Interim and Proposed Technical Support Document:

Nonconformance Penalties for On-highway Heavy-Duty Diesel Engines

United States Environmental Protection Agency

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Nonconformance Penalties for On-highway Heavy-Duty Diesel Engines

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

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

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List of Acronyms

AEO	Annual Energy Outlook
CH_4	methane
CL	compliance level
CO	carbon monoxide
CO_2	carbon dioxide
COC50	estimate of the average total incremental cost to comply with standard relative to complying with the upper limit
COC90	estimate of the 90th percentile total incremental cost to comply with standard relative to complying with the upper limit
CPI	Consumer Price Index
DEF	diesel exhaust fluid
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
F	factor used to estimate the 90th percentile marginal cost based on the average marginal cost
$F_{E\&D}$	engineering and development factor
FEL	family emission limit
g/hp-hr	gram per horsepower-hour
GHG	greenhouse gas
GVWR	gross vehicle weight rating
HC	hydrocarbon
HD	heavy-duty
HDDE	heavy-duty diesel engine
HDE	heavy-duty engine
HDGE	gasoline-fueled heavy-duty engine
HDOBD	heavy-duty onboard diagnostics
HDV	heavy-duty vehicle
HLDT	heavy light-duty truck
ICM	indirect cost multiplier
LDT2	Light-Duty Truck 2
LHDGE	gasoline-fueled light heavy-duty engine
MC50	estimate of the average marginal cost of compliance with the standard
MC90	estimate of the 90th percentile marginal cost of compliance with the standard
MOVES	Motor Vehicle Emissions Simulator
mpg	miles per gallon
N_2	nitrogen
N_2O	nitrous oxide
NCP	nonconformance penalty
NHTSA	National Highway Traffic Safety Administration

NOx	oxides of nitrogen
NPV	net present value
OBD	onboard diagnostics
PM	particulate matter
S	emission standard
SCR	selective catalytic reduction
TSD	Technical Support Document
UL	upper limit
VMT	vehicle miles travelled
X	compliance level above the standard at which NCP equals COC50

Chapter 1: Introduction

The Technical Support Document (TSD) for this rulemaking presents analyses and supporting data for the provisions EPA used for establishing nonconformance penalties (NCPs) for model year 2012 and later on-highway heavy-duty diesel engines. Note that this TSD serves as a supporting document for both an Interim Final Rule establishing interim NCPs for heavy heavy-duty diesel engines and the Notice of Proposed Rulemaking seeking comments on establishing NCPs for other engines.[A]

1.1 Background on Nonconformance Penalties

Section 206(g) of the Clean Air Act (the Act), 42 U.S.C. 7525(g), allows EPA to promulgate regulations permitting manufacturers of heavy-duty engines (HDEs) or heavy-duty vehicles (HDVs) to receive a certificate of conformity for HDEs or HDVs that exceed the applicable emissions standard, provided that they pay a nonconformance penalty (NCP) and that their emissions do not exceed an appropriate upper limit. Congress adopted section 206(g) in the Clean Air Act Amendments of 1977 as a response to perceived potential for problems with technology-forcing heavy-duty emissions standards. If strict technology-forcing standards were promulgated, then some manufacturers, "technological laggards," might be unable to comply initially and would be forced out of the marketplace. NCPs were intended to remedy this potential problem. The laggards would have a temporary alternative that would permit them to sell their engines or vehicles by payment of a penalty. At the same time, conforming manufacturers would not suffer an economic disadvantage compared to nonconforming manufacturers, because the NCP would be based, in part, on money saved by the technological laggard. The resulting provisions of the Act require that NCPs account for the degree of emission nonconformity; increase periodically to provide incentive for nonconforming manufacturers to achieve the emission standards; and, most importantly, remove any competitive disadvantage to conforming manufacturers.

Under section 206(g)(1), NCPs may be offered for HDVs or HDEs. The penalty may vary by pollutant and by class or category of vehicle or engine. HDVs are defined by section 202(b)(3)(C) as vehicles in excess of 6,000 pounds gross vehicle weight rating (GVWR).

Section 206(g) authorizes EPA to require testing of production vehicles or engines in order to determine the emission level on which the penalty is based. If the emission level of a vehicle or engine exceeds an upper limit of nonconformity established by EPA through regulation, the vehicle or engine would not qualify for an NCP under section 206(g) and no certificate of conformity could be issued to the manufacturer. If the emission level is below

[A] Note that the NPRM proposes to establish NCPs for medium heavy-duty diesel engines, but not light heavy-duty diesel engines or gasoline engines.

the upper limit but above the standard, that emission level becomes the "compliance level," which is also the benchmark for warranty and recall liability; the manufacturer who elects to pay the NCP is liable for vehicles or engines that exceed the compliance level in-use, unless, for the case of HLDTs, the compliance level is below the in-use standard. The manufacturer does not have in-use warranty or recall liability for emissions levels above the standard but below the compliance level.

1.2 Previous NCP Rulemakings and Regulations

The generic NCP rule (Phase I) was promulgated August 30, 1985 (50 FR 35374). It established regulations for calculating NCPs in 40 CFR Part 86 Subpart L. It also established three basic criteria for determining the eligibility of emission standards for nonconformance penalties in any given model year. First, the emission standard in question must become more difficult to meet. This can occur in two ways, either by the emission standard itself becoming more stringent, or due to its interaction with another emission standard that has become more stringent. Second, substantial work must be required in order to meet the emission standard. EPA considers "substantial work" to mean the application of technology not previously used in that vehicle or engine class/subclass, or a significant modification of existing technology, in order to bring that vehicle/engine into compliance. EPA does not consider minor modifications or calibration changes to be classified as substantial work. Third, a technological laggard must be likely to develop. A technological laggard is defined as a manufacturer who cannot meet a particular emission standard due to technological (not economic) difficulties and who, in the absence of NCPs, might be forced from the marketplace. EPA will make the determination that a technological laggard is likely to develop, based in large part on the above two criteria. However, these criteria are not always sufficient to determine the likelihood of the development of a technological laggard. An emission standard may become more difficult to meet and substantial work may be required for compliance, but if that work merely involves transfer of well-developed technology from another vehicle class, it is unlikely that a technological laggard would develop.

The above criteria were used to determine eligibility for NCPs during Phase II of the NCP rulemaking process (50 FR 53454, December 31, 1985). NCPs were offered for the following 1987 and 1988 model year standards: the particulate matter (PM) standard for 1987 diesel-fueled light-duty trucks with loaded vehicle weight in excess of 3,750 pounds (LDDT2s), the 1987 gasoline-fueled light HDE (LHDGE) HC and CO emission standards, the 1988 diesel-fueled HDE (HDDE) PM standard, and the 1988 HDDE NOx standard. As discussed in the Phase II rule, NCPs were considered, but not offered, for the 1987 HLDT NOx standard and the 1988 (later, the 1990) gasoline-fueled HDE (HDGE) NOx standard.

The availability of NCPs for 1991 model year HDE standards was addressed during Phase III of the NCP rulemaking (55 FR 46622, November 5, 1990). NCPs were offered for the following: the 1991 HDDE PM standard for petroleum-fueled urban buses, the 1991 HDDE PM standard for petroleum-fueled vehicles other than urban buses, the 1991 petroleum-fueled HDDE NOx standard, and the PM emission standard for 1991 and later model year petroleum-fueled light-duty diesel trucks greater than 3,750 lbs loaded vehicle weight (LDDT2s). As discussed in the Phase III rule, NCPs were also considered, but not offered for the methanol-fueled heavy-duty diesel engine and heavy-duty gasoline engine standards as it was concluded that those standards did not meet the eligibility criteria established in the generic rule. In addition, Phase III of the NCP rulemaking described how NCPs would be integrated into the HDE NOx and PM averaging program.

The availability of NCPs for HDVs and HDEs subject to the 1994 and later model year emission standards for particulate matter (PM) was addressed by Phase IV of the NCP rulemaking (58 FR 68532, December 28, 1993). NCPs were offered for the following: the 1994 and later model year PM standard for heavy-duty diesel engines (HDDEs) used in urban buses and the 1994 and later model year PM standard for HDDEs used in vehicles other than urban buses. NCPs were also considered, but not offered, for the 1994 and later model year methanol-fueled HDE PM standard and the 1994 and later model year cold carbon monoxide (CO) standard for heavy light-duty gasoline fueled trucks.

The availability of NCPs for HDVs and HDEs subject to the 1998 and later model year emission standards for NOx was addressed by Phase V of the NCP rulemaking (61 FR 6949, February 23, 1996). NCPs were offered for the following: the 1998 and later model year NOx standard for heavy-duty diesel engines (HDDEs), the 1996 and later model year for Light-Duty Truck 3 (LDT3) NOx standard, and the 1996 and later urban bus PM standard. A concurrent but separate final rule (61 FR 6944, February 23, 1996) established NCPs for the 1996 LDT3 PM standard and discussed other standards for which NCPs were considered.

The availability of NCPs for 2004 model year HDE standards was addressed during Phase VI of the NCP rulemaking (67 FR 51464, August 8, 2002). NCPs were offered only for the NOx+NMHC standards. One notable aspect of that rule was that the upper limit for heavy heavy-duty diesel engines was set at a level above the previous standard. This was done because a legal settlement of compliance violations (i.e. a consent decree) allowed certain manufacturers to exceed the otherwise applicable 4.0 g/hp-hr NOx standard for a brief period.[B] The upper limit for these engines was set at 6.0 g/hp-hr to allow manufacturers to continue producing engines allowed by the consent decree.

[B] On October 22, 1998, the Department of Justice and the Environmental Protection Agency announced settlements with seven major manufacturers of diesel engines. The settlements resolved claims that they installed illegal computer software on heavy-duty diesel engines that turned off the engine emission control system during highway driving. The settlements were entered by the Court on July 1, 1999. The Consent Decrees allowed heavy-heavy service class diesel engines to continue to use emission control strategies which could result in NOx emission levels as high as 6 or even 7 g/hp-hr NOx.

1.3 Promulgation of 2007/2010 Emission Standards

The 0.20 g/hp-hr NOx standard currently applicable to heavy-duty engines was adopted January 18, 2001 (66 FR 5001) and first applied in the 2007 model year. However, because of phase-in provisions adopted in that rule and use of emission credits generated by manufacturers for early compliance, manufacturers were able to continue to produce engines with NOx emissions over 0.20 g/hp-hr until (and in some cases after) 2010 model year. The phase-in provisions ended after model year 2009 so that the standards were fully phased-in for model year 2010. Equally important, the cap applicable to Family Emission Limits for credit-using engine families was lowered to 0.50 g/hp-hr beginning in model year 2010. Because of these changes that occurred in model year 2010, the 0.20 g/hp-hr NOx emission standard is often referred to as the 2010 NOx emission standard, even though it applied to engines as early as model year 2007. For this rulemaking, the fully phased-in NOx requirements are referred to as the 2010 NOx standards.

While some manufacturers still retain NOx emission credits that currently allow them to produce engines with NOx emissions as high as 0.50 g/hp-hr, we expect that one or more of these manufacturers could exhaust their supplies of credits as early as model year 2012. As seen in Figure 1-1, all manufacturers certified their model year 2011 medium and heavy-heavy duty engine families at NOx levels below 0.50 g/hp-hr.

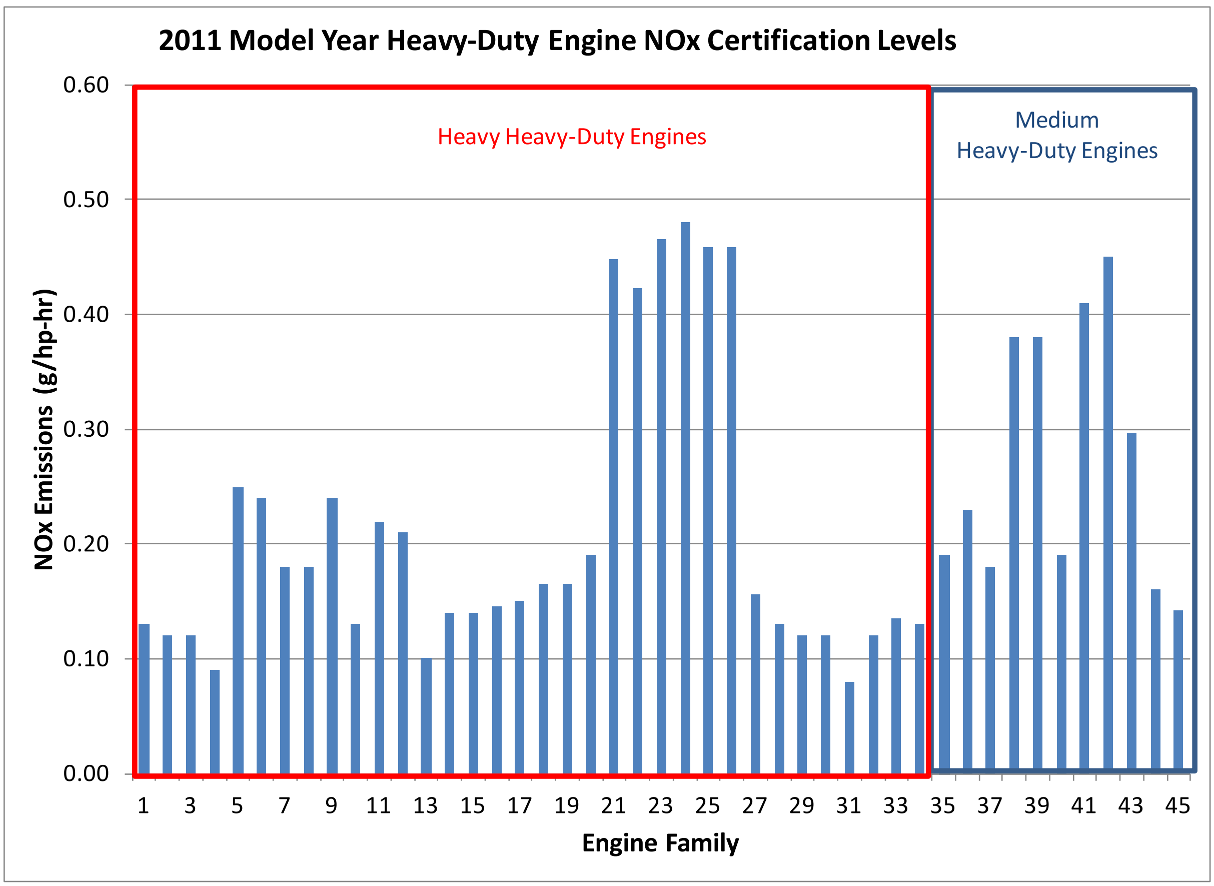

Figure 1-1: 2011 Model Year Heavy-Duty Engine NOx Emissions Certification Levels

1.4 The Onboard Diagnostics (OBD) System Requirements for 2010 and Later Heavy- Duty On-highway Engines

For 2010 and later model year heavy-duty diesel and gasoline engines used in highway applications over 14,000 pounds gross vehicle weight rating, EPA requires that all major emissions control systems be monitored and malfunctions be detected prior to emissions exceeding a set of emissions thresholds. Most notably, we require that the aftertreatment devices—e.g., the diesel particulate filters and NOx reducing catalysts—that will be used on highway diesel engines to comply with the 2010 emissions standards will be monitored and their failure will be detected and noted to the driver. We also require that all emission-related electronic sensors and actuators be monitored for proper operation.

For these highway applications over 14,000 pounds, we require that one engine family per manufacturer be certified to the OBD requirements in the 2010 through 2012 model years. Beginning in 2013, all highway engines for all manufacturers will have to be certified to the OBD requirements. This phase-in is designed to spread over a number of years the development effort required of industry and to provide industry with a learning period prior to implementing the complex OBD requirements on 100 percent of their highway product line.

These OBD requirements are potentially relevant to this NCP rulemaking because lower emission standards can make the OBD requirements more difficult.

1.5 The Heavy-Duty Vehicle and Engine Greenhouse Gas Emissions Standards

EPA and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) issued the first-ever program to reduce greenhouse gas (GHG) emissions and improve fuel efficiency of heavy-duty trucks and buses in 2011.[1] The agencies adopted complementary standards under their respective authorities covering model years 2014-2018 and beyond, which together form a comprehensive national program, referred to in this document as the Heavy-Duty GHG rule. While improvements in the whole vehicle will be required, these regulations will specifically require reductions in the engine's brake-specific fuel consumption (BSFC). The program regulates combination tractors and vocational vehicles separately from the engines installed in these vehicles. This approach ensures existing technologies readily available to improve fuel efficiency are applied to both engines and trucks resulting in the maximum improvement in overall vehicle efficiency possible.

The Heavy-Duty GHG rule begins in model year 2014 and controls the CO_2, N_2O, and CH_4 emissions and fuel consumption from HD engines. The program drives approximately 3 to 5 percent improvements in CO_2 emissions from engines in model year 2014 and an additional 2 to 4 percent improvement in model year 2017. The program also allows manufacturers to generate greenhouse gas emission credits by meeting these greenhouse gas emission standards prior to model year 2014.

The greenhouse gas requirements are potentially relevant to this NCP rulemaking because they affect the types of emission controls manufactures would pursue. As noted later, we believe that it is appropriate to assume that even if the NOx standard was higher, manufacturers would not have chosen emission controls that would have increased fuel consumption rates because they must also meet the greenhouse gas emission standards.

1.6 Characterization of the Heavy-Duty Engine and Vehicle Industries

1.6.1 Vehicle Applications and Classes

Heavy-duty engines are used in a wide variety of vehicle applications. Smaller engines are used in heavy-duty pickup trucks, vans and other vehicles using those same chassis. At the other extreme, the largest engines are used in cement mixers, garbage trucks, and line-haul tractors. In matching the engines to the vehicles, the minimum requirement is that the engine would be large enough to power a fully-loaded truck up a hill. More typically, especially for the larger trucks, the engine is selected to provide the best fuel consumption. In other cases, especially for light heavy-duty, larger engines are used to provide additional performance.

In applying heavy-duty emission standards, EPA categorizes heavy-duty vehicles into three service classes: light heavy-duty; medium heavy-duty; and heavy heavy-duty. Light heavy-duty includes pickup trucks and vans. Medium heavy-duty includes delivery trucks and recreational vehicles. Heavy heavy-duty includes buses and line-haul tractors. Table 1-1 lists the gross vehicle weight rating of the vehicles by service class. Engines are classified by the primary service class for which the engine is intended.

Table 1-1: Gross Vehicle Weight Rating of Light, Medium, and Heavy Heavy-Duty Engines and Vehicles

Service Class	DOT Weight Classes	GVWR (lbs.)
Light Heavy	2b-5	8,500 - 19,500
Medium Heavy	6-7	19,501 - 33,000
Heavy Heavy	8	33,001 +

1.6.2 Engine and Vehicle Manufacturers

Table 1-2 shows the major heavy-duty engine and vehicle manufacturers for the U.S. What is not shown in the table is the degree to which vehicle manufacturers buy engines from different engine manufacturers. The industry operates such that the vehicle manufacturer decides during the design stage which engines it will make available in its vehicles, and the ultimate customer chooses its engine from among the available options. The result is that most of the vehicle manufacturers use engines from two or more engine suppliers for at least some of their vehicle models. This practice makes the industry a very competitive marketplace. This is particularly true for the medium heavy-duty and heavy heavy-duty marketplace, where the Navistar International Corporation is currently the only engine and vehicle manufacturer that is not offering engines from another manufacturer in its U.S. vehicle models. The light heavy-duty market is a mix of integrated manufacturers and exclusive relationships between vehicle manufacturers and diesel engine manufacturers. Specifically, General Motors and Ford currently supply their own diesel engines in the light heavy-duty pick-up trucks for their respective companies. Chrysler exclusively uses Cummins supplied diesel engines in their Dodge light heavy-duty pickup trucks. However, in the medium heavy-duty and heavy heavy-duty vehicle market, there is a wider range of engines available to choose from for the same vehicle. For example, an end-user can purchase a Western Star vehicle with either a Cummins or a Detroit Diesel engine in it. Engines produced by Cummins tend to be offered by all of the major heavy duty truck manufacturers in at least some of their truck models. In this sense, it has been common practice in the medium and heavy heavy-duty marketplace to treat the engine almost as a commodity.

Table 1-2 Heavy-Duty Engine and Vehicle Manufacturers

Heavy-Duty Diesel Engine Manufacturers (Brands)	Cummins Daimler (Detroit Diesel, Mercedes Benz) Ford General Motors Hino Navistar PACCAR Volvo Truck (Volvo, Mack)
Heavy-Duty Vehicle Manufacturers (Brands)	Chrysler (Dodge) Daimler Trucks (Freightliner, Western Star) Ford (Ford) General Motors (Chevrolet, GMC) Hino (Hino) Navistar (International) PACCAR (Kenworth, Peterbilt) Volvo Truck (Volvo, Mack)

Figure 1-2 contains an estimate of the 2010 market share by sales volume of diesel engine manufacturers in the heavy-duty market for the major engine manufacturers in the U.S. This table indicates that Ford dominates the sales of diesel engines with just above 60 percent, while General Motors follows at approximately 13 percent. The remaining quarter of the diesel engine sales are made up of Cummins, Navistar, Mack, Detroit Diesel, Volvo, PACCAR, Hino, and Mercedes Benz. It is important to note that when all service classes are considered together, the distribution is dominated by light heavy-duty pickups and vans, which are sold in much higher numbers than medium heavy-duty and heavy heavy-duty trucks.

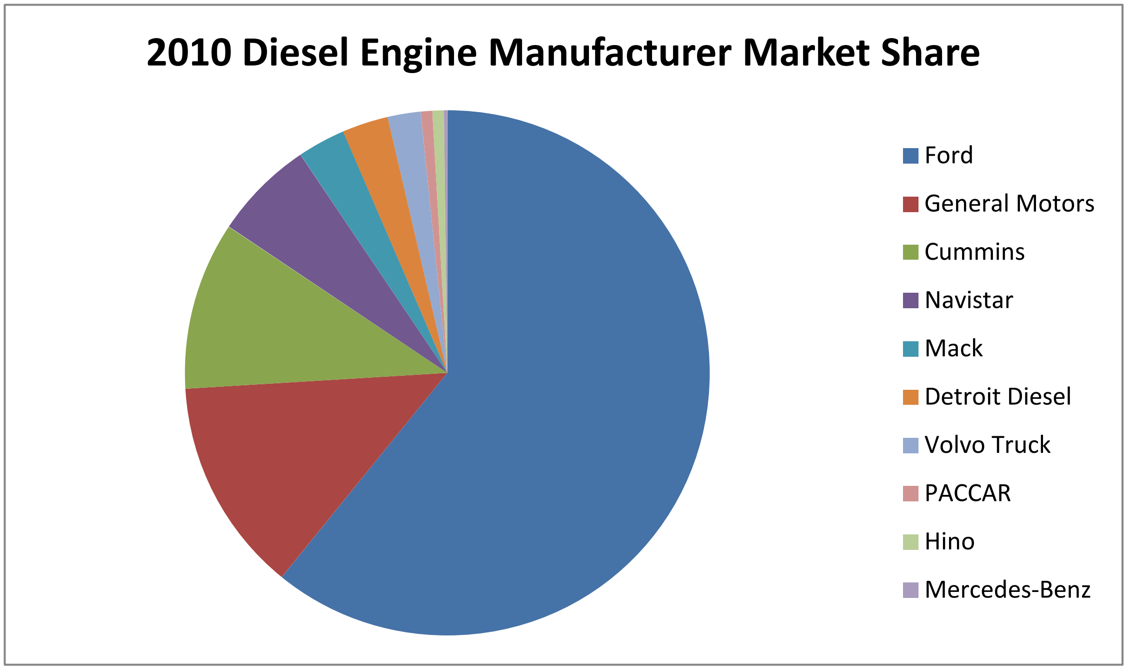

Figure 1-2: 2010 Diesel Engine Manufacturer Market Share. Source: Ward's Automotive Group

Figure 1-3 illustrates by sales volume that in a similar manner to the HD engine market, the HD truck market is a competitive marketplace with a number of players.

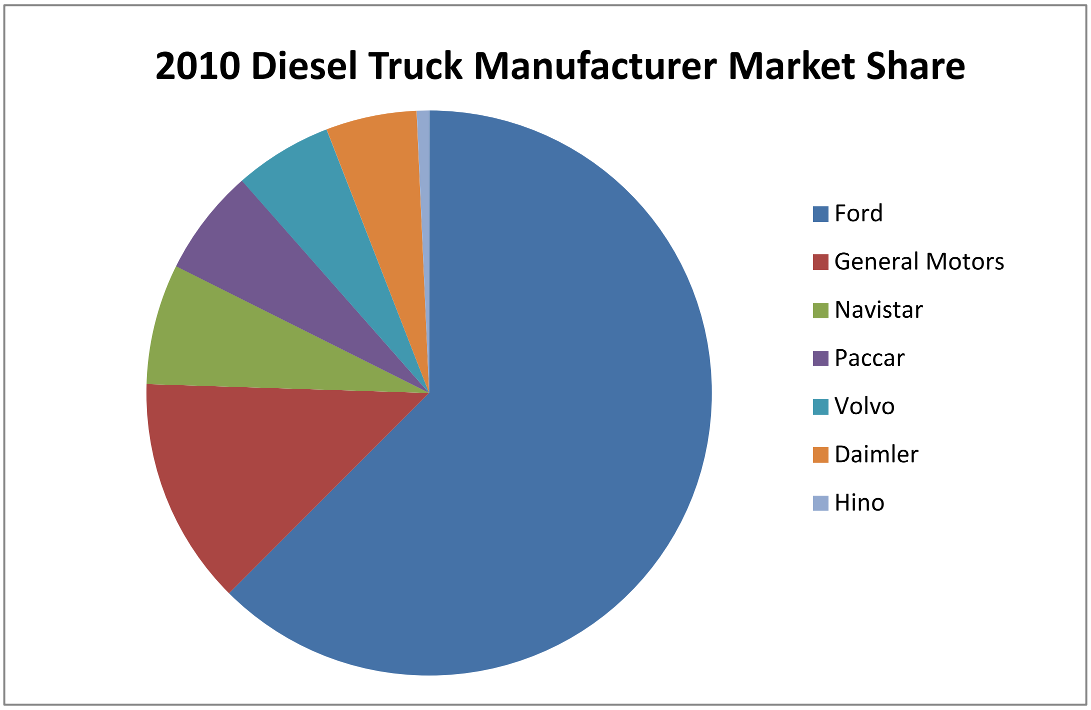

Figure 1-3: 2010 Diesel Truck Manufacturer Market Share. Source: Ward's Automotive Group

We also separately evaluated the market share by sales volume of each of the largest Class 8 heavy-duty truck manufacturers in 2008 through October 2011 (shown in Figure 1-4). These are the trucks for which the interim NCPs may be used. Although the market share of each varies from year to year, each manufacturer generally has about 20 to 30 percent of the Class 8 market. These annual variations occur for a variety of reasons, such as introduction of a new model by one manufacturer or new purchases by large fleets (which represent a large fraction of new Class 8 purchases). When considering these data, it is important to note that economic conditions in 2009 and 2010 led to significantly reduced sales in the heavy-duty market relative to 2008, and market shares in these years may be especially variable. However, sales in 2011 have returned to 2008 levels or better. The 2011 year-to-date market share of each manufacturer closely resembles the 2008 breakdown.

Since producing engines that comply with a 0.20 g/hp-hr NOx emission standard is more difficult than producing those with NOx emissions at 0.50 g/hp-hr, it can be presumed that allowing a manufacturer to produce engines with NOx emissions at 0.50 g/hp-hr without paying an NCP would bestow some competitive advantage. However, such advantage does not appear to have affected market share. Only Navistar is using non-SCR engines in its 2011 Class 8 trucks, and it is using them in all of its trucks.[C] So the small decrease in

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[C] Note that while some other manufacturers have certified engines using emission credits, only Navistar is selling non-SCR engines for the U.S. market. So the market share for Navistar trucks is exactly the same as the market share for Navistar engines and the market share for non-SCR engines.

Navistar's market share between 2008 and 2011 indicates that, while selling non-SCR engines in its trucks may provide some competitive advantage, it has not allowed Navistar to increase in market share.

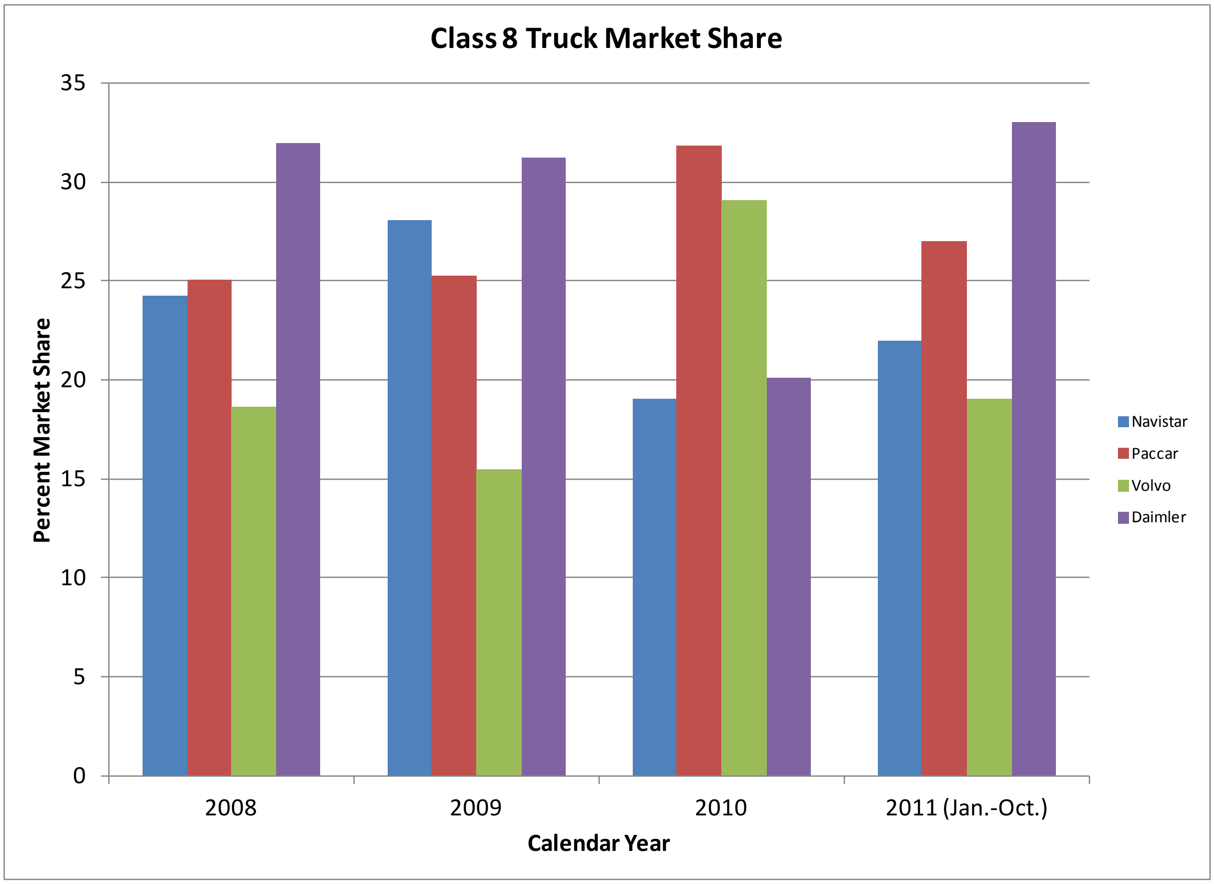

Figure 1-4: Class 8 Truck Market Share. Source: Ward's Automotive Group

Chapter 2: Technologies to Meet the 2010 NOx Standard

All engines that currently meet the 2010 0.20 g/hp-hr NOx emission standard without using credits rely on selective catalytic reduction (SCR) aftertreatment systems that use diesel exhaust fluid (DEF) to reduce NOx emissions. They also include traditional emission control technologies such as cooled EGR and injection timing optimization to reduce engine-out NOx emissions. The one non-SCR manufacturer also uses these traditional emission controls, but to a greater degree. All of the manufacturers use integrated diesel oxidation catalysts (DOC) and diesel particulate filters (DPFs) to control particulate matter (PM). This chapter summarizes these technologies and explains the effect on costs for different strategies for optimizing them.

2.1 Engine Service Classes

Manufacturers design light heavy-duty, medium heavy-duty, and heavy heavy-duty engine differently. The lighter duty engines tend to have smaller displacements, operate at higher engine speeds, and are not as likely to be rebuilt. This impacts mixing, heat rejection, and engine life. These differences affect which emission controls are most appropriate for each service class. In general, it is more difficult to reduce engine-out NOx emissions from the light and medium heavy-duty engines than it is from heavy heavy-duty engines.

2.2 Emission Control Technologies for Diesel Engines

This section describes the emission control technologies that were used to meet the 2007 NOx and PM standards and are being used to meet the 2010 NOx standard. See Section 2.4 for a discussion of how the different engine manufacturers are using these technologies.

2.2.1 Air Handling System and Turbocharging Technology

Cooled exhaust gas recirculation (EGR) lowers NOx emissions principally by replacing a portion of the fresh intake air oxygen with exhaust by-products and other inert gases, such as CO_2, water vapor, and N_2. The amount of exhaust that is recirculated varies with engine conditions. Thus, a cooled EGR system must be capable of routing different amounts of exhaust gas from the exhaust system to the intake system, as well as cooling the exhaust during that process. These inert gases dilute the in-cylinder mixture and reduce the peak cylinder temperatures during the combustion process and thus reduce NOx formation. The downside of EGR is that it tends to increase PM emissions and fuel consumption and can degrade engine oil. Manufacturers are continuing to make improvements to EGR systems, such as reducing pumping loss in the EGR piping system, which allows more EGR to flow without sacrificing engine performance. All engines that currently meet the 2010 0.20 g/hp-hr NOx emission standard use EGR as part of their emissions solution.

Advancements in turbocharger technology can improve engine performance while meeting emissions standards. Variable geometry turbines with better control and higher efficiency, allow optimal EGR control, thus better emission control. While turbo-compound is mainly used to improve engine thermal efficiency, its integration with the engine air handling system provides the engine manufacturer more flexibility for combustion optimization, thus delivering optimal overall engine system performance. The DD15 and DD16 engines developed by Detroit Diesel are an example of this strategy.

2.2.2 Advanced Fuel Injection Systems

Modern fuel injection systems for HD diesel engines, such as the common-rail system or advanced electronically controlled injectors, provide engineers with the ability to perform pilot injection, ramped injections, and post injections (in some cases multiple pilot and/or post injections). They can also provide engineers with complete control over injection timing, pressure and duration. These systems provide important flexibilities for engineers, including the ability for improved engine-out NOx and PM emissions performance. They are especially significant with respect to minimizing a trade-off between NOx emissions and fuel consumption.

2.2.3 Diesel Particulate Filters and Oxidation Catalysts

A diesel particulate filter (DPF) is a ceramic device that collects PM in the exhaust stream. The high temperature of the exhaust heats the ceramic structure and allows the particles inside to break down (or oxidize) into less harmful components. All on-highway heavy-duty diesel engine manufacturers use DPFs to reduce PM. Periodic regeneration to oxidize and remove loaded soot is required for all DPFs. One method of regeneration, called active regeneration, directly injects the fuel into exhaust stream and a diesel oxidation catalyst (DOC) or other device then oxidizes the fuel in the exhaust stream, providing the heat required for DPF regeneration. Active regeneration increases the fuel consumption of the vehicle, in some cases by more than one percent. The other regeneration method , called passive regeneration, uses NO_2 to directly react with soot in the exhaust at much lower exhaust temperature than active regeneration. This requires increasing the NO_2 fraction of the NOx, which is usually low coming out of the engine. Advanced thermal management can be used in production engines to eliminate active regeneration, thus significantly improving fuel efficiency. Volvo's 2010 DPF+SCR system has eliminated active regeneration for on-highway vehicles.[2] All other manufacturers using SCR are working in the same direction, minimizing or eliminating active regeneration, thus improving fuel economy, providing efficiency improvements in the real world, although they are not directly reflected in the HD engine test procedure.

2.2.4 Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) is an exhaust aftertreatment system used to control NOx emissions from heavy-duty engines by converting NOx into nitrogen (N_2) and water (H_2O). The technology depends on the use of a catalytic converter and a chemical reducing agent, which generally is in an aqueous urea solution, and is often referred to as diesel exhaust fluid (DEF). DEF injected into the exhaust upstream of the catalyst where it forms ammonia and carbon dioxide according to the following equation:

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2$$

The ammonia then reacts with NO and NO_2 molecules according to the following equations:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

Thus, one molecule of urea can reduce two molecules of NO or one molecule of NO_2. However, not all urea molecules will find NOx molecules with which to react. Manufacturers design their system to inject slightly more urea than this stoichiometric amount. This is called overdosing the system. The excess ammonia reacts with oxygen to form N_2 and water. DEF dosing rates vary among engines and are roughly proportional to the amount of NOx being reduced. For 2010 model year engines, DEF rates typically range between one and three percent of fuel consumption. In other words, DEF consumption is approximately one to three gallons for every 100 gallons of fuel consumed.

The catalyst in the SCR systems used today in the HD engine industry generally contains either copper/zeolite or iron/zeolite formulations. Both formulations can achieve NOx conversion rates of over 90 percent. In general, iron/zeolite substrates have a greater acceptable maximum temperature for durability; whereas the copper/zeolite substrates have higher NOx efficiency rates at lower exhaust temperatures.[3]

A robust SCR system can achieve about 90 percent reduction in cycle-weighted NOx emissions. Improvements have been made over the last several years to improve the NOx conversion rate and reduce the impact of temperature on the conversion rate. Figure 2-1 shows the improvement over a three year period in both NOx conversion efficiency and maximizing conversion efficiency over a wider gas temperature range.[4]

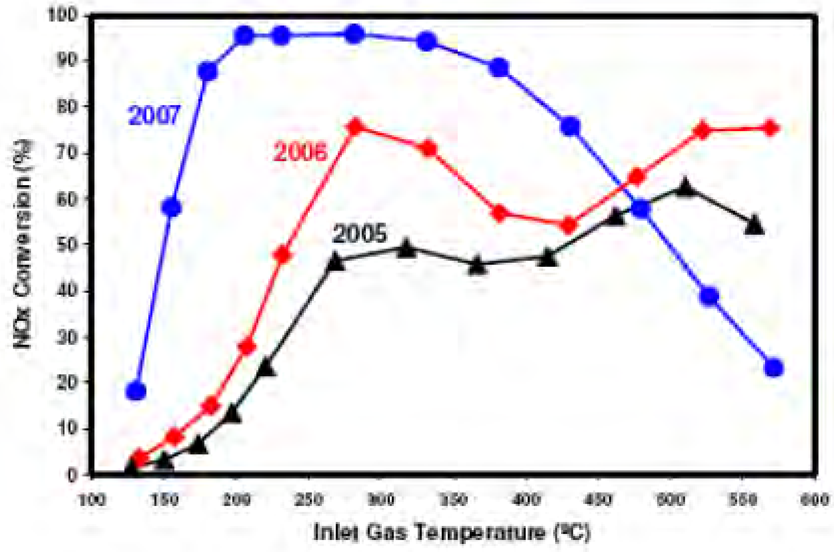

Figure 2-1: SCR Efficiency Rate Improvement over Time. W. Tang, et. al., BASF. DOE DEER Conference, October 4, 2011. Page 3.

2.3 Optimization Strategies

Manufacturers can design and calibrate the EGR, fuel injection, and aftertreatment systems in different ways to optimize engines with respect to hardware costs, performance, emissions, operating costs, and reliability. In the context of this rulemaking, one of the central trade-offs to be optimized is the one between engine-out NOx emissions and DEF consumption rates.

There are two typical paths to reduce NOx emissions at the tailpipe – improving the NOx conversion efficiency of the aftertreatment or reducing the NOx emissions coming out of the engine. However, the most effective way to meet 2010 emissions standards is the use of integrated engine and aftertreatment approach while continuously improving engine fuel economy. The next few sections will discuss each approach in more detail.

All on-highway heavy-duty diesel engine manufacturers except one rely on SCR to reduce NOx emissions. SCR NO_X conversion efficiency allows higher engine-out NO_X emissions (while still meeting the tailpipe NO_X standard due to the aftertreatment), and therefore, gives more room for engine system optimization.

2.3.1 Engine-Out NOx Emission Reduction Strategies

Tailpipe NOx emissions reductions (i.e., downstream of any aftertreatment) can be achieved by reducing the NOx emissions from the engine (i.e., engine-out emissions) by different methods. First, engine-out NOx emissions can be reduced by optimization of combustion. This includes retarding injection timing and combustion chamber optimization in matching different fuel injection strategies depending on applications. Retarding injection timing tends to reduce the peak pressure and temperature inside the engine cylinder and therefore reduce the amount of NOx created in the cylinder. However, this type of injection timing change can increase fuel consumption of the engine. By appropriately optimizing piston bowl geometry and matching it with the injection angle and pressure, NOx emissions can be reduced in certain operating modes, but benefits would be limited over a wide range of operating conditions.

An increased EGR rate can also reduce the amount of NOx produced in the engine. EGR replaces a portion of the fresh intake air oxygen with exhaust by-products and other inert gases, such as CO_2, water vapor, and N_2. It leads to lower cylinder pressure and therefore less NOx emissions. EGR rates have a linear impact on NOx emissions. However, an increase in EGR rates may lead to a reduction in power and increase PM emissions. Although this approach is one of the ways to reduce overall NOx emissions, the challenges in balancing the benefits of emissions reduction and thermal efficiency are significant.

2.3.2 Integrated Aftertreatment System

An advanced integrated aftertreatment system can allow individual components to be optimized, such as DOC, DPF, and SCR, on a system level. In general, catalyst efficiency is dependent on catalyst volume, surface area, chemical composition of the substrate, and packaging configurations. An increase in catalyst volume can increase the amount of emissions that are converted. However, a larger catalyst would typically have a higher hardware cost. An increase in surface area of the catalyst increases the amount of exhaust gas which can be catalyzed. Surface area increases can be achieved through smaller pore sizes, however, this can lead to higher system backpressure which can reduce engine power and increase fuel consumption of the engine. Optimization of DOC and DPF precious metal loading can have profound impacts on NOx reduction of a downstream SCR catalyst, while reducing system cost.

Depending on technologies as well as applications, different manufacturers use different system configurations to achieve optimal NOx reduction. An example of this approach is the one-box system that packages the DOC, DPF, and SCR together, such as the one being used by Detroit Diesel in its 2010 production engine.[5] This integrated system makes the vehicle packaging more compact and the engine more efficient in performance due to lower back pressure. Cummins' 2010 SCR system utilizes a decomposition reactor that is integrated with the total aftertreatment system, which is different from other manufacturers' aftertreatment systems.[6] This decomposition reactor component converts DEF into ammonia through hydrolysis. A long pipe between DPF and SCR ensures DEF to be well mixed with exhaust gas, thus achieving optimal NOx conversion efficiency.

2.3.3 Integrated Engine and Aftertreatment Strategies

An increase in aftertreatment efficiency allows an engine to maintain constant or even increasing engine-out NOx emissions while reducing tailpipe NOx emissions. Aftertreatment efficiency is impacted by DEF rates. An increase in DEF rate can increase the efficiency of the NOx conversion in the SCR system with proper engine control strategies. The ammonia produced from the DEF along with the catalyst converts NOx into nitrogen and water. As shown in Figure 2-2, DEF consumption rates have a linear impact on NOx emissions over a broad range. However, the benefits of increasing DEF rates will decline at some point and the conversion efficiency will be limited more by the residence time and other catalyst characteristics.

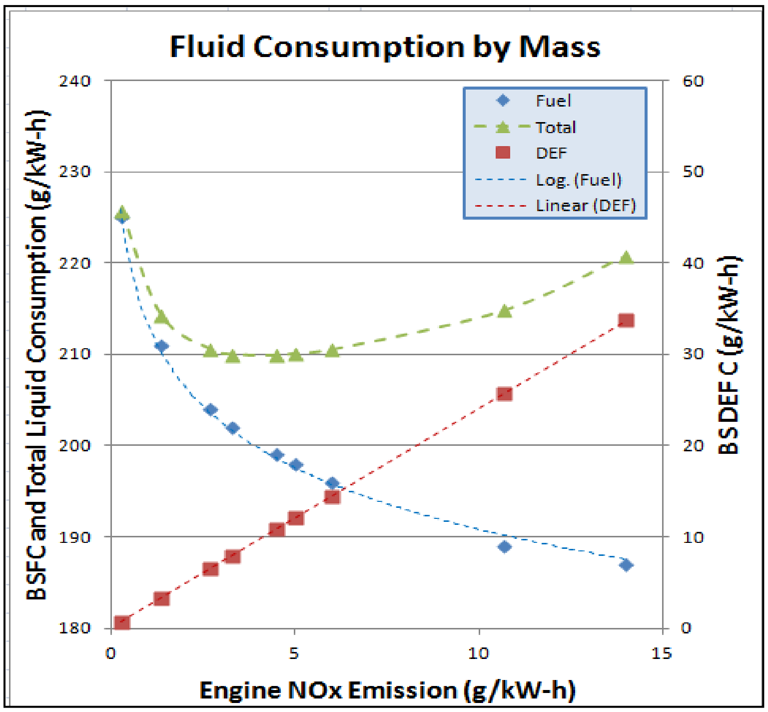

Figure 2-2: Fluid Consumption Impact on Engine NOx Emissions Rates. Source: T. Johnson, Corning. DOE DEER Conference, October 4, 2011. Page 20.

There are some negative impacts of increased DEF dosing rates. First, the operating cost of the vehicle increases with dosing rates. As discussed in more detail in Chapter 3 below, DEF costs approximately $3 per gallon. As an example, an increase in DEF of 0.5 gallon of DEF consumption for every 100 gallons of fuel consumed (which would generally be described as a one-half percent increase in DEF) may lead to an increase annual operating costs ranging between a few dollars and $220 per year depending on the number of miles travelled. Second, an increase in DEF consumption will require either an increase in DEF capacity on the vehicle or an increase in the frequency of DEF refills. Optimal points with balance of the fuel and DEF consumptions can be found as indicated in Figure 2-2.

More advanced and higher efficiency aftertreatment systems provide engine manufacturers more opportunities to improve engine fuel economy while meeting emissions standards. Figure 2-4 shows NOx trade-off on fuel economy and PM emissions with different engine technology road maps. Although some of the technologies noted in this figure may be beyond current production feasibilities and more in the area of research today, the figure does show the relation between SCR efficiency and engine technology requirements in order to meet 2010 emissions standards. This figure also qualitatively highlights the penalty of fuel economy for an engine that solely relies on non-SCR solution in order to meet 2010 emissions standards.

As indicated in Figure 2-3, the typical technologies to improve both engine emissions and fuel economy include, but not limited to, better air handling system, lower friction loss of EGR piping, optimal fuel injection strategies, optimized combustion system, and advanced engine and aftertreatment system control.[7]

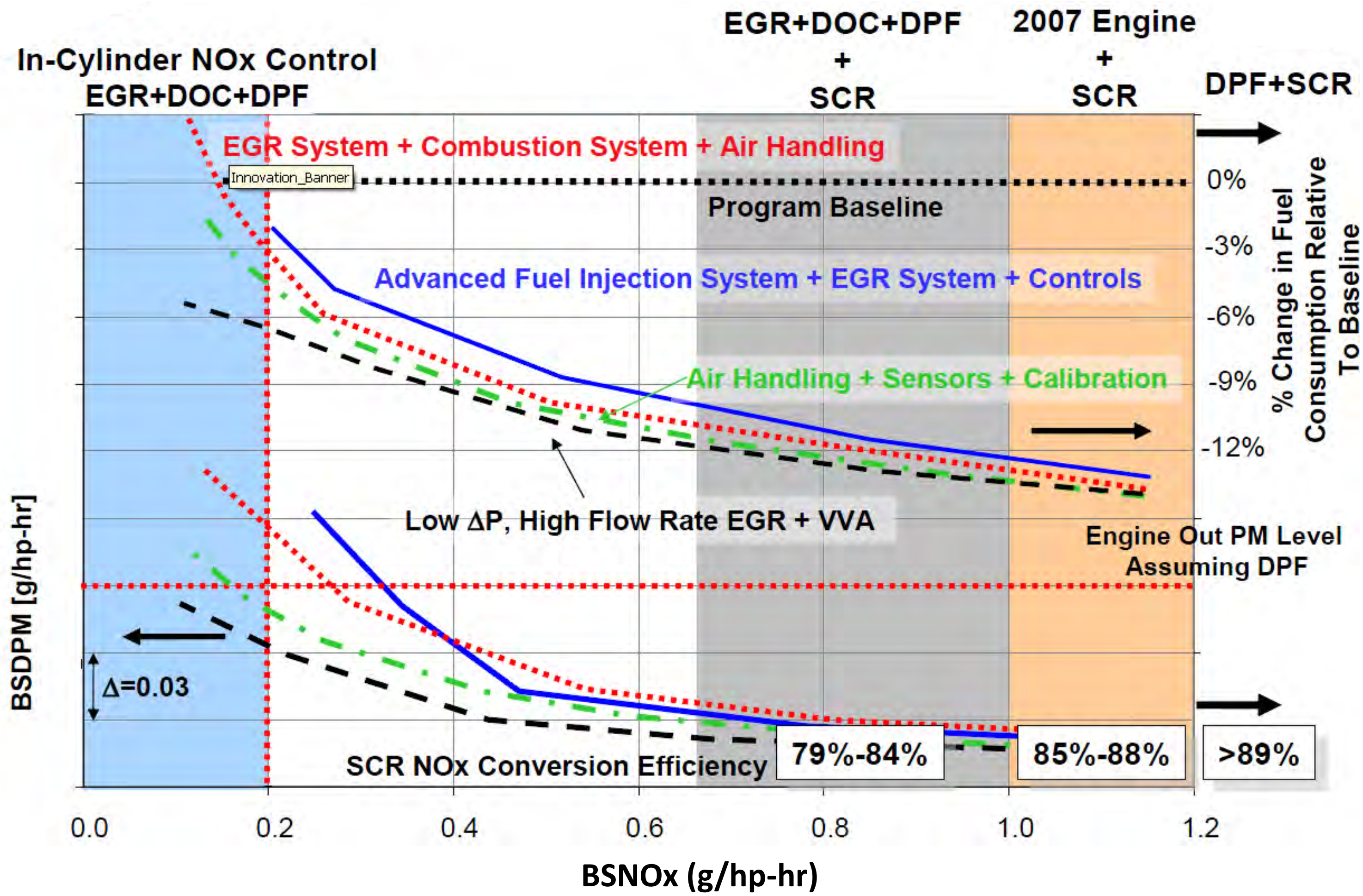

Figure 2-3: Fuel economy, NOx, and PM emissions with different engine technology road maps

2.3.4 Integrated Engine and Vehicle Strategies

Engine manufacturers develop engines to achieve the optimum balance of emissions, fuel consumption, horsepower, costs, among other aspects. Vehicle manufacturers conduct similar optimizations of the vehicle and have an impact on the overall fuel consumption. The recent Heavy-Duty GHG rule noted the opportunities to reduce GHG emissions and fuel consumption through both engine technologies and vehicle improvements. Aerodynamics, rolling resistance, weight, and other systems in the vehicle will impact the power required to move the vehicle down the road. For example, an improvement to a vehicle's aerodynamics will reduce the amount of power required from the engine and thus reduce the fuel consumed. When considered together, improvement to the vehicle efficiency can be well over 10 percent, which would be enough to offset any increase in fuel consumption due to specific emission reduction strategies used to reduce NOx to meet the 2007 and 2010 NOx emission standards (such as EGR). This can make it difficult for purchasers to discern whether changes in fuel consumption are due to changes in the engine or vehicle.

2.4 Summary of Strategies Used by Engine Manufacturers for 2010

Most engine manufacturers chose to comply with the 2010 NOx emission standard by adding SCR to the engine models they produced in 2007-2009. They also recalibrated the engines to reduce fuel consumption rates to levels lower than the 2007-2009 engines. In general, the approach with an SCR system appears to be a sound and cost effective pathway to achieve 2010 emissions standards while improving fuel economy and it is the primary path being used around the world. The reduction in operating costs due to improved fuel consumption was more than enough to offset the cost of supplying the SCR system with DEF. So the incremental savings to the operator is the net effect of an upfront increase in hardware costs that is offset significantly by reduced operating costs.

One engine manufacturer chose instead to comply with the 2010 NOx emission standard by using in-cylinder EGR solution in combination with NOx emission credits earned prior to the 2010 model year. In this solution, a higher EGR rate is required in order to meet desired emission target, compared to typical engine system with the SCR solution. Therefore, requirements on air handling, EGR and charged air cooling are much higher than the 2007-2009 engines. Consequently, a two-stage turbocharger system with a relatively large intercooling system is used. In addition, the 2010 model year engines contained many other improvements in the fuel injection and combustion systems, as well as better integration between engine and aftertreatment system relative to the engines they produced in 2007-2009. Electronic control on the total engine and aftertreatment system is also considerably enhanced. Many of these changes were made to partially offset the tendency of the increased EGR to increase fuel consumption.

Chapter 3: Compliance Costs

This chapter describes our analysis of the costs of compliance. The analysis is based on our projections of costs to engine and vehicle manufacturers and operating costs for vehicle owners. This chapter generally does not include analysis of engine pricing or vehicle purchaser perceptions that could affect purchase decisions.

3.1 Methodology

3.1.1 General Methodology

The costs of compliance for model year 2012 are the primary inputs for determining NCPs. In each of our six previous NCP rulemakings, we estimated costs using a methodology appropriate for the specific circumstances that applied at the time. None were approached in exactly the same way. In each case we considered key factors such as differences in calibration, hardware, and operating costs, but there have been some NCP calculations where other potential individual cost or cost saving elements have been included or excluded for various reasons.

We requested cost of compliance information from several engine manufacturers and used that information to inform our own analysis of compliance costs. In past rules, EPA has based the NCPs directly on the average of actual compliance costs for all manufacturers. This was possible because each of the manufacturers had actually produced engines at the upper limit (which was almost always the previous emission standard). It was relatively simple for them to provide us with a confidential engineering analysis of the costs they actually incurred, the cost of the additional hardware, and differences in performance characteristics. It was also reasonable for EPA to assume a high degree of accuracy in these costs. In the case of this NCP rule, most manufacturers generally have never had production engines at 0.50 g/hp-hr (the upper limit). So averaging the manufacturers' estimates of expected compliance costs does not necessarily lead to the average actual compliance costs.

The NCP penalty formulas are based primarily on the cost difference between an engine emitting at the upper limit (the baseline engine) and one emitting at the standard (the compliant engine). Thus, the assumption of what technologies are on the baseline engine is central to the calculation of the penalties. As described in Section 3.3.2, we are assuming the baseline engine is already equipped with SCR. Specifically, EPA is assuming that the baseline engine (or upper limit engine) is an optimized, SCR-equipped engine that complies with all other emission standards and requirements. We estimated incremental costs both in terms of dollars per engine and dollars per g/hp-hr for the theoretical average and worst case manufacturers.

It is worth noting that each of the five engine manufacturers contacted assumed a different technology package on its baseline engine. Manufacturers that produced engines below 0.20 g/hp-hr based their compliance costs on the following baseline engines: engines equipped with similar (but not identical) SCR and EGR hardware, SCR-equipped engines without EGR, an EGR version of its own engine, or the non-SCR engines produced by a competitor. Some of these manufacturers estimated costs relative to more than one baseline engine, while others provided costs relative to a single baseline engine. Four of the manufacturers compared the costs for their assumed baseline engine to the costs for their actual compliant engines. The one non-SCR manufacturer we contacted provided its projections of what it will spend to bring its current 2011 engine below 0.20 g/hp-hr.

3.1.2 Net Present Value of Costs

All costs are presented in 2011 dollars. Because the NCP is paid by the manufacturer in the model year that the engine is produced, we need to account for cost differences at the point of sale. All costs were calculated or converted to net present value (NPV) for calendar year 2012. Costs that occur after production (e.g., DEF costs) are discounted by 7.0 percent per year. It is also important to remember that since all costs are presented in terms of constant 2011 dollars, the discount rate does not include an adjustment with respect to the rate of inflation.

Costs expressed in terms of 2010 or earlier dollars were adjusted upwards based on the Consumer Price Index (CPI) to be equivalent to 2011 dollars. For example, the difference between a 2009 dollar and a 2011 dollar would be approximately five percent. We recognize that concerns have been raised about using the CPI to adjust costs for inflation. However, we are not aware of a better method for adjusting general costs for inflation. Also, given the relatively small number of years involved in the inflation adjustments (generally three years or less), we believe that any errors introduced into the analysis by using the CPI would not be significant.

3.1.3 Costs Analysis

This section describes the cost categories that we considered in our analysis. These costs include engine manufacturing costs, vehicle manufacturing costs, and operating costs. Engine manufacturer costs of emissions control include variable costs (for incremental hardware, assembly, and associated markups), fixed costs (for tooling, research and development, etc.), and warranty costs. We also evaluated whether vehicle manufacturers are expected to incur some variable hardware costs or some fixed costs. Owner costs can include fuel costs, diesel exhaust fluid costs, maintenance and repair costs, and costs associated with any time that the vehicle is down for repair.

To produce a unit of output, engine and truck manufacturers incur direct and indirect costs. Direct costs include cost of materials and labor costs. Indirect costs are all the costs associated with producing the unit of output that are not direct costs – for example, they may be related to production (such as research and development), corporate operations (such as salaries, pensions, and health care costs for corporate staff), or selling (such as transportation, dealer support, and marketing). Indirect costs are generally recovered by allocating a share of the costs to each engine or vehicle sold.

For this cost analysis, EPA considered both the direct or "piece" costs and indirect costs of individual components of technologies. For the direct costs, we followed a bill of materials approach utilized in the Heavy-Duty GHG rule.[8] A bill of materials, in a general sense, is a list of components or sub-systems that make up a system— in this case, an item of technology which reduces NOx emissions.

Indirect costs were accounted for using the Indirect Cost Multiplier (ICM) approach. The heavy-duty engine cost projections in this analysis used this same approach in the Heavy-Duty GHG rule. For the GHG rule, EPA contracted with RTI International to update EPA's methodology for accounting for indirect costs associated with changes in direct manufacturing costs for heavy-duty engine and truck manufacturers.[9] These indirect cost multipliers are intended to be used, along with calculations of direct manufacturing costs, to provide improved estimates of the full additional costs associated with new technologies. As shown in Table 3-1 below, the ICM varies with the complexity of the technology and the maturity of the technology.

Table 3-1: Indirect Cost Multipliers Used in this Analysis[a]

CLASS	COMPLEXITY	NEAR TERM	LONG TERM
HD diesel engines	Low	1.15	1.12
	Medium	1.24	1.18
	High1	1.28	1.19
	High2	1.43	1.29

Note:

[a] Rogozhin, A., et. al., "Using indirect cost multipliers to estimate the total cost of adding new technology in the automobile industry," International Journal of Production Economics (2009); "Documentation of the Development of Indirect Cost Multipliers for Three Automotive Technologies," Helfand, G., and Sherwood, T., Memorandum dated August 2009; "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers," Draft Report prepared by RTI International and Transportation Research Institute, University of Michigan, July 2010.

The NCP regulations contain provisions to refund manufacturers for their research and development costs. Thus, EPA notes that the near term, low complexity ICM value of 1.15 includes an ICM for research and development of 0.02.[10]

Any DEF or fuel cost impacts on the operator are dependent on the number of miles projected to be driven by the vehicle, along with assumptions for a price for fuel and DEF. For this analysis, we used the projected mileage accumulation rates generated by the Motor Vehicle Emissions Simulator, more commonly called MOVES, EPA's official mobile source emission inventory model.[11] The MOVES2010a version was used along with some post-processing of the MOVES output to develop separate projections of vehicle miles travelled (VMT) for the medium and heavy heavy-duty engine classes. These annual VMT projections are shown in Appendix A and include a projection of vehicle survival fractions that are based on scrappage rates. (Note that the mileage estimates in this rule are slightly different from the estimates used in the final rulemaking that established the 2010 heavy-duty engine criteria pollutant standards). We used the Energy Information Administration's (EIA) Annual Energy

Outlook 2011(AEO2011) to project fuel prices through 2035.[12] The annual price values (dollars per gallon) used in this analysis were adjusted from 2009 dollars (as supplied in AEO2011) to 2011 dollars. The annual fuel price projections are included in Appendix A. We also used a DEF cost of $2.99 per gallon based on the national retail pump average in November 2011.[13] We are using a constant value for the DEF price because we are not aware of any reliable projections that the price will change significantly in the coming years.

3.1.4 Upper Limit Engine

The upper limit (UL) used in the NCP derivation is the emission level established by regulation above which NCPs are not available and a heavy-duty engine cannot be certified or introduced into commerce. CAA section 206(g)(2) refers to the upper limit as a level above the emission standard, set by regulation, that corresponds to an emission level EPA determines to be "practicable." The upper limit is an important aspect of the NCP regulations not only because it establishes an emission level above which no engine can be certified, but it is also a critical component of the cost analysis used to develop the NCP factors. The regulations specify that the relevant NCP costs for determining the COC_{50} and the COC_{90} factors are the cost difference between an engine emitting at the upper limit and one that meets the new standards (see 40 CFR 86.1113-87).

The regulatory approach adopted under the prior NCP rules sets the default upper limit at the prior emission standard when a prior emission standard exists and that standard is changed and becomes more stringent. EPA concluded that the UL should be reasonably achievable by all manufacturers with vehicles in the relevant class. It should be within reach of all manufacturers of HDEs or HDVs that are currently allowed so that they can, if they choose, pay NCPs and continue to sell their engines and vehicles while finishing their development of complying engines. A manufacturer of a previously certified engine or vehicle should not be forced to immediately remove an HDE or HDV from the market when an emission standard becomes more stringent. The prior emissions standard generally meets these goals, because manufactures have already certified their vehicles to that standard.

In the past, EPA has rejected suggestions that the upper limit should be more stringent than the prior emission standard because it would be very difficult to identify a limit that could be met by all manufacturers. For this rule, however, all manufacturers are currently certifying all of their engines at or below the 0.50 g/hp-hr FEL cap. Thus, since NCPs were not intended to allow manufacturers to increase emissions, we are setting the upper limit at 0.50 g/hp-hr. This will conform to the purpose of NCPs, which is to allow manufacturers to continue selling engines they are producing, but not to allow backsliding.

3.2 Manufacturer Cost Data

Prior to this IFR/NPRM, we requested from several of the engine manufacturers cost estimates to identify the incremental costs they would expect to take a model year 2012 engine from 0.50 g/hp-hr NOx to 0.20 g/hp-hr. The incremental costs could include variable costs such as the hardware component cost, fixed costs such as R&D costs, and operating costs such as fuel costs. These costs were supposed to include costs for vehicle manufacturers and operators as well as engine manufacturers. We requested that all costs be presented in 2011 dollars. We also requested that manufacturers include only emission-related costs.

We received responses from all of the manufacturers that we contacted, representing virtually all of the current U.S. heavy heavy-duty diesel engine market. However, all of the data that we received were identified as confidential business information (CBI). Therefore, we are not including details of the information in this document. Instead we are presenting only a broad description of the information provided.

As discussed above in Chapter 2, there are a variety of means to reduce NOx. Each of the manufacturers who currently produce heavy heavy-duty diesel engines which emit less than 0.20 g/hp-hr NOx provided information about at least one pathway to reduce NOx from 0.50 to 0.20 g/hp-hr. Each provided a combination of changes to hardware (and other associated costs such as warranty costs), DEF consumption rate, engine-out NOx emissions, and/or fuel consumption. However, none of the manufacturers selected the same combination of changes. In general, there were three distinct options presented to the Agency for baseline engine technology as shown in Table 3-2.

Table 3-2 Manufacturer Baseline Engine Scenarios

	SCR?	EGR?
Baseline Engine Option #1	Yes	Yes
Baseline Engine Option #2	No	Yes
Baseline Engine Option #3	Yes	No

More than one manufacturer chose Option #1 and assumed the baseline 0.50 g/hp-hr engine would contain both SCR and EGR. One of these manufacturers stated that relatively small changes would have been needed to hardware, such as changes to the loading in the SCR catalyst and the addition of a sensor to control DEF dosing, along with a re-optimization of engine-out NOx emissions, fuel consumption, and DEF dosing to achieve 0.20 g/hp-hr NOx. Similarly, another manufacturer stated hardware changes may be required to the DOC and DPF system, along with possible changes to the turbocharger and EGR configuration. Based on these manufacturers' projections that fuel will be much more expensive than DEF, they assumed that 0.50 g/hp-hr engines would have been recalibrated to have much higher engine-out NOx emissions. This would reduce fuel costs but increase DEF costs. It should be noted that in some cases, when these costs were recalculated using EPA's projections of fuel and DEF prices, the compliance costs for these recalibrated engines were less than EPA's estimated COC90.

Another SCR manufacturer suggested that the Option #2 pathway, which assumed a non-SCR baseline engine with high performance EGR system, could have achieved a the 0.50 g/hp-hr level and that they would have added an SCR system to achieve the 0.20 g/hp-hr NOx emissions. In its estimate for this scenario, the improvement to the fuel consumption due to the SCR system would be offset by the DEF consumption required for the SCR, and thus produce a neutral fluid economy impact. The manufacturer estimated costs based on its approximation of the costs and performance of engines produced by a competitor with NOx levels above 0.20 g/hp-hr and their own engine which emits at less than 0.20 g/hp-hr.

The fourth SCR manufacturer suggested an approach which assumed the 0.50 g/hp-hr NOx engine would contain SCR, but not require EGR. This strategy would lead to an increase in engine-out NOx emissions which would require a change in DEF and fuel consumption.

The non-SCR manufacturer also projected the costs it will ultimately incur to achieve 0.20 g/hp-hr. Its methodology is not summarized here because we cannot do so without disclosing its product plans. We merely note that it projected costs lower than EPA's estimated COC50 and COC90 costs.

In summary, all of the SCR manufacturers stated that the compliance costs should include some cost for additional hardware (several hundred to a few thousand). Although not all of them estimated total incremental compliance costs to reduce NOx emissions from 0.50 g/hp-hr to 0.20 g/hp-hr, those that did generally estimated the incremental costs to be in the $3,000 to $5,000 range. They recommended that EPA set the maximum penalty at a level at least as high as these cost estimates.

3.3 EPA Analysis of Costs

The NCP regulations are structured to calculate the penalty amounts based on certain cost parameters, primarily on the total incremental and marginal costs for the average and highest cost manufacturer. EPA has independently estimated these costs.

3.3.1 Consideration of Manufacturer Costs Estimates

In past rules, EPA has based the NCPs directly on the average of actual compliance costs for all manufacturers. This was possible because each of the manufacturers had actually produced engines at the upper limit (which was almost always the previous emission standard). It was relatively simple for them to provide us with a confidential engineering analysis of the costs they actually incurred, the cost of the additional hardware, and differences in performance characteristics. There was little opportunity for strategic estimates since manufacturers needed to reflect actual costs that EPA could confirm. Thus, it was reasonable for EPA to assume a high degree of accuracy in these costs.

The same cannot be said for this NCP rule. Those manufacturers that have reached 0.20 g/hp-hr generally have never had production engines at 0.50 g/hp-hr (the upper limit). In some cases they had development engines, but this does not fully address the costs that would have been incurred for production engines. While manufacturers have a great deal of experience projecting production costs based on development engines, there is no way for us to verify the actual hardware, fuel, and DEF costs that would have occurred. Thus, we must consider the costs to be at least somewhat speculative.

It also must be considered that each of the manufacturers was aware that their estimated costs could be used to determine the amount of the NCP paid by a competitor. We are concerned about this because we cannot independently verify the validity of the manufacturers' costs. Thus, while we have used the technical and cost inputs from all of the manufacturers to inform our estimate, we believe under these circumstances it would be inappropriate to simply average these inputs.

3.3.2 Basis of EPA Cost Estimates

Each manufacturer identified a different technology that it would have taken to reduce NOx emissions from 0.50 to 0.20 g/hp-hr. Each provided a combination of changes to hardware (and other associated costs such as warranty costs), DEF consumption rate, engine-out NOx emissions, and fuel consumption. Based on our technical judgment and discussions with engine manufacturers, EPA is assuming the baseline engine used to meet the 0.50 g/hp-hr NOx level is equipped with SCR (as well as a cooled EGR system) to control the tailpipe NOx emissions. We believe estimating costs from this scenario is the least speculative method to estimate compliance costs. As noted later in Chapter 4 of this document, we also believe this method leads to penalty parameters that will remove the competitive disadvantage for complying manufacturers.

Specifically, we developed a pathway to reduce tailpipe NOx emissions by maintaining constant engine-out NOx emissions (and thus having no impact on fuel consumption), but include some hardware modifications and a higher DEF consumption rate to reduce tailpipe NOx emissions. Based on our analysis and discussions with manufacturers, we estimate an average increase of 0.004 gallons of DEF per gallon of fuel consumption would have been needed to reduce the NOx emissions from 0.50 to 0.20 g/hp-hr. In addition to the DEF rate change, we project that some hardware costs would be incurred to achieve the NOx reduction to the standard level.

We did consider the other technology paths suggested by manufacturers (which assumed baseline engines with EGR but not SCR, or baseline engines with SCR but not EGR). However, we believe it is likely that these baseline engines would have had high operating costs. In general, relying on EGR to reduce NOx emissions significantly increases fuel consumption. Technology paths that involve significant changes in fuel consumption possess high degrees of uncertainty in their COC90 estimates due to the uncertainty associated with the price of fuel in the future. Similarly, relying on SCR to reduce NOx emissions without EGR requires large amount of DEF. We are not aware of an authoritative estimate of future DEF prices. For the more modest change in the amount of DEF in EPA's approach, we assumed a constant DEF price. In either case, it is possible that over the life of a truck, the increased operating costs could be greater than the original hardware cost. We do not have the information required to calculate these operating costs with the accuracy needed to use these scenarios as the basis of our NCPs. In addition, since there is only one manufacturer producing low-NOx engines without SCR, we believe that we could not have developed an accurate estimate of the actual compliance costs for non-SCR engines without revealing confidential business information from that manufacturer.

3.3.3 NCP Compliance Costs

This section provides details on the total compliance costs to reduce the tailpipe NOx emissions of a baseline engine at 0.50 g/hp-hr to 0.20 g/hp-hr. As mentioned above, our assumed baseline engine with 0.50 g/hp-hr NOx emissions contains an SCR aftertreatment system. As discussed in Chapter 2 above, there are many pathways that can be used to reduce tailpipe emissions, including changing the engine-out emissions, increasing the efficiency of the aftertreatment system, and hardware changes. We selected a pathway to determine the total compliance cost which assumes that the engine-out emissions remain constant and the NOx emissions are reduced primarily with an increase in DEF consumption, along with small hardware modifications. Without a change to engine-out NOx emissions levels, the agency assumes that there will be no impact on the fuel economy of these vehicles (see discussion below).

We calculated two parallel estimates of compliance costs. The first was COC50, which represents the total life-cycle costs to reduce a typical baseline engine's emissions to the level of the standard. The second was COC90, which represents the total life-cycle costs for reducing the emissions to the standard level for an engine produced by the manufacturer with the highest production costs. Our estimated average compliance costs (COC50) and 90th percentile costs (COC90) are shown in Table 3-3 and Table 3-4. The derivation of these estimates is described in detail below.

Table 3-3: Medium Heavy-Duty COC50 and COC90 Estimates (Net Present Value to 2012 in 2011$)

	COC50	COC90
NPV of Hardware and Lifetime DEF Consumption Costs	$462	$682

Table 3-4 Heavy Heavy-Duty COC50 and COC90 Estimates (Net Present Value to 2012 in 2011$)

	COC50	COC90
NPV of Hardware and Lifetime DEF Consumption Costs	$1,561	$1,919

3.3.3.1 Operating Costs: DEF Consumption

The rate of DEF consumption can be calculated from the chemical reaction necessary to convert urea to ammonia and the reactions to reduce NOx. These reactions proceed according to the following chemical equations:

$$CO(NH_2)_2 + H2O \rightarrow 2NH_3 + CO_2$$

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

As these equations show, one molecule of urea can reduce two molecules of NO or one molecule of NO_2. So the minimum molar ratio of urea needed to NOx reduced is equal to the NO_2 fraction plus one-half the NO fraction. This stoichiometric rate can be thought of as the ideal rate. This ideal rate can be calculated relative to fuel consumption rates for a given brake-specific NOx reduction from the following equation:

$$Ideal\ DEF\ to\ Fuel\ Ratio = \left(\frac{BSFNOx}{BSFC}\right)\left(\frac{1}{MW_{NOx}}\right)\left(\frac{Moles\ Urea}{Moles\ NOx}\right)\left(\frac{1}{Urea\ Molar\ Density}\right)$$

For the purpose of this rule, we calculated the ideal DEF rate needed to achieve a 0.30 g/hp-hr NOx emission reduction based on the assumptions shown below in Table 3-5.

Table 3-5: DEF Calculation Assumptions

Assumptions for DEF Calculations	
Brake-Specific Fuel Consumption	0.2173 liter/hp-hr[14]
Molar Percent of Total NOx that is NO at SCR Inlet	50%
Urea Concentration in DEF	32.5% by mass (5.904 mol/liter)

$$Ideal\ DEF\ to\ Fuel\ Ratio = \left(\frac{0.30\frac{g}{hp-hr}}{0.2173\frac{liters}{hp-hr}}\right)\left(\frac{1}{46.006\ g/mol}\right)\left(\frac{0.75}{1}\right)\left(\frac{1}{5.904}\right) = 0.003812$$

This means that under these conditions, the DEF rate would need to be increased by 0.38 gallons for every 100 gallons of fuel consumed.

We recognize that in many cases manufacturers use dosing strategies that overdose by five percent or more of the total DEF rate to account for maldistribution of the ammonia in the catalyst. For this rule, we believe that a five percent DEF overdose rate is appropriate for the marginal increase in DEF consumption. Thus, we calculated the incremental DEF rate increase as 1.05 times the ideal DEF rate of 0.38 percent, for a total DEF rate increase of 0.40 percent, to reduce NOx emissions by 0.30 g/hp-hr.

Next we calculated the NPV of this impact using a DEF price of $2.99 per gallon for calendar years 2012 and beyond. The DEF price represents today's national average retail pump price of on-highway DEF.[15] Appendix A contains the baseline fuel economy and the baseline DEF consumption rate, and projected vehicle miles travelled (VMT) for both medium and heavy heavy-duty engines. The baseline fuel economy of a typical medium and heavy heavy-duty vehicle were based on the baseline fuel consumption rates generated for the Heavy-Duty GHG rule.[16] The baseline fuel economy used in the analysis was 9.71 mpg for medium heavy-duty vehicles and 4.93 mpg for heavy heavy-duty vehicles. Table 3-6 contains the projected annual incremental cost due to the 0.40 percent increase in DEF consumption.

Table 3-6: Incremental DEF Cost due to 0.40% Increase in DEF Consumption (2011$)

Calendar Year	Medium HD Vehicle	Heavy HD Vehicle
2012	$45	$208
2013	$43	$205
2014	$39	$191
2015	$36	$176
2016	$33	$162
2017	$30	$149
2018	$27	$137
2019	$24	$125
2020	$22	$115
2021	$20	$104
2022	$18	$94
2023	$16	$85
2024	$14	$77
2025	$13	$70
2026	$12	$64
2027	$11	$58
2028	$10	$52
2029	$ 9	$47
2030	$ 8	$43
2031	$ 7	$38
2032	$ 6	$35
2033	$ 6	$31
2034	$ 5	$28
2035	$ 5	$26
2036	$ 4	$23
2037	$ 4	$21
2038	$ 3	$19
2039	$ 3	$17
2040	$ 3	$16
2041	$ 3	$14

The NPV of the lifetime costs of the incremental increase in DEF consumption, using a seven percent discount rate, is $275 for medium heavy-duty engines and $1,374 for heavy

heavy-duty engines (in 2011 dollars). The heavy heavy-duty engine cost is greater due to the higher average vehicle miles travelled and lower miles per gallon for these vehicles over their lifetimes, as compared to medium heavy-duty engines.

3.3.3.2 Operating Costs: Fuel Consumption

As noted earlier, we are estimating that the 0.50 g/hp-hr baseline engine and the fully compliant engine will have the same fuel consumption rates. The two primary reasons for this are the relative importance operators place on keeping fuel consumption rates low for the customer and the upcoming GHG emission standards. The Heavy-Duty GHG rule requires that manufacturers reduce their CO_2 emissions/fuel consumption starting in 2014 model year by an average of three to five percent from a baseline 2010 model year engine. Thus, a pathway to reduce NOx that leads to an increase in fuel consumption in 2012 model year would require the manufacturer to apply technologies to recover the increase by 2014 model year.

As a sensitivity analysis, we estimated the lifetime costs of a 0.25 percent increase in fuel consumption using VMT (vehicle-miles traveled) patterns listed in Appendix A. We calculated the NPV of these impacts using projected diesel fuel prices, also included in Appendix A.

The NPV of the lifetime costs of a 0.25 percent incremental increase in fuel consumption, using a seven percent discount rate, would be $196 for medium heavy-duty engines and $986 for heavy heavy-duty engines (in 2011 dollars). The heavy heavy-duty engine cost is greater due to the higher average vehicle miles travelled and lower miles per gallon for these vehicles over their lifetimes, as compared to medium heavy-duty engines.

3.3.3.3 Hardware, Warranty, and Research & Development Costs

An SCR aftertreatment system may require hardware modifications to achieve tailpipe emissions levels of 0.20 g/hp-hr. Based on conversations with manufacturers, we believe that the lower NOx emissions levels would require the addition of a sensor for better control over the urea injection. This cost would apply for both the typical and worst case engines. In addition, for the worst case manufacturer, we believe a larger SCR catalyst would be required to increase the NOx conversion efficiency, and a separate ammonia sensor would be needed for better control. We estimate that the size and loading of the catalyst would need to increase by about 20 percent. Note that this would be proportional to the increase in NOx reductions for engines with engine-out emissions of 2.0 g/hp-hr (1.5 g/hp-hr reduction versus 1.8 g/hp-hr reduction).

We estimate hardware costs to reduce NOx emissions from 0.50 to 0.20 g/hp-hr. The hardware costs fall into two categories – improved SCR catalyst to increase the NOx conversion efficiency and an additional sensor to improve the ammonia dosing control.

The incremental catalyst costs were estimated from the retail cost of a SCR system available today on a 6.6L diesel engine used in a heavy-duty pickup truck, which is a light heavy-duty engine.[17] We scaled the retail cost of the SCR system based on the ratio of typical engine displacement in each engine class, as shown in Table 3-7 below.

Table 3-7: SCR Retail Price

	LHD (6.6L)	MHD (8L)	HHD (13L)
Complete SCR Catalyst Retail Price	$1,076	$1,304	$2,119

Next, the direct manufacturing costs were calculated based on the Retail Price Equivalent (RPE) as shown in Table 3-8. The RPE for heavy-duty engines is 1.36 as found in the study conducted by ICF International for the Heavy-Duty Greenhouse Gas Emissions rulemaking.[18]

Table 3-8: Direct Manufacturing Cost of SCR Catalyst

	MHD	HHD
Complete SCR Catalyst Direct Manufacturing Cost	$959	$1,558

The incremental cost of the catalyst to improve the NOx conversion efficiency through increased SCR catalyst volume and/or improved loading is estimated to be 20 percent of the total catalyst cost, as shown below. The agency then applied a 1.15 indirect cost multiplier (ICM) to convert the direct manufacturing costs to marked up costs. The 1.15 multiplier consists of two percent for research and development and 13 percent for warranty and other costs.[19] The marked up costs are shown below in Table 3-9.

Table 3-9: SCR Catalyst Incremental Cost

	MHD	HHD
Incremental Direct Manufacturing Cost	$192	$312
Research and Development Cost (2%)	$4	$6
Warranty and Other Cost (13%)	$25	$41
Total Incremental SCR Catalyst Cost	$221	$358

The cost for an ammonia sensor was developed by converting a sensor's retail price to a direct manufacturing cost and then to a marked up cost, similar to the procedure used above for the SCR catalyst cost. The costs are shown in Table 3-10.[20] The same sensor could be used for both the medium and heavy heavy-duty engines, thus we estimated that the sensor cost be the same for both engine classes.

Table 3-10: Incremental Sensor Cost

	MHD	HHD
Sensor Retail Price	$221	$221
Sensor Direct Manufacturing Cost	$163	$163
Sensor Research and Development Cost (2%)	$3	$3
Sensor Warranty and Other Cost (13%)	$21	$21
Total Incremental Sensor Cost	$187	$187

The total incremental hardware costs for the SCR catalyst and sensor are estimated to be $407 for MHD and $545 for HHD for COC90. The total incremental sensor cost is estimated to be $187 for both MHD and HHD engines for COC50.

3.3.3.4 Total Costs

The total estimated costs for COC50 and COC90 for MHD and HHD engines are included below in Table 3-11.

Table 3-11: COC50 and COC90 Costs

	MHD		HHD	
	COC50	COC90	COC50	COC90
DEF Operating Costs	$275	$275	$1,374	$1,374
Hardware Costs	$163	$192	$163	$474
Research and Development Cost	$3	$4	$3	$9
Warranty and Other Cost	$21	$25	$21	$62
Total Cost	$462	$682	$1,561	$1,919

3.3.4 MC50 and F

MC50 and F are two parameters used in the existing regulations in the calculation of the value X (see 40 CFR 86.1113-87 (a)(4)). X is the compliance level (g/hp-hr) above the standard where the penalty equals COC50. This section describes the derivation of MC50 and F for medium and heavy heavy-duty engines.

3.3.4.1 Estimated value of MC50

MC50 is the marginal cost of compliance for the average vehicle, expressed in terms of dollars per g/hp-hr of NOx emission controlled. In concept, it would be based on the difference in total compliance costs for an engine that had emissions equal to the standard (i.e., 0.20 g/hp-hr) and an engine that had emissions slightly above the standard. For example, if we had an estimate of the total cost of compliance for a typical engine with emissions equal to 0.30 g/hp-hr, then we would calculate MC50 as the difference between that cost and the average divided by the difference in emissions (0.10 g/hp-hr). However, in the case of this rulemaking, we do not have such detailed information. Moreover, the range of NOx emissions control is narrow, which means that marginal cost can reasonably be assumed to be constant over the range. Therefore, we have calculated MC50 as COC50 (the estimated costs of the average control strategies that we believe will be used by manufacturers to achieve NOx control in the 0.20 to 0.50 g/hp-hr range), divided by the difference between the upper limit and the standard (0.30 g/hp-hr). This would be $1,540 per g/hp-hr for medium heavy-duty and $5,203 per g/hp-hr for heavy heavy-duty.

3.3.4.2 Estimated value of F

The parameter F is defined in the existing regulations as a value from 1.1 to 1.3 that describes the ratio of the 90th percentile marginal cost (MC90) to MC50. We calculated F by first calculating an MC90 in the same way that we calculated MC50. We then calculated the value of F that would give these values of MC90, and then set F equal to MC90 divided by MC50. Using this approach we calculated MC90 to be $2,273 per g/hp-hr for medium heavy-duty and $6,397 per g/hp-hr for heavy heavy-duty. This led to F values of 1.48 for medium heavy-duty and 1.23 for heavy heavy-duty. However, since F is capped at 1.3 under the regulations, we set F equal to 1.3 for medium heavy-duty engines and adjusted MC90 to equal $2,002 per g/hp-hr.

Chapter 4: Regulatory Parameters for NCPs

4.1 NCP Equations and Parameters

EPA's existing regulations for calculating NCPs are contained in 40 CFR Part 86 Subpart L. NCP schedules can be calculated from those same equations using the Upper Limit, COC50, COC90, MC50, and F values from the previous chapter, and a standard level (S) of 0.20 g/hp-hr NOx. The values for X are calculated using these values and the following equation from Subpart L:

$$X = (COC50 / F / MC50) + S$$

The purpose of this equation is to achieve a penalty curve in which the slope for engines with compliance levels near the standard is equal to the 90th percentile marginal cost of compliance (MC90 equals MC50 times F).

Table 4-1: NCP Parameters

NCP Parameter	Medium Heavy-Duty Engines	Heavy Heavy-Duty Engines
COC50	$462	$1,561
COC90	$682	$1,919
MC50 ($ per g/hp-hr)	$1,540	$5,203
MC90 ($ per g/hp-hr)	$2,002	$6,397
F	1.3	1.23
UL (g/hp-hr)	0.50	0.50
S (g/hp-hr)	0.20	0.20
X (g/hp-hr)	0.43	0.44

When the factors listed in Table 4-1 are input into the existing NCP equations specified in 40 CFR 86.1113(a)(1) and (2), for year n=1 (that is, the first year the penalties are available, thus the annual adjustment factor is equal to 1), the resulting penalty versus compliance level for each service class are shown in Figure 4-1 and Figure 4-2. Note that the bend in the penalty curve medium heavy-duty engines in Figure 4-2 occurs because F is capped at 1.3.

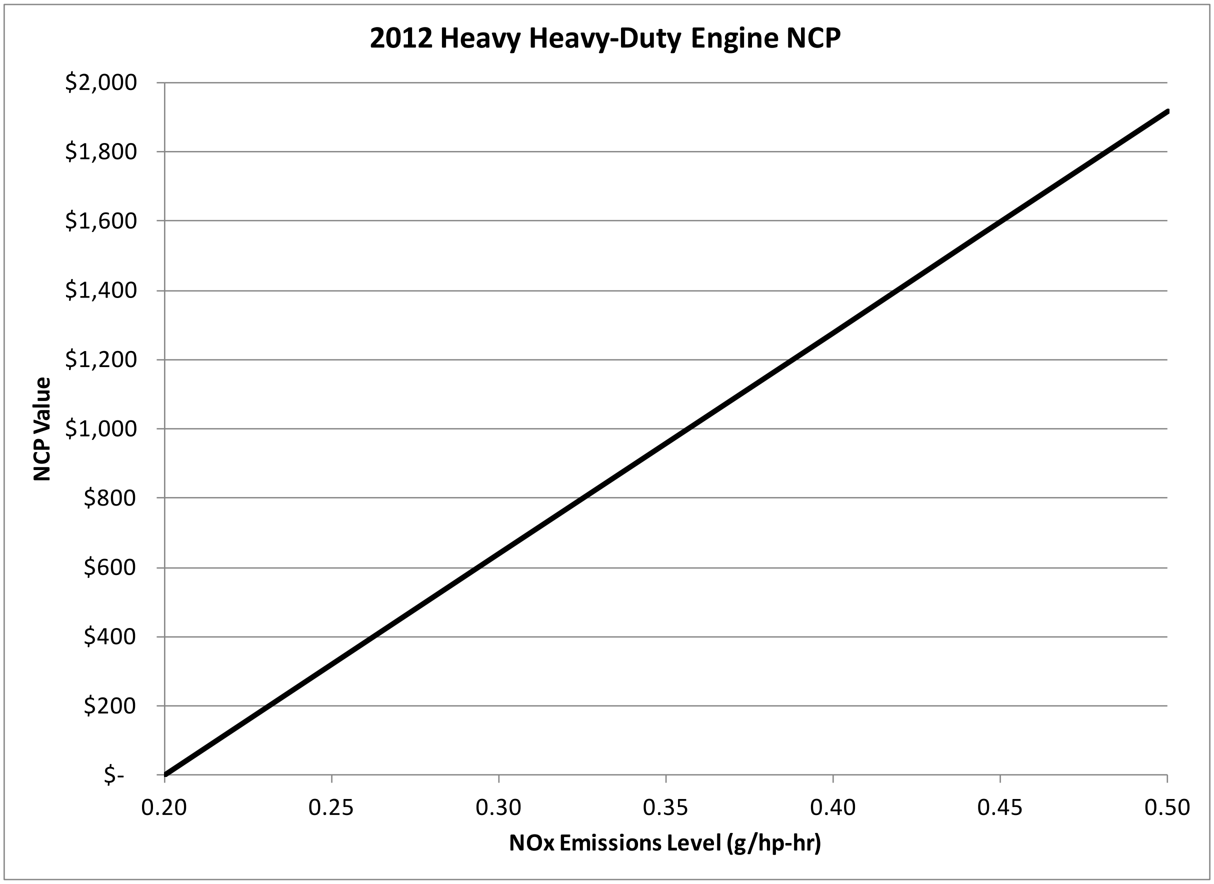

Figure 4-1: Heavy Heavy-Duty Engine NCP

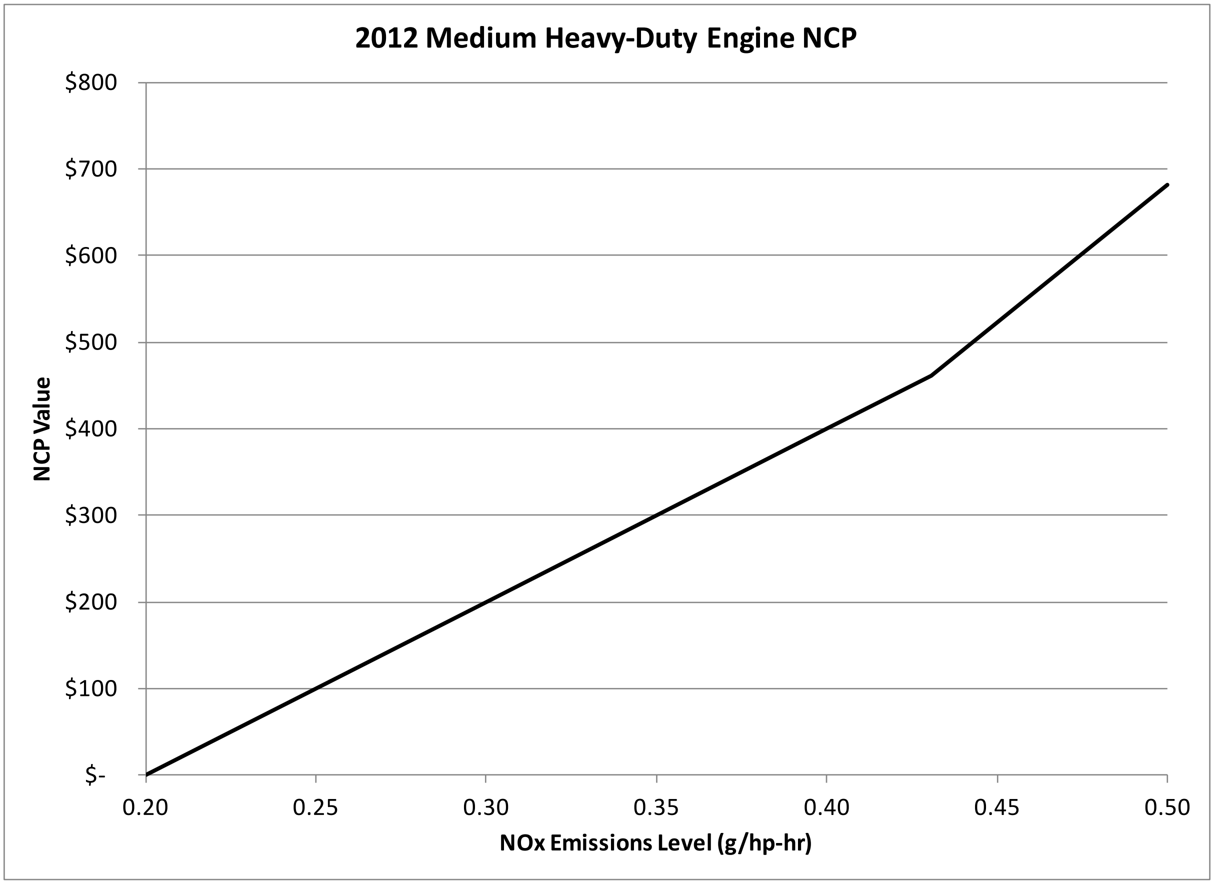

Figure 4-2: Medium Heavy-Duty Engine NCP

4.1.1 Refund for Engineering and Development Costs

Section 1113-87(h) of the existing regulations specify provisions under which a manufacturer that pays NCPs can recover some of the amount it has paid, provided it certifies a conforming replacement for the engines which used the NCPs. The maximum amount that can be recovered is limited to 90 percent of the portion of the penalty which EPA determines to be related to engineering and development. Thus, it is necessary for EPA to establish in each NCP rule a factor for each service class ($F_{E\&D}$) which define the fractions of the NCP which is considered to be related to engineering and development. We are setting these factors equal to 90 percent of the value which is equal to 0.02 times the direct manufacturing costs of the incremental hardware costs. The factors are listed in Table 4-2.

Table 4-2: Engineering and Development Refund Factors

Service Class	$F_{E\&D}$ Factor
Medium Heavy-Duty Engines	0.009
Heavy Heavy-Duty Engines	0.004

4.2 Statutory Evaluation of NCPs

Section 206(g) of the Clean Air Act, which provides EPA authority to set NCPs, also sets some conditions. Specifically, section 206(g)(3) requires that NCPs meet three conditions:

1) It must account for the degree of emission nonconformity.
2) It must increase periodically to provide incentive for nonconforming manufacturers to achieve the emission standards.
3) It must remove the competitive disadvantage to conforming manufacturers.

The existing regulations are structured so that NCPs based on the default formulas will automatically conform to the first two conditions. This structure is also intended to result in NCPs that will also remove the competitive disadvantage to complying manufacturers. It does this by setting the maximum penalty based directly on the worst case (90th percentile) cost that a complying manufacturer had to pay to reduce emissions from the upper limit to the standard.

However, subjective factors can possibly make the monetary value of the competitive advantage higher or lower than the compliance costs incurred by the complying manufacturers and users. Possible factors include:

- Perceived inconvenience of using DEF
- Public relations benefits for a company using the cleanest engines
- Fears of new technology
- Uncertainty about future fuel and DEF prices
- Operator preference for a particular vehicle manufacturer limiting engine choice
- Marketing claims and unknown performance characteristics

For example, a purchaser unfamiliar with SCR technology may imagine that costs and convenience will be worse than they actually would be, and as a result may avoid purchasing an SCR-equipped truck unless the manufacturer discounts the price. This would exacerbate the disadvantage for SCR manufacturers beyond what would be calculated based on costs alone. On the other hand, a trucking company that promotes itself as being an environmentally responsible company may be willing to pay a premium to ensure that its trucks have low-emitting engines. Similarly, a purchaser with a strong preference for a particular truck brand may be relatively unaffected by the price of the compliant engines if they are the only engines it can get in a truck of that brand. These factors would tend to make the disadvantage for compliant manufacturers less than what would be calculated based on costs alone.

EPA recognizes that insufficient information is available to conclusively prove that the NCP removes all competitive disadvantages to all complying manufacturers. However, it is still helpful to consider market data to put the amount of the NCPs into context. To do this, EPA considered the available information about market prices and market share. As described below, both market prices and market shares support our conclusion that the NCPs are large enough to remove the competitive disadvantage to complying manufacturers. The analyses are presented here for the comparison of engines equipped with SCR to those that are not equipped with SCR.

4.2.1 Market Prices

When heavy-duty truck manufacturers increase prices to recover costs associated with reducing emissions, they typically identify the cost as an emission surcharge. The surcharges are applied at the time the trucks are purchased and are intended to cover all additional costs to the engine and truck manufacturers, including R&D, tooling, hardware, warranty and other overhead. They are not intended to cover operating costs. In many cases, purchasers may negotiate a lower surcharge, especially when purchasing a large number of trucks at once.

We considered the surcharges that manufacturers publicly released as the additional cost for the 2010 emission controls. The surcharges ranged from $9,000 to $9,600 for SCR equipped heavy heavy-duty engines, and was $8,000 for the one non-SCR manufacturer.[21] To the extent these surcharges are based on the actual costs, it suggests that the *cost* advantage for non-SCR engines is about $1,000 to $1,600 dollars. Of course, different manufacturers may be applying different discounts to their surcharges, or use different factors to markup their actual costs.

Note that these costs are relative to the manufacturers' 2009 engines which generally had NOx emissions near 1.2 g/hp-hr, which is significantly above the upper limit for the NCPs. So these costs do not reflect the costs upon which the NCP are based. For complying manufacturers, the surcharges include the costs that would be associated with reducing NOx emissions to 0.50 g/hp-hr as well as the cost associated with further reducing NOx emissions to 0.20 g/hp-hr.

These surcharges are not fundamentally inconsistent with our understanding of the differences in hardware costs between the two technology paths. SCR manufacturers need to recover the costs of the SCR catalyst itself, as well as the costs of the urea supply and delivery systems. The non-SCR manufacturer needs to recover the costs of the additional turbochargers and EGR coolers. We believe the hardware costs of SCR systems to be at least $1,000 more than the hardware costs of the non-SCR system. Of course, each manufacturer also needs to recover its R&D, warranty and other overhead costs.

4.2.2 Market Share

As noted in Chapter 1, we also evaluated the market share of each of the largest Class 8 heavy-duty truck manufacturers in 2008 through October 2011 (shown in Figure 1-4). Although the market share of each manufacturer normally varies from year to year (for a variety of reasons, such as introduction of a new model by one manufacturer or new purchases by large fleets), observing longer term trends can be instructive. The most significant trend observed is that the one non-SCR manufacturer has not gained market share since 2008, even though it appears to be offering its engines for a lower price. The market appears to consider the SCR engines to be worth about $1,000 to $1,600 more than the non-SCR alternative.

APPENDIX A: Calculations

This appendix provides additional details for the calculations used to estimate the NCP costs. The appendix is split into two sections –DEF Consumption Rates and Fuel Prices and Costs.

Calculation of DEF Consumption Costs

This section of the appendix includes the values used in the DEF consumption cost calculations. The first table lists the inputs used for the analysis. The second table shows the fleet average annual vehicle miles travelled (VMT) of all 2012 model year vehicles within a given class (e.g., medium heavy-duty diesel vehicles) after considering the survival fraction of each vehicle class.

Table: Inputs Used for DEF Consumption Analysis

Parameter	Input
Medium HD Vehicle Typical Fuel Economy (mpg)	9.7
Heavy HD Vehicle Typical Fuel Economy (mpg)	4.9
Incremental DEF Consumption to Achieve 0.20 g/hp-hr NOx (gallon DEF/gallon fuel)	0.0040
DEF Price ($/gallon)	$2.99
Discount Rate	7%

Table: Annual Vehicle Miles Traveled by Calendar Year for a Typical 2012 Model Year Vehicle

Calendar Year	Medium HD Vehicle	Heavy HD Vehicle
2012	34,698	82,130
2013	33,610	81,056
2014	30,664	75,406
2015	27,882	69,566
2016	25,349	64,019
2017	22,988	58,820
2018	20,822	54,014
2019	18,851	49,532
2020	17,074	45,303
2021	15,326	41,073
2022	13,784	37,113
2023	12,410	33,674
2024	11,212	30,606
2025	10,161	27,805
2026	9,180	25,162
2027	8,280	22,781
2028	7,460	20,553
2029	6,721	18,605
2030	6,109	16,822
2031	5,520	15,190
2032	4,934	13,679
2033	4,493	12,408
2034	4,054	11,206
2035	3,682	10,140
2036	3,321	9,172
2037	2,977	8,272
2038	2,683	7,484
2039	2,460	6,789
2040	2,185	6,133
2041	1,973	5,537

Fuel Prices

EPA did not include additional fuel operating costs as part of the NCP calculation. However, if we did project an impact on fuel consumption, then we would have used the Annual Energy Outlook (AEO) 2011 fuel price projections adjusted to 2011 dollars. Below is the Consumer Price Index used in the fuel price conversion and a table with the annual diesel fuel price projections.

The annual Consumer Price Index values used in this analysis are the following:[22]

- 1982-1984 = 100
- 2009 = 214.537
- 2010 = 218.056
- 2011 (average January through October) = 224.740

The AEO 2011 fuel price forecasts are provided by EIA in terms of 2009 dollars. Thus, for this analysis, we adjusted EIA's diesel fuel price projections upward by a factor equal to 224.740 divided by 214.537 to convert them into 2011 dollars. The diesel fuel prices used in the analysis are included in the table below.

Table: Post-Tax Diesel Fuel Price Projections (2011$)

Calendar Year	Diesel Fuel Price per Gallon
2012	$ 3.06
2013	$ 3.11
2014	$ 3.17
2015	$ 3.23
2016	$ 3.34
2017	$ 3.45
2018	$ 3.54
2019	$ 3.63
2020	$ 3.69
2021	$ 3.71
2022	$ 3.78
2023	$ 3.80
2024	$ 3.88
2025	$ 3.90
2026	$ 3.93
2027	$ 3.98
2028	$ 4.00
2029	$ 4.05
2030	$ 4.02
2031	$ 4.02
2032	$ 4.03
2033	$ 4.03
2034	$ 4.06
2035	$ 4.07
2036	$ 4.15
2037	$ 4.22
2038	$ 4.30
2039	$ 4.38
2040	$ 4.46
2041	$ 4.54

Table: Operating Cost Increase Due to a 0.25% Increase in Fuel Consumption

Calendar Year	MHD Engine	HHD Engine
2012	$27	$128
2013	$27	$128
2014	$25	$122
2015	$23	$114
2016	$22	$109
2017	$20	$103
2018	$19	$97
2019	$18	$92
2020	$16	$85
2021	$15	$77
2022	$13	$71
2023	$12	$65
2024	$11	$60
2025	$10	$55
2026	$9	$50
2027	$9	$46
2028	$8	$42
2029	$7	$38
2030	$6	$34
2031	$6	$31
2032	$5	$28
2033	$5	$25
2034	$4	$23
2035	$4	$21
2036	$4	$19
2037	$3	$18
2038	$3	$16
2039	$3	$15
2040	$3	$14
2041	$2	$13

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