly, complicating the control system. Controlling reductant feed rates is especially difficult during transients; the limited transient response of most existing SCR system designs has complicated attempts to apply this technology to highway vehicles. Current truck SCR systems rely on a detailed map of engine NOx emissions vs. speed and load; future designs may use an exhaust NOx sensor for feedback control. The latter would help greatly to improve efficiency: with open-loop control systems, the maximum NOx injection rate must be limited to avoid excessive ammonia slip, and this limits the efficiency possible with the system.

The Danish company Technik Thermische Maschinen (TTM) has successfully installed an SCR catalytic converter system on a 2.4 MW (3200 HP) diesel ferry, using urea as the reductant. Over a combined steady-state and part-load duty cycle (average 37.1% load), with extreme load change rates, the open-loop system reportedly achieved 95% NO reduction at less than 2 ppm ammonia slip[22]. After 6000 hours of service, it was reported that there had been no detectable degradation of performance, no soot or ash deposition, and no mechanical breakdowns. This system used a vanadia-titania catalyst. A similar system is now being demonstrated in vehicles by Siemens[23], and has reportedly achieved NOx reduction efficiencies of 60 to 80% with no deterioration after 80 to 110,000 miles of service. The system is also effective in reducing hydrocarbons by around 80%, and PM emissions by 15 to 40% depending on the PM characteristics.

7.2 EFFECTS OF FUEL SULFUR CONTENT

Existing SCR technology is tolerant of fuel sulfur levels of 500 ppm. The titania-vanadia catalysts used by Siemens and TTM are not affected by sulfur, and have been demonstrated to be able to reduce NOx by 60 to 80% in automotive service. To achieve higher efficiencies may require reducing fuel sulfur, however. Existing base-metal catalysts have low efficiency at temperatures below 200 °C, and the problem of ammonium sulfate formation means that ammonia feed is normally cut off at low temperatures. In road vehicles, however, a significant portion of engine operation takes place at light load, resulting in exhaust temperatures often less than 200°C. Reducing the fuel sulfur level would help to reduce this problem.

Increasing SCR system efficiency may require the addition of a platinum catalyst. This catalysts would help to increase efficiency at low-temperature operation, and would also be useful at higher temperatures for oxidizing unreacted ammonia, thus allowing greater ammonia concentrations to be used without excessive "slip". Such a catalyst would also help to further reduce PM, HC, and toxic emissions. Unless low-sulfur fuel is provided, however, the catalyst loading would have to be strictly limited to avoid sulfate production at high temperatures.

7.3 SYSTEM COST ESTIMATES VS FUEL SULFUR LEVEL

Retail Price Equivalent - We estimated the costs of SCR systems under each of the three fuel sulfur levels: 500, 30, and 10 ppm. The corresponding platinum loadings were assumed to be limited by sulfate production to zero for the 500 ppm sulfur fuel. For 30 and 10 ppm sulfur fuels the estimated platinum loadings were 10 and 20 g/ft^3, respectively, based on information from the an SCR system supplier.

Responses to our questionnaire by the engine manufacturers indicated that the catalyst size for a urea-SCR system should be twice the engine displacement. We used this assumption in the cost analysis. Thus, the dimensions of a urea-SCR system assumed in the cost analysis were the same as those for the DPF system.

The cost for the urea fuel supply and injection assembly was estimated to be about $250[10, 24], and the cost for a 30-40 gallon urea-solution tank was estimated to range from $40 to $60, depending on the vehicle class. We estimated that it would require about two hours to assemble and install a urea-SCR system.

Operating Costs – The only significant operating cost for the SCR system is expected to be the cost of the urea used as a reductant. These costs are shown in Table 21. Wholesale costs of urea are about $0.85 per gallon in truckload lots. We assumed that light-heavy and medium-heavy duty vehicles would pay a 50% retail markup at the service station, on average. This is higher than the typical markup percentage on motor fuels, but much less than the typical markup on incidental automotive fluids such as coolant and lubricating oil. This reflect the fact that - at 4% of diesel fuel consumption - the volumes of urea sold would be much less than typical fuel volumes, but more than the volumes of other, higher-profit fluids such as lubricating oil. For heavy-heavy duty vehicles, we assumed that most fleets would have their own urea tank, and purchase it in wholesale quantities. The costs of ownership and operation of the tank and dispensing system (plus retail purchases at truck stops and service stations where fleet facilities are not available) were estimated to add 30% to the wholesale cost, on average.

Table 18: Cost estimate for SCR system with estimated 80% NOx reduction and 20% PM reduction using 500 ppm sulfur in fuel

Urea-SCR Systems 500 ppm Sulfur Content	Vehicle Classes		
	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Liter)	12	16	26
Substrate	$ 105	$ 140	$ 227
Washcoating and Canning	$ 350	$ 500	$ 600
Platinum	$ -	$ -	$ -
Catalyst Can Housing	$ 7	$ 10	$ 14
Urea Fuel Injection Assembly w/ECU	$ 250	$ 250	$ 300
Urea-Solution Tank+Brackets	$ 40	$ 50	$ 60
Direct Labor Costs			
Estimated Labor hours	2	2	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 35	$ 35	$ 35
Labor Overhead @ 40%	$ 14	$ 14	$ 14
Total Direct Costs to Mfr.	$ 801	$ 999	$ 1,250
Warranty Cost (5% fail)	104	129	160
Mfr. Carrying Cost	$ 24	$ 30	$ 37
Total Cost to Dealer	$ 929	$ 1,157	$ 1,447
Dealer Carrying Cost	28	35	43
Total Cost to Buyer	$ 956	$ 1,192	$ 1,491
Lifecycle Cost	$ 1,279	$ 2,033	$ 3,489

Table 19: Cost estimate for SCR system with estimated 90% NOx reduction and 25% PM reduction using 30 ppm sulfur in fuel

Urea-SCR Systems	Vehicle Classes		
30 ppm Sulfur Content	L-HDVs	M-HDVs	H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Liter)	12	16	26
Substrate	$ 105	$ 140	$ 227
Washcoating and Canning	$ 350	$ 500	$ 600
Platinum	$ 51	$ 68	$ 110
Catalyst Can Housing	$ 7	$ 10	$ 14
Urea Fuel Injection Assembly w/ECU	$ 250	$ 250	$ 300
Urea-Solution Tank+Brackets	$ 40	$ 50	$ 60
Direct Labor Costs			
Estimated Labor hours	2	2	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 35	$ 35	$ 35
Labor Overhead @ 40%	$ 14	$ 14	$ 14
Total Direct Costs to Mfr.	$ 851	$ 1,066	$ 1,359
Warranty Cost (5% fail)	110	137	174
Mfr. Carrying Cost	$ 26	$ 32	$ 41
Total Cost to Dealer	$ 987	$ 1,235	$ 1,574
Dealer Carrying Cost	30	37	47
Total Cost to Buyer	$ 1,017	$ 1,272	$ 1,621
Lifecycle Cost	$ 1,339	$ 2,113	$ 3,620

Table 20: Cost estimate for SCR system estimated 95% NOx reduction and 30% PM reduction using 10 ppm sulfur in fuel

Urea-SCR Systems 10 ppm Sulfur Content	Vehicle Classes L-HDVs	 M-HDVs	 H-HDVs
Average Engine Displacement (Liter)	6	8	13
Material and Component Costs			
Catalyst Volume (Liter)	12	16	26
Substrate	$ 105	$ 140	$ 227
Washcoating and Canning	$ 350	$ 500	$ 600
Platinum	$ 101	$ 135	$ 220
Catalyst Can Housing	$ 7	$ 10	$ 14
Urea Fuel Injection Assembly w/ECU	$ 250	$ 250	$ 300
Urea-Solution Tank+Brackets	$ 40	$ 50	$ 60
Direct Labor Costs			
Estimated Labor hours	2	2	2
Labor Rate ($/hr)	17.5	17.5	17.5
Labor Cost	$ 35	$ 35	$ 35
Labor Overhead @ 40%	$ 14	$ 14	$ 14
Total Direct Costs to Mfr.	$ 902	$ 1,134	$1,469
Warranty Cost (5% fail)	117	146	188
Mfr. Carrying Cost	$ 27	$ 34	$ 44
Total Cost to Dealer	$ 1,046	$ 1,313	$1,701
Dealer Carrying Cost	31	39	51
Total Cost to Buyer	$ 1,077	$ 1,353	$1,752
Lifecycle Cost	$ 1,399	$ 2,193	$3,750

Table 21: Estimated urea consumption and cost for urea-SCR systems.

Urea-SCR Systems Operating Costs	Vehicle Classes L-HDVs	 M-HDVs	 H-HDVs
Vehicle Lifetime (mi)	110,000	185,000	400,000
Baseline Fuel Economy (mpg)	12.6	8.1	6.4
Urea Cost			
Urea Consumption (% of Fuel Consumption)	4%	4%	4%
Lifetime Urea Consumption (gallon)	350	913	2,505
Average Urea Cost ($/gal)	1.275	1.275	1.105
Lifetime Urea Cost ($)	446	1,164	2,768
Lifetime Discounted Urea Cost ($)	322	841	1,998

7.4 CONCLUSIONS

An SCR system using a combination of base metal and precious-metal catalyst could drastically reduce NOx and HC emissions (including toxic air contaminants), and would help to reduce the SOF content of the PM as well. The efficiency these systems would be moderately affected by the sulfur content of the fuel. Like diesel oxidation catalysts, precious-metal SCR systems could increase PM emissions at high exhaust temperatures due to sulfate make. To reduce sulfate make under high loads, manufacturers would have to reduce catalyst loading and/or position the SCR catalyst further downstream in the exhaust. Both of these measures would reduce its efficiency. Sulfur also poisons the precious metal catalyst itself, and may combine with ammonia at low temperatures to form ammonium sulfate particles.

With 500 ppm sulfur in the fuel, we estimate that an SCR system would be limited to 70% efficiency for NOx, and 50% for HC, with no net PM reduction. If fuel sulfur levels were limited to 30 or 10 ppm, SCR system manufacturers could use higher precious catalyst loading, and the catalyst would suffer less from sulfur poisoning. This would increase low-temperature NOx performance, as well as reducing PM SOF, HC, and sulfate emissions. We estimate that an SCR system designed for 30 ppm fuel could attain 90% efficiency for NOx, while matching the performance of a DOC for PM and HC reduction. An SCR system designed for 10 ppm fuel could attain 95% efficiency for NOx, 30% for PM, and 85% for HC.

8. SUMMARY AND CONCLUSIONS

Feasible aftertreatment technologies for each fuel sulfur level are summarized in Table 22. The costs shown in this table are total lifecycle costs – the sum of retail price equivalent and discounted operating costs. Some rough estimates of the emission control efficiency likely to be achievable by each technology at each fuel sulfur level are also given. These estimates are based on the fragmentary emission data available (notably the DECSE progress report[16]), together with engineering judgment. Based on our estimates, reductions in diesel fuel sulfur levels should help to increase the range of aftertreatment systems that are feasible, as well as increasing the efficiency of sulfur-tolerant aftertreatment systems. A major benefit of lowering fuel sulfur would be for PM emissions, as this would make passively-regenerating trap-oxidizer systems possible, with an increase in reliability and considerable saving in complexity compared to other PM aftertreatment systems.

Table 22: Summary of estimated lifecycle costs and efficiency of diesel aftertreatment systems

Technologies	Lifecycle Cost			Estimated Efficiency		
	L-HDV	M-HDV	H-HDV	NOx	PM	HC
500 ppm Sulfur in Fuel						
Diesel Oxidation Catalyst	$233	$297	$393	0%	10%	50%
Catalytic DPF	$1,228	$1,700	$2,822	5%	70%	50%
Selective Catalytic Reduction	$1,279	$2,033	$3,489	80%	20%	70%
30 ppm Sulfur in Fuel						
Diesel Oxidation Catalyst	$304	$391	$548	0%	25%	80%
Catalytic DPF	$775	$1,091	$1,720	5%	80%	80%
Continuously Regenerating DPF	$774	$1,069	$1,685	5%	80%	80%
Lean NOx Catalyst	$999	$1,394	$2,363	25%	0%	-200%
NOx Adsorption Catalyst	$1,167	$1,557	$2,583	70%	0%	??
Selective Catalytic Reduction	$1,339	$2,113	$3,620	90%	25%	80%
10 ppm Sulfur in Fuel						
Diesel Oxidation Catalyst	$361	$467	$671	0%	30%	85%
Catalytic DPF	$836	$1,172	$1,851	5%	95%	85%
Continuously Regenerating DPF	$835	$1,150	$1,817	5%	95%	85%
Lean NOx Catalyst	$1,242	$1,718	$2,890	30%	10%	-200%
NOx Adsorption Catalyst	$1,156	$1,367	$1,872	80%	0%	??
Selective Catalytic Reduction	$1,399	$2,193	$3,750	95%	30%	85%

Low sulfur fuel would also have important benefits for NOx control. Reducing fuel sulfur levels to 10 or 30 ppm would make possible the use of lean NOx catalysts and NOx adsorption catalyst systems, neither of which would be practical at 500 ppm sulfur. Although SCR systems could be used at 500 ppm sulfur to reduce NOx, lowering fuel sulfur make possible an increase in low-temperature effectiveness and precious-metal catalyst loading for these system, and would thus increase their efficiency.

To meet future emission standards, diesel vehicles will likely have to employ both NOx and PM aftertreatment systems. Since these systems have many elements in common, it is likely that considerable savings could be achieved by combining them. An SCR system with precious-metal catalyst would itself function as a diesel oxidation catalyst to reduce PM and HC emissions as well. Another promising combination would include a continuously regenerating DPF upstream from an SCR system (the SCR system could not come first, as the DPF requires NOx to achieve regeneration). With low-sulfur fuel, this system should be capable of achieving 95% control of engine-out PM, and 90% control of engine-out HC and NOx emissions from diesel engines. Yet another potentially promising technology would be the combination of a continuously regenerating DPF upstream from a NOx adsorption catalyst system. Finally, a recent SAE paper[25] describes a combined catalytic DPF and lean NOx system. The authors have claimed 95% efficiency for HC and CO, 90% efficiency for PM, and 46% efficiency for NOx.

REFERENCES

[1] 64 Fed. Reg. 26142, May 13, 1999.

[2] Manufacturers of Emission Controls Association, The Impact of Sulfur in Diesel Fuel on Catalyst Emission Control Technology, submission to EPA Docket No. A-99-06, MECA, Washington DC, March 15, 1999.

[3] Jack Faucett Associates, 1985. "Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula," Rept. No. JACKFAU-85-322-3, Jack Faucett Associates, Chevy Chase, MD.

[4] L.H. Lindgren. Cost Estimations for Emission Control Related Components/Systems and Cost Methodology Description, EPA-460/3-78-002, U.S. EPA, Ann Arbor, MI, 1978.

[5] Putnam, Hayes, and Bartlett, Inc., "Report on EPA's Retail Price Equivalent Methodology," Memo to Willard Smith, U.S. EPA, Office of Policy Planning and Evaluation, 1984.

[6] Engine Manufacturers Association, statement submitted to EPA Docket No. A-99-06, July 13, 1999.

[7] Manufacturers of Emission Controls Association, Data extracted from a letter from Mark Gollub to Bruce Bertelsen, MECA, Washington DC, December 17, 1998.

[8] Data calculated based on EPA document EPA420-P-98-014 entitled "Update Heavy-Duty Engine Emission Conversion Factors for MOBILE6: Analysis of Fuel Economy, Non-Engine Fuel Economy Improvements, and Fuel Densities," May 1998, and EPA document EPA420-P-99-011 entitled "Fleet Characterization Data for MOBILE6: Development and Use of Age Distributions, Average Annual Mileage Accumulation Rates, and Projected Vehicle Contents for Use in MOBILE6," March 1999.

[9] Browning, L. etc., Estimated Economic Impact of New Emission Standards for Heavy-Duty On-Highway Engines, report under EPA Contract No. 68-C5-0010, March, 1997.

[10] Browning, L., and Kamakale, F., Sterndrive and Inboard Marine SI Technologies and Costs, report to the Engine Programs and Compliance Division of EPA, September, 1999.

[11] ICF, 1999. Data were provided by David Helzner/Ann Wolverton of ICF. Data were average prices over all 12 months for 1998. Platinum-group metal price was based on the Johnson-Matthey 1999 Platinum Report. Gold and silver prices came from the USGS web site and the Gold Institute, October 1999.

[12] Dystrup, J.A., W.H. Lane, J.P. Timmons, and A.L. Smith, "The Development of a Production Qualified Catalytic Converter", SAE Paper No. 930133, SAE International, Warrendale, PA, 1993.

[13] Weaver, C.S., M. Balam A., C.J. Brodrick, C. Tran, J. Heiken, and A. Pollack, Modeling Deterioration in Heavy-Duty Diesel Particulate Emissions, report under EPA Contract No. 8C-S112-NTSX, September, 1998.

[14] Farrauto, R.J. and J.J. Mooney, "Effects of Sulfur on Performance of Catalytic Aftertreatment Devices", SAE Paper No. 920557, SAE International, Warrendale, PA, 1992.

[15] Robota, H.J., K.C.C. Kharas, and O. Bailey, Controlling Particulate Emission from Diesel Engines with Catalytic Aftertreatment, SAE Paper No. 962471, SAE International, Warrendale, PA, 1996.

[16] DOE, 1999. Diesel Emission Control Sulfur Effects (DECSE) Program: Phase 1 Interim Data, Report No. 1, U.S. Department of Energy, August, 1999.

[17] Information received from conference calls with OEMs, and faxed response from OEMs.

[18] Heck, R.M., and Farrauto, R.J., Catalytic Air Pollution Control: Commercial Technology, John Wiley & Sons, Inc., New York, NY, 1995.

[19] Hawker, P., N. Myers, G. Huthwohl, H.Th. Vogel, B. Bates, L. Magnusson, and B. Bronnenberg, "Experience with a New Particulate Trap Technology in Europe", SAE Paper No. 970182, SAE International, Warrendale, PA, 1997.

[20] Weaver, C.S. "Draft Documentation of Cost-of-Compliance Estimates for Federal 1994 Heavy-Duty Diesel Engine Emissions Standards", technical memorandum prepared under EPA Contract No. 68-W9-0080, Work Assignment No. 72, April 9, 1992.

[21] White, J. et. al., "Three-Way Catalyst System for Off-Road Gasoline and LPG Equipment," report to California Air Resources Board, 1998.

[22] Hug, H.T., Mayer, A., & Hartenstein, A. Off-Highway Exhaust Gas After-Treatment: Combining Urea-SCR, Oxidation Catalysis, and Traps", SAE Paper No. 930363, SAE International, Warrendale, PA, 1993

[23] Fritz, N., W. Mathes, J. Zuerbig, and R. Mueller, "On-Road Demonstration of NOx Emission Control for Diesel Trucks with SINOx Urea SCR System", SAE Paper No. 1999-01-0111, SAE International, Warrendale, PA, 1999.

[24] White, J. et. al., "Three-Way Catalyst System for Off-Road Gasoline and LPG Equipment," report to California Air Resources Board, 1998.

[25] Page, D.L., R.J. MacDonald, and B.L. Edgar, "The QuadCat™ Four-Way Catalytic Converter: an Integrated Aftertreatment System for Diesel Engines", SAE Paper No. 1999-01-2924, SAE International, Warrendale, PA.