DISSERTATION

ECONOMIC EFFICIENCY OF US 2007 HEAVY-DUTY DIESEL EMISSION STANDARDS: A LIFECYCLE-BASED APPROACH

Submitted by

Aaron Anderson

Department of Economics

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY AARON ANDERSON ENTITLED "ECONOMIC EFFICIENCY OF US 2007 HEAVY-DUTY DIESEL EMISSION STANDARDS: A LIFECYCLE-BASED APPROACH" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

____
Alexandra Bernasek

____
Terrence W. Iverson

____
Bryan D. Willson

____
Advisor: Robert W. Kling

____
Department Head: Steven J. Shulman

ABSTRACT OF DISSERTATION

ECONOMIC EFFICIENCY OF US 2007 HEAVY-DUTY DIESEL EMISSION STANDARDS: A LIFECYCLE-BASED APPROACH

A new method of evaluating vehicle emission standards is developed and applied to US 2007 heavy-duty diesel emission standards. The method is closely related to lifecycle analyses because it relies on the calculation of lifecycle costs of a single vehicle meeting the new standards, as well as the lifecycle costs of a vehicle compliant with previous standards. This allows the calculation of a per-vehicle net benefit, which is then, along with forecasted vehicle sales, used to estimate the total net benefit of the standards imposed over some period of years. There are multiple advantages to the approach developed here relative to that used by the EPA. Primarily, it allows a comparison of benefits and costs that occur across different periods of time, it relies on marginal damage estimates from the peer-reviewed literature, and it is easily adaptable to different emission standards. In contrast to the result of the EPA analysis, it is found that the net benefit of the standards is negative.

Aaron Anderson
Department of Economics
Colorado State University
Fort Collins, CO 80523
Fall 2010

TABLE OF CONTENTS

LIST OF TABLES

Chapter One: Introduction

1.1 Purpose

The purpose of this research is twofold. First, an improved method of evaluating the efficiency of vehicle emission standards is developed. The method is based on lifecycle analyses of single vehicles. Benefits and costs that occur throughout the life of a vehicle are calculated, and a net benefit of the standards for a desired time frame is produced. Two important features of this method are that it can account for short-run and long-run effects of the policy, and it correctly matches the benefits of the policy with the cost of achieving those benefits. This method will then be used to evaluate the US 2007 heavy-duty diesel emission standards.

1.2 Motivation

Regulation of emissions from heavy-duty on-road diesel vehicles in the US began in 1974. Emissions from these vehicles have continued to fall, most recently as a result of new emission standards that took effect in 2007. This new set of standards was phased in from 2007 to 2009 and will be fully implemented in 2010. A large burden has been placed on the manufacturers and buyers in the heavy-duty diesel market due to the severe reductions in emissions of nitrogen oxides (NOx) and particulate matter (PM) that are required by these standards. A number of technologies must be used to achieve these reductions, which lead to large increases in vehicle production costs. At the same time, large reductions in NOx and PM emissions imply significant environmental benefits.

Thorough evaluation of any vehicle emission standards is complicated by several factors. There is often uncertainty about the cost of emission standards. Technologies used to reduce emissions may have other benefits such as improved fuel economy or vehicle performance, and it may be unclear which of the technologies were adopted specifically to address emissions. Estimation of benefits is problematic because there are so many types and many are difficult to estimate. The benefits are also affected by the rate of turnover of the vehicle fleet, which is likely dependent on the standards. Calculating the net benefit is complicated by the fact that the costs and resulting benefits occur at different times. One of the primary costs of emission standards is the cost of the control technologies. This is incurred at the time of vehicle production, yet the benefits provided by these technologies are realized as the vehicle is operated. Finally, as the timeframe of analysis is extended, a large number of additional uncertainties are introduced.

There have been few previous attempts to quantify the full benefits and costs of the US 2007 standards. As part of the EPA's impact analysis of the 2007 standards, a benefit-cost analysis was performed (US EPA 2000). However, there are several problems with the EPA analysis that limit its usefulness. In particular, it ignores many of the short-run effects of the policy and does not correctly match benefits with the cost of achieving those benefits. The method presented here allows for a more comprehensive evaluation of the policy by accounting for both short-run and long-run effects if desired, as well as correctly matching benefits and costs. Another advantage is that it can be easily modified to account for previously unaccounted for benefits and costs or to evaluate some other set of emission standards. This analysis also has several advantages over the EPA analysis unrelated to the methodology. Specifically, it accounts for more types of damages including those that result from black carbon and ammonia emissions, and it relies on correct assumptions about the control technologies used to meet the standards.

The US 2007 heavy-duty diesel emission standards have already been implemented and the result provided by any ex-post analysis is unlikely have any impact on the standards. However, the methodology and results provided by this analysis have implications that extend beyond the US market for heavy-duty diesel trucks. Current US light-duty diesel vehicle emission standards are forcing similar control technologies. Additionally, recent standards in Japan and coming standards in Europe will force similar control technologies in the heavy-duty market. Although the results provided here will not be directly applicable to these other markets, they will provide policy makers with relevant information and highlight the need for careful analysis in these markets. Additionally, the methodology developed here can be used to evaluate these other standards when sufficient information is available.

1.3 Organization of the Study

The analysis will proceed as follows. In Chapter Two, the method used by the EPA to evaluate emission standards will be discussed to further motivate this analysis. Several other related studies will also be discussed. Chapter Three will examine diesel emissions and the regulations that limit them. The progression of emission control technologies will then be outlined, and Chapter Four examines recent advances in control technologies. In Chapter Five, the method used here will be developed. Parametric calibration will be discussed in Chapter Six, and primary results will be presented in Chapter Seven. Chapter Eight presents a sensitivity analysis in light of the large amount of uncertainty present in many of the parameter estimates. In Chapter Nine, the results from this analysis will be compared to a set of results from a method similar to that employed by the EPA. Finally, Chapter Ten discusses the advantages and shortcomings of this analysis, as well as its implications. A number of appendices will then provide further information on several topics.

Chapter Two: Literature Review

2.1 EPA Impact Analysis

A brief discussion of the methodology used by the EPA to evaluate the standards is needed to justify the approach developed in this research. The EPA analysis is concerned primarily with the long-run effects of the policy. Specifically, the EPA calculates the predicted benefits of the standards in the year 2030 and compares that benefit with the cost of the policy in that year. The year 2030 was chosen on the assumption that the heavy-duty vehicle fleet will be completely turned over by that year. It should be emphasized that the reported benefits and costs are not a sum of all benefits and costs of the policy until 2030. Rather, they are the benefits and costs realized in that future year alone. These benefits and costs are then used to calculate a net benefit of the standards in 2030, which is estimated at $85 billion[1]. The purpose of focusing on a single year is to avoid the need to model air quality changes over many years. The EPA notes that a more comprehensive approach would calculate a net present value of benefits and costs over some number of years. This, however, would require modeling air quality changes in each of those years, which it states is not feasible with the resources available.

The EPA estimates benefits in 2030 by estimating emissions in that year with and without the 2007 standards. It is determined how the resulting difference in ambient concentrations will affect human health, visibility, and agricultural productivity. These physical impacts are then monetized. The cost of the policy in 2030 is calculated by multiplying the per-vehicle technology cost attributable to the standards by forecasted vehicle sales in 2030. Changes in fuel costs due to the required ultra-low sulfur diesel

[1] All dollar amounts are expressed in 2008 US dollars. This net benefit includes diesel and gasoline vehicle emissions standards.

(ULSD) and changes in operating costs are also accounted for. By focusing on benefits and costs in 2030, it is clear that many short-run impacts of the policy are ignored. While the EPA acknowledges this omission, the method also fails to correctly match benefits with the cost of achieving those benefits. It is reasonable to calculate both the benefits and costs of the policy that occur in some year, but these values cannot then be used to calculate a net benefit. This is because the benefits that occur in 2030 were created not only as a result of the costs that occur in that year. Rather, they were created by all vehicles on the road in 2030 that meet the new standards. Thus, the EPA method will generally not provide correct results.

To prove this inaccuracy, let *MB* and *MC* represent the per-vehicle annual benefit and cost attributable to new standards. Assume these are constant across time. The EPA method can be presented by the following:

(1) $$net\ benefit_y = MB \times \sum_{0}^{T} sales_{y-t} - MC \times sales_y,$$

where *y* is the year of interest and *T* is the lifespan of the vehicles in years.

An approach that clearly matches the benefits and costs would be an approach that compares the benefits in some year *y* with the cost of achieving those benefits. Benefits realized in a particular year depend on emissions from all vehicles in operation that year. Therefore, the costs of all vehicles in operation need to be considered. Assuming the bulk of costs are realized at the time of production, the costs must be annuitized. Calculating a net benefit for a single year based on the annuitized cost of all vehicles on the road in that year yields the following equation:

(2) $$net\ benefit_y = MB \times \sum_{0}^{T} sales_{y-t} - \frac{MC}{\sum_{0}^{T} \frac{1}{(1+r)^t}} \times \sum_{0}^{T} sales_{y-t}.$$

If the two equations above are to produce the same result, it requires

(3) $$MC \times sales_y = \frac{MC}{\sum_{0}^{T} \frac{1}{(1+r)^t}} \times \sum_{0}^{T} sales_{y-t}.$$

It can be seen that equation (3) requires $r = 0$ and $sales_y = sales_{y-t}$ for all t. Thus, the EPA approach will only provide correct results under the assumption that the discount rate is zero and sales are constant. It should also be noted that the EPA method, when applied to years in which the fleet is not fully turned over, will produce especially poor results. This is because for those years, $sales_{y-t}$ for some t will be zero. This makes the assumption of constant sales clearly incorrect.

The long-run focus is also problematic due to the high amount of uncertainty associated with many of the inputs. Calculation of benefits and costs in 2030 requires the EPA to forecast and make assumptions about many inputs three decades in advance. On the benefit side, these sources of uncertainty include emission inventories, the relationship between emissions and ambient concentrations, concentration-response functions, valuation of physical impacts, population estimates, income estimates, fleet size, and miles traveled. On the cost side, uncertainty arises from technology cost estimates, fleet size, and miles traveled. The EPA acknowledges this uncertainty and attempts to address it by presenting results based on alternative scenarios. There is not, however, any attempt to quantify this uncertainty.

Although not problems with the methodology, several other shortcomings of the EPA analysis should be mentioned. First, the EPA presented the net benefit of the entire rule. That is, the net benefit reflects the new standards for heavy-duty diesel vehicles, new diesel fuel standards, and new standards for heavy-duty gasoline vehicles. While it makes sense to include the benefits and costs of the new diesel fuel standards because they enable diesel vehicles to meet the new emission standards, it makes less sense to include benefits and costs of the new standards for heavy-duty gasoline vehicles. The new standards for diesel and gasoline vehicles are separate and different, and there is no reason they must be implemented together. Therefore, it would be beneficial for each to have its own analysis.

An additional problem with the EPA analysis is related to the assumptions made about control technologies. Specifically, the predicted technology for control of NOx emissions has not progressed as quickly as expected. Instead, an entirely different technology is being used. The primary effect of this error is inaccurate estimates of the cost of technologies used to meet the new standards. It also affects assumptions about fuel economy and operating costs.

2.2 Other Related Work

While the EPA's benefit-cost analysis described above is the most relevant in terms of topic, the methodology used here is different. In terms of methodology, the present analysis is more similar to lifecycle analyses or cost-effective analyses. Life-cycle analyses range from a simple description of the effects of a vehicle over its lifetime, to a full monetization of all those effects. These studies typically examine the desirability of alternative fuels or powertrain technologies for vehicles.

Maclean and Lave (2003) is an example of a lifecycle analysis at its most simple. The authors only describe the lifecycle of several different types of light-duty vehicles. No attempt is made to quantify the differences between the various vehicle types examined. A somewhat more detailed analysis can be found in Lave et al. (2000). The authors of this study do quantify the effects of various vehicle designs, but do not monetize all of them. Similar to the approach taken in the present analysis, the authors make an attempt to control for the benefits provided by vehicles by keeping the basic vehicle constant as different powertrain options are examined. They also assume that the vehicle lifespan and age at scrappage are constant over the different powertrains. These assumptions make the analysis simpler due to the fact that it allows the benefits to be ignored because they will remain the same as powertrain technology varies.

Hahn (1995) is another study that involves a lifecycle analysis in which some of the costs are not monetized. This study conducts a cost-effectiveness analysis of alternative fuels and vehicle technologies for reducing ozone pollution. Similar to Maclean and Lave (2003), assumptions are made about vehicle age and miles traveled at scrappage. Assumptions about emission rates from the baseline gasoline vehicle are estimated based on government test results, and the effects of various technologies and alternative fuels on emission rates are estimated based on previous work.

Keefe et al. (2007) is a good example of a the most comprehensive type of lifecycle analysis. This study was based loosely on the work of Hahn (1995) and Maclean and Lave (2003), but takes the additional step of monetizing all benefits and costs. Again the application was alternative fuels and technologies for light-duty vehicles. The key difference in the methodology used in Keefe et al. (2007) and the methodology used in the present analysis is the treatment of benefits. Here, benefits provided by the vehicle remain constant as that vehicle is modified to meet different emission standards. Keefe et al. (2007) does not assume benefits remain constant as powertrain technology changes.

Both approaches are reasonable. In the present analysis, the changes to the vehicle to meet varying emission standards do not significantly affect benefits. Vehicle longevity will remain about the same, performance will be nearly identical, and fuel economy will not change much. Thus, assuming constant benefits is reasonable. However, the changes considered by Keefe et al. are significant enough such that benefits cannot be assumed constant. If, for example, the two technologies under consideration are gasoline and diesel engines, it is likely that the marginal cost of travel will be significantly different due to different fuel prices and different fuel economies. Therefore, one type of vehicle will travel more miles each year because the marginal cost is lower. This implies a difference in benefits that must be estimated.

Several other lines of research are loosely related. One of these is cost-effective analyses and benefit-cost analyses applied to retrofit programs. These studies are concerned with the benefits and costs of retrofitting various technologies to existing diesel vehicles for the purposes of reducing emissions. An example is Stevens et al. (2005) which estimates the net benefits of two alternative strategies of addressing PM emissions from heavy-duty diesel trucks and buses in Mexico City. Wang (2004) provides a more general set of results with a review of a number of cost-effective analyses of various control technologies.

Studies concerned with retrofit technology are not, however, directly applicable here. First, estimating the cost of retrofit technologies is more straightforward than estimating the costs of technologies applied to new vehicles. Costs associated with new vehicles are less transparent for several reasons. First, prices of the technologies are not directly observed as they are in retrofit programs. Second, there is often considerable integration with other engine systems when technologies are applied to new vehicles. The cost of this integration is difficult to estimate.

Additionally, the benefits of retrofit technology may be more certain. Retrofit technologies have typically been proven in other applications so that their affect on emissions is known. However, when emission standards force new technology to be used on new vehicles there is often considerable uncertainty about the results. The technology may be relatively unproven or there may be uncertainty due to the integration with other engine systems. If multiple new technologies are being used, there may also be complex and unpredicted interactions between the technologies.

Chapter Three: Diesel Emissions

3.1 Types of Emissions

Ideally, combustion of diesel fuel produces only carbon dioxide (CO_2) and water. However, a number of imperfections in the combustion process lead to other unwanted byproducts. Four of these are regulated by the US EPA: hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), and nitrogen oxides (NOx). These four pollutants are a concern primarily due to their effects on human health, although they are also responsible for other problems. Although CO_2 does not impact human health directly, it is a concern due to its contribution to climate change. However, CO_2 emissions are solely determined by the quantity of diesel fuel consumed, and no abatement technologies exist for mobile sources other than those that decrease fuel consumption. Thus, regulation of this pollutant is not part of the 2007 standards.

Diesel engines generally do not emit large quantities of hydrocarbons, and emission rates are typically lower than those for gasoline engines. The EPA no longer regulates total hydrocarbons from diesel vehicles, but instead has regulated non-methane hydrocarbons (NMHC) since 2004. Diesel engines do not emit large quantities of methane (CH_4), and the EPA advises that NMHC emissions are typically 2% lower than total HC emissions (US EPA 1997). Diesel engines are also not large emitters of CO, with emission rates significantly lower than gasoline engines.

Currently, the main concern with diesel exhaust is NOx and PM emissions. PM emissions are defined as particles 10 micrometers in diameter or smaller. These particles consist of a variety of substances including nitrates, sulfates, organic chemicals, and metals. Nitrogen oxides include nitrogen dioxide (NO_2) and nitric oxide (NO) (US EPA

2009b). Diesel engines emit considerably larger quantities of these pollutants compared to gasoline engines. An additional problem is there is typically a tradeoff between PM and NOx emissions. PM emissions result from incomplete combustion, and NOx emissions are exacerbated when cylinder temperatures rise. Complete combustion raises cylinder temperatures relative to incomplete combustion such that in-cylinder techniques for addressing one of these pollutants often lead to an increase in emissions of the other. However, recent advances in after-treatment technology have made this less of a concern (Majewski and Khair 2006).

3.2 Emission Standards

The technological advances that have reduced diesel emissions have been driven by a number of factors. Some of this progress has also improved vehicle performance and fuel economy, and it has sometimes been the demand for these that has driven the technology. Performance of heavy-duty diesel engines is critical in many of their applications, with large power output and good drivability characteristics being highly desirable. Additionally, with an average fuel economy of about 7 MPG, and with the typical class 8 vehicle travelling about than 120,000 miles per year, fuel economy is an obvious concern.[2] Since emission standards were implemented for the first time in 1974, their increasing strictness has also played a major role.

Emission standards for heavy-duty on-road vehicles were first required as a result of the Clean Air Act of 1970. The first standards took effect in 1974 and have repeatedly been tightened. This increasing strictness has culminated with the US 2007 standards. Table 3.1 shows the progression of the standards from 1974 through 2007. It should be

[2] See Chapter Six for a detailed discussion of the estimates used here. Also see Appendix A for a description of heavy-duty vehicle classes.

Table 3.1 - US Emission Standards for Heavy-Duty Diesel On-Road Vehicles (g/bhp-hr)[3]

Year	NOx	PM	NMHC+NOx	NMHC	HC	CO
1974			16			40
1979			10		1.5	25
1985	10.7				1.3	
1988	6.0	0.6			1.3	
1991	5.0	0.25			1.3	
1994	5.0	0.1			1.3	
1998	4.0	0.1			1.3	
2004		0.1	2.4			
2007	0.2	0.01	2.4	0.14		

noted that there are some exceptions to the numbers listed. Urban buses, for example, were held to a stricter PM standard through 2006. Also, the 2007 standards contained a provision which gradually phased in some of the new standards. Table 3.2 describes this

Table 3.2 - Percent of Manufactured Vehicles Required to Meet New Standard[4]

Year	NOx	PM	NMHC
2007	50	100	50
2008	50	100	50
2009	50	100	50
2010	100	100	100

phase in schedule. It can been seen that there is a considerable tightening of the standards in 2010 specifically due to the NOx standard becoming fully implemented. However, even before 2010, no manufacturer certified half of their produced vehicles to the 0.20 g/bhp-hr NOx standard. This was possible due to the credits earned in the average, banking, and trading (ABT) program. The ABT program was applied to NOx and PM standards until 2004. After 2004, it was only applied to the NMHC+NOx standard. This

[3] The information contained in Table 3.1 is from US EPA (2009b)
[4] The information contained in Table 3.2 is from US EPA (2001).

allowed all manufacturers to exceed the NOx standard from 2007 through 2009 by redeeming credits earned elsewhere.

To understand how the 2007 standards affected actual emissions, it is necessary to compare actual emissions before 2007 to actual emissions after the new standards took effect. To do this, test results from 2005 and 2007 engines as reported by the EPA are compared.[5] These test results are those reported to the EPA by the manufacturers for the purpose of certification. Engines included in the comparison are selected based on two criteria. First, only engines from five major manufacturers are selected: Caterpillar, Cummins, Detroit Diesel, International (Navistar), and Volvo. Mack is not included because no results were reported in 2007 for its engines. Of the five manufacturers included, engines were only selected if they were medium or heavy heavy-duty diesel engines. Table 3.4 presents the average emissions for each manufacturer for 2005 and 2007.[6] Table 3.3 presents the percent changes in the emissions between the two years.

Table 3.3 - Percent Change in Emissions Performance
(2005 to 2007)

NOx	PM	NMHC+NOx	NMHC	CO
-47.298	-95.345	-48.436	-79.244	-56.682

It can be seen that there were significant improvements made in all five categories. However, NOx emissions do not decrease by nearly the amount the 2007 standards would seem to indicate. For 2010, all manufacturers, with the exception of Navistar, claim they

[5] The full data sets for all years are available from the US EPA's website at http://www.epa.gov/otaq/certdata.htm. (US EPA 2009a)
[6] See Appendix B for information on the construction of Table 3.4.

Table 3.4 - Average Emissions by Manufacturer (g/bhp-hr)[7]

Manufacturer	Displacement (L)	NOx	PM	NMHC+NOx	NMHC	CO
2005						
Caterpillar	10.114	2.243	0.064	2.357	0.114	1.871
Cummins	8.933	2.348	0.079	2.495	0.147	1.238
Detroit Diesel	13.350	2.282	0.081	2.400	0.118	0.610
International	8.167	2.333	0.057	2.333	0.000	0.350
Volvo	12.100	2.282	0.085	2.400	0.118	0.700
Overall	10.533	2.298	0.073	2.397	0.099	0.954
2007						
Manufacturer	Displacement (L)	NOx	PM	NMHC+NOx	NMHC	CO
Caterpillar	11.575	0.900	0.003	0.950	0.025	1.050
Cummins	10.450	1.708	0.008	1.714	0.010	0.229
Detroit Diesel	11.333	1.088	0.004	1.103	0.015	0.210
International	8.450	1.409	0.001	1.425	0.016	0.578
Volvo	13.233	0.950	0.002	0.988	0.037	0.000
Overall	11.008	1.211	0.003	1.236	0.021	0.413

will meet the 0.2 g/bhp-hr NOx standard. Navistar, using its EGR-only strategy, claims it will certify at the 0.5 g/bhp-hr NOx level (Leavitt 2009).

3.3 Progression of Emission Control Technology

The technology used to meet earlier standards (1974-2004) was almost exclusively improvements in engine design and fuel injection systems. Generally, HC and CO standards have not presented a major challenge for manufacturers. Most efforts were aimed at reducing NOx or PM. Prior to 1988 there was no PM standard, which meant that designers could reduce NOx without addressing the tradeoff between NOx and PM emissions. During this time, a number of strategies were used to address NOx emissions. The most important strategies involved changes to the fuel injection system.

[7] The NOx and NMHC estimates often do not sum correctly to the reported NMHC+NOx estimates. This is due to the way manufacturers rounded their test results.

Retarded injection timing was used to meet the earliest standard (Patten). By delaying the start of injection, peak cylinder temperatures are kept lower, resulting in lower NOx emissions. The drawback to this was reduced fuel economy (DieselNet 2009b).

The late 1970's brought further refinements in injection strategy, as well as increased injection pressures. The increased injection pressures (10,000-11,000 psi) (DieselNet 2009b) produced an effect similar to retarded injection. The higher pressure resulted in a given amount of fuel being injected in less time. Thus, the start of injection could be delayed while the amount of fuel delivered remained the same (Majewski 2007). Still further refinements to fuel injection systems came in the 1980's, as well as adoption of intercoolers (DieselNet 2009b). The biggest advance in fuel injection systems was electronic control, which did not start until the late 1980's in the heavy-duty vehicle market (Khair 2003). The primary benefit of this was improved control of injection. Injection pressures were also increased to about 15,000 psi by the middle of the decade (Patten). Most diesel engines had turbochargers by the 1980's so the adoption of intercoolers was an important advance. Intercoolers cool the air entering the engine, which produces two results. First, the cooler air is denser so that the engine can produce more power. Second, and more important for this discussion, the cooler air leads to lower temperatures within the cylinders, thus reducing NOx emissions.

Manufacturers faced a more difficult challenge starting in 1988 with the addition of a PM standard. As a result, there has been continuous progress in injection pressures as well as new types of injection systems developed. Injection pressures had risen to 21,000 psi by 1991 (Patten), and current technology is capable of pressures as high as 35,000 psi (Mele 2008). Fuel injection systems have also changed, and current systems are completely different than the traditional pump-line-nozzle systems. Common rail as well as unit injection systems, or some combination of the two, are used exclusively today. These direct injection systems yield not only extremely high pressures, but they also give complete control of injection. This control includes not just timing and duration, but also the ability to inject fuel at different times during the same combustion cycle. These capabilities allow these systems to achieve low NOx, while limiting increases in PM and fuel consumption.

Turbocharger design has also progressed. The two major developments, which are discussed in some detail in Appendix C, have been waste-gated turbochargers and turbochargers with variable turbine geometry. Variable turbine geometry, in particular, has reduced PM emissions by reducing turbo lag. Some manufacturers have also specified multiple turbochargers for a single engine, which can also reduce turbo lag. A final development in engine design has been the application of exhaust gas recirculation (EGR) to heavy-duty diesel engines. This technology works by routing small amounts of exhaust gases into the engine's air intake. The effect is a decrease in peak cylinder temperatures and a decrease in NOx emissions (Majewski and Khair (2006). A more detailed discussion of this technology is included in the next chapter.

Surprisingly, there was limited use of after-treatment technology before US 2007 standards were implemented. Diesel oxidation catalysts were briefly used in 1994 on heavy-duty diesel vehicles that still relied on mechanical fuel injection systems. However, as electronic controls became universal, the catalysts were phased out (DieselNet 2009b). There were several problems with after-treatment devices during this time period. First, some of the technology was simply not available. Second, there were reliability and cost concerns with the technology that was available. Diesel particulate filters, for example, were still not sufficiently developed for use in heavy-duty vehicles. SCR systems either were not yet developed, or were simply too costly to be used to meet standards that could be met using less costly technology that was well proven. The next section will discuss the technology that is relevant to achieving 2007 and 2010 emissions.

Chapter Four: Recent Advances in Emission Control

4.1 Exhaust Gas Recirculation

This chapter will discuss more recent developments in heavy-duty diesel emission control technologies. A solid understanding of these technologies and the role they play in achieving recent emission performance is critical to correctly identifying the costs and benefits of 2007 and 2010 emissions.[8] The first of the technologies to be discussed is exhaust gas recirculation (EGR).

EGR has been in use since the 1970's in gasoline-powered vehicles to reduce NOx emissions. Its use in diesel engines, for the same purpose, began in passenger cars sold in Europe in the early 1990's in response to Euro 1 standards (Khair 2006). The technology's use in heavy-duty diesel engines did not occur until 2002. Five companies adopted the technology in that year: Cummins, Detroit Diesel, International (Navistar), Mack, and Volvo (Moore 2003). This adoption was the result of a settlement between these companies and the US EPA. The EPA had alleged that the five companies, as well as Caterpillar, had intentionally equipped earlier models with technology that allowed the vehicles to meet the standards when tested, but exceed the standards during typical, real-world operating conditions. As part of the settlement, all six companies, which make up 95% of the US heavy-duty diesel market, agreed to reduce NOx emissions by 80% by 2002.[9] This basically amounted to these companies meeting the US 2004 NOx standard two years early. With the implementation of 2007 standards, all heavy-duty manufacturers adopted the technology (Khair 2006). EGR will also play a role in meeting

[8] 2007 emissions refers to emissions during the phase-in of 2007 standards. 2010 emissions refers to the fully phased-in 2007 standards.
[9] See the EPA's press release titled "PR DOJ, EPA Announce One Billion Dollar Settlement with Diesel Engine Industry for Clean Air Violations" for more information on this settlement (US EPA 1998).

the US 2010 standards. All manufacturers will continue to use EGR, although other strategies to reduce NOx will also be employed by most manufactures. Navistar is the one exception to this and will continue to rely on EGR as the primary way to control NOx emissions (Leavitt 2009).

EGR systems work by directing exhaust gases back into the combustion chamber. The EGR valve allows varying amounts of exhaust gases to be directed back into air intake system. These exhaust gases mix with the intake air and the result is lower peak temperatures within the cylinders. High peak temperatures within the cylinders are the primary cause of high NOx, emissions. Thus, by reducing these temperatures, EGR systems reduce NOx emissions. Cooling the exhaust gases before they are mixed with the intake air further reduces peak cylinder temperatures and NOx emissions.

Cooled EGR systems can be low pressure loop (LPL) EGR or a high pressure loop (HPL) EGR. Early diesel EGR systems were primarily HPL. This type works by removing exhaust gases from the exhaust system upstream of the turbocharger. These exhaust gases for EGR then pass through an air-to-air cooler. After the cooler, the EGR valve directs varying amounts of the cooled gases into the air intake after the intercooler. The purpose of taking the exhaust upstream of the turbo is that they are under higher pressure at this point. This ensures that the exhaust system pressure is greater than the intake manifold pressure. If this was not the case, the exhaust would not flow into the intake; rather, the flow would be reversed (Khair 2006). A downside to this type of system is that turbocharger performance is degraded because less exhaust gas flows through the turbocharger.

More recent applications of EGR, which typically also incorporate diesel particulate filters, are LPL systems. In LPL systems, exhaust gases are removed from the exhaust system downstream from the turbocharger. This preserves turbocharger function, but the pressure in the exhaust system is lower. To address this, re-circulated exhaust gases are introduced to the intake before the turbocharger. This preserves the pressure difference between the exhaust system and the intake system. When a particulate filter is in use, it is desirable to remove exhaust for EGR downstream from the particulate filter. This introduces cleaner exhaust into the engine and results in improved engine durability. Another advantage that this system has relative to HPL systems is superior fuel economy. This is due to the better turbocharger performance.

The benefits of cooled EGR systems are substantial. Cooled EGR systems were the primary NOx control strategy used to meet US 2004 standards and the phase in period limits of US 2007 standards. At least one company believes the technology will be sufficient for meeting the fully-implemented standards in 2010. Estimates of NOx reductions resulting from cooled EGR systems range from 30% to 60%. The US EPA places the estimate at 50%, Krishnan and Tarabulski (2005) estimate 50% to 60% efficiency, and Majewki (2007a) places it at 30% to 50%.[10]

Cost estimates for cooled EGR systems are rare. According to Parry (2001), Cummins claimed their 2002 cooled EGR system was going to add $2,154 to $3,590 to the cost of their 2002 heavy-duty engines. The more advanced EGR system that will be used by Navistar will lead to a claimed $6,000 to $8,000 price increase for 2010 engines (Cullen 2009 and Mele 2009). These reported numbers would approximate the hardware

[10] The EPA's estimate is based on information provided by its Diesel Retrofit Technology Verification program (US EPA 2007).

costs associated with the system itself as well as required engine integration. Fuel injection systems must be adjusted to counteract increased PM emissions and deal with the variable introduction of the exhaust gases into the combustion chamber. There are numerous costs associated with these systems besides the hardware costs. The increase in PM emissions is also an important consideration. At high levels of exhaust gas recirculation, HC and CO emissions may also increase. Besides the increased emissions, fuel economy typically falls by a small amount. International (Navistar) claims users of their engines and Cummin's engines may experience a 0-5% reduction in fuel economy due to their 2002-compliant EGR systems. These are all costs that should be considered.

4.2 Diesel Particulate Filters

US 2007 emission standards caused wide scale adoption of another technology: the diesel particulate filter (DPF). These particulate filters were first used in Mercedes diesel passenger cars sold in California in 1985, but subsequent problems forced their removal from the market (Abthoff 1985). They were then adopted for use in off-highway vehicles that operated in closed environments. In the mid 1990's, particulate filters were retrofitted to several urban bus fleets. Factory installations of particulate filters did not resume until 2000 and 2001 when they were introduced by Peugeot and Citroen on some passenger cars. Navistar was the first to install a DPF on a heavy-duty on-road diesel, although it was only applied to some school buses sold in California (Majewski 2007a). Widespread adoption on heavy-duty diesels in the US did not occur until 2007, when new emission standards took effect. In that year, every heavy-duty diesel sold in the US for on-road use was equipped with a DPF. They remain an integral part of 2010 strategies for all manufacturers.

Diesel particulate filters consist of a ceramic wall-flow monolith structure contained within a steel case. The channels of the structure run parallel to the flow of exhaust, and adjacent channels are blocked at opposite ends. Thus, exhaust gases must flow through the walls of the structure which act as the filter medium (Majewski 2007a). Particulate matter from the exhaust accumulates in the filter and must be oxidized to prevent excessive back pressure. There are several methods by which this process, also known as regeneration, can be accomplished. The first is called passive regeneration. Passive regeneration requires no special actions by the driver or engine. Instead, a catalyst is applied to the medium. This lowers the oxidation temperature of the collected soot to a level that can be reached during normal vehicle operation. A second method involves injecting a small amount of fuel into the exhaust after the turbo. This raises exhaust temperatures to levels sufficient for oxidation to occur. Most current (2009) systems rely on both methods.

The filters also require occasional service. While the regeneration process removes the soot from the filter, ash from engine oil also accumulates slowly. This ash cannot be removed regardless of exhaust temperatures. When exhaust system backpressure increases too much as a result of this ash buildup, the filter must be removed and cleaned (Baxter 2006). The EPA requires a 150,000 mile service interval for particulate filters, so this maintenance is relatively infrequent.

Modern diesel particulate filters on heavy-duty vehicles are typically combined with diesel oxidation catalysts (DOC), often in the same structure. The exhaust is routed through the DOC before it enters the DPF. The purpose of routing the exhaust gases through the DOC first is that the temperature of the exhaust gases and filter structure will be increased substantially. This increases the rate of passive regeneration within the DPF, lessening the need for active regeneration. This is important because there is a small fuel economy penalty associated with active regeneration. The structure containing the DOC and DPF is typically about three feet long and about one foot in diameter. It will typically reduce exhaust noise enough such that the muffler can be eliminated (Baxter 2006).

Performance of diesel particulate filters is excellent. Most estimates, including those from the California Air Resource Board (CARB) and the EPA indicate that the devices reduce PM emissions by at least 90%.[11] However, they are costly. Estimates of their costs range from $3,700 to $13,000. CARB (2000) estimates the cost at about $13,000 for a 400 hp engine, while the EPA's Diesel Retrofit Verification program places it between $6,500 and $10,000. An estimate from the Manufacturers of Emission Controls Association (MECA) places the estimate somewhat lower at $3,700 to $5,700. Reports from New York City Transit and the City of Seattle indicate that the costs range from $6,000 to $8,500 (WSU 2004). Maintenance costs should also be considered. CARB (2000) estimates annual maintenance costs to range from $156 to $312. CARB (2000) also estimates that fuel economy will drop by 1% to 1.5% in retrofit applications due to additional exhaust system backpressure.

Another cost related to DPF is the required ultra-low sulfur diesel (ULSD). ULSD contains no more than 15 ppm sulfur. When the EPA wrote the 2007 standards, they introduced a new diesel fuel standard as well. Previous sulfur levels in on-road diesel fuel (low sulfur diesel) were 500 ppm. The new regulation required ULSD to be available at the retail level by October of 2006. However, several provisions in the new regulation

[11] See CARB (2000) and the EPA's Diesel Retrofit Verification Program website (US EPA 2007) for more information.

have allowed 500 ppm diesel (LSD) to remain available. By May of 2010, all on-road diesel fuel must be ULSD (DieselNet 2009c). Availability of this fuel allowed engine manufacturers to use DPF technology to meet the new standards in 2007. Estimates of the additional production costs associated with ULSD typically fall between $0.05 and $0.09 per gallon. This adds a considerable amount to the operating cost of heavy-duty vehicles that use this fuel.

4.3 Selective Catalytic Reduction

2010 emissions require a large reduction in NOx emissions. All but one heavy-duty diesel manufacturer has chosen to use selective catalytic reduction technology to meet the new NOx standard.[12] Selective catalytic reduction (SCR) technology has been in use for about three decades in stationary applications including power plants, refineries, and waste incinerators (Cobb et al. 1991). Mobile application began in marine vessels in the 1990's (Emissions Advantage, LLC. 2005) and Nissan Diesel was first to apply SCR technology to heavy-trucks in 2004 (Hirata et al. 2005). The technology has also been in use for several years in Europe in order to meet Euro IV (2006) standards. SCR was not adopted by any manufacturer to achieve US 2007 emissions, but it is the leading technology for 2010 compliance.

SCR systems consist of several components. An oxidation catalyst is installed in the exhaust system downstream from the DOC and DPF catalyst. The catalyst device consists of a stainless steel case which contains the catalyst support on which the various catalysts are applied. The purpose of the catalyst is to convert NOx to nitrogen and water. To facilitate the conversion, a reductant is injected into the engine exhaust upstream of

[12] Navistar will not use SCR in 2010.

the catalyst. In mobile applications, this reductant is a urea solution (32.5% urea, 67.5% water), often called diesel exhaust fluid (DEF). In stationary applications of SCR, ammonia is often used. However, the need for a non-toxic reductant led to the decision to use urea as a substitute (Majewski 2005). Thus, the system consists not only of the catalyst, but also the other hardware associated with the urea injection system. This hardware includes a sizeable tank for the urea solution, a tank heater, a pump, and the injector itself.

Selective catalytic reduction's ability to reduce NOx emissions is considerable, although not large enough to permit elimination of EGR. All manufacturers will rely on EGR in 2010. The EPA's Diesel Retrofit Verification program (US EPA 2007) estimates a 60% reduction in NOx by SCR. Other estimates range from 55% to 90% (Majewski 2005), although estimates around 90% are most common (Majewski 2007a). The EPA also estimates that SCR will reduce HC and CO by about 50% each, and PM emissions may be reduced by 0% to 30%, although other studies indicate conflicting results.[13]

Besides reducing emissions, SCR catalysts may improve fuel economy when applied to engines that already utilize EGR. EGR systems have a detrimental effect on fuel economy. As the desired level of NOx emissions is lowered, engine designers must introduce higher rates of EGR, which leads to decreases in fuel economy. By using SCR, less EGR is required for a given level of NOx emissions, leading to improved fuel economy.[14] Detroit Diesel expects an improvement of 0% to 5% relative to 2007-compliant engines, while Cummins' testing indicates a 5% to 9% improvement compared

[13] See Majewski (2005) for more details.
[14] Volvo estimates EGR rates will drop to 15-25% from 20-35% (Sturgess 2008a).

to in-cylinder approaches for 2010 emissions.[15] This is a significant advantage of using SCR technology. Volvo claims an additional benefit of SCR (Leavitt 2009). The company has been able to eliminate active regeneration of the DPF, further increasing fuel economy. To achieve this, the engine is allowed to produce more NOx, which speeds up passive regeneration. Further downstream in the exhaust system, the SCR system removes much of the additional NOx, enabling the vehicle to meet emission targets.

Like the other technologies discussed, there are significant costs associated with SCR. Estimates of the costs of the system itself range from $4,000 to more than $10,000. The EPA's Diesel Retrofit Verification program places the cost significantly higher at $10,000 to $20,000. Daimler (Detroit Diesel) estimates the new systems will add $4,000 to the price of a truck (Kilcarr 2007), while Volvo estimates a price increase of $9,600 (Carretta 2009). It is unclear how these reported price increases are linked to production costs, but it seems very unlikely that manufactures would price the systems above costs considering the uncertainty surrounding them. Thus, these price increases are probably a lower bound for increases in actual production costs.

Although the systems require no maintenance, the DEF does have to be replenished at frequent intervals. The DEF is expected to be available at truck stops, auto part stores, and dealers. Typical tank sizes will range from 10 to 20 gallons, according to Cummins Filtration (2009). Sturgess (2008b) claims that a truck will need about 400 gallons of DEF per 120,000 miles traveled. Cummins Filtration (2009) believes DEF usage will be about 2% of fuel usage. Both of these estimates equate to 1 gallon per 300 miles for a truck that obtains 6 miles-per-gallon. DEF is expected to be priced at $2 to $3

[15] These fuel economy estimates will be reviewed in more detail in Chapter Six.

per gallon (Cummins Filtration 2009). If the typical truck travels about 120,000 miles per year, the annual cost associated with DEF will be about $800 to $1,200.

4.4 NOx Adsorbers

Although not currently in use in heavy-duty vehicles, NOx adsorbers are another strategy for addressing NOx emissions. Also called NOx storage catalysts, these devices have seen limited use. The only vehicles to use them in the US have been Mercedes' E320, Dodge's Ram pickup truck, and Volkswagen's diesel passenger cars (Parks et al. 2009). The E320 and Ram using NOx adsorbers debuted in 2007, while Volkswagen incorporated the technology into their 2008 models. At this time (2009), the technology has not been used commercially on any heavy-duty diesels in the US. However, when the EPA wrote the US 2007 standards, they incorrectly expected NOx adsorbers to be the preferred choice among heavy-duty diesel manufacturers to meet the much more stringent NOx standards. Thus, a short discussion of the technology is warranted.

NOx adsorbers consist of a catalyst mounted in the exhaust system, typically upstream from the DPF (Yezerets et al. 2007). Operation is characterized by two phases. During the adsorption phase, NOx is captured by the device. This cycle occurs during lean-burn operation of the engine. Gradually, the capacity to capture the NOx is decreased such that active regeneration must occur. This is accomplished by decreasing the air-fuel ratio. This characterizes the regeneration cycle. The need to manage the air-fuel ratio for regeneration purposes requires considerable integration with the engine. The active regeneration also results in lower fuel economy (because decreasing the air-fuel ratio is achieved by injecting more fuel) and may lead to greater PM emissions.

NOx adsorbers can reduce NOx emissions by about 70% to 90% (Majewski 2007a). The EPA estimates the cost of a NOx adsorber for a 400 hp engine to be $2,466 (Alpha-Gamma Technologies 2005). While this number is considerably lower than the cost of a SCR system applied to an equivalent sized engine, there remain several problems with NOx adsorbers for heavy-duty engines. First, there are concerns about durability. This is in part due to the degradation that occurs when exposed to sulfur in diesel fuel. Ultra-low sulfur diesel will slow this degradation, but not stop it (Majewski 2007b). If performance is sufficiently diminished, the device must be replaced at considerable cost. The fuel economy penalty is also a concern. Fuel costs comprise a large portion of the operating costs of heavy-duty vehicles due to poor fuel economy and the large number of miles travelled. Even a small decrease in fuel economy can impose significant additional cost on the vehicle owner. It is for these two reasons that SCR technology is the preferred choice to achieve 2010 emissions. SCR systems have been proven durable through their use in Europe, and they tend to increase fuel economy rather than decrease it.

Chapter Five: Methodology

5.1 Discussion of Benefits and Costs

The methodology used here is based on that used by lifecycle analyses. Lifecycle analyses are often used to evaluate alternative versions of some type of vehicle. The most comprehensive of these monetize all of the benefits and costs that occur over the life of each version of the vehicle.[16] These monetized benefits and costs include the private benefits and costs of the vehicle, as well as external costs associated with vehicle production and use. A net benefit is then calculated for each version of the vehicle.

The costs of some version of a vehicle have both private and external components. Private vehicle costs include vehicle production costs, fuel production costs, and maintenance costs. External costs arise primarily from emissions associated with the vehicle, but also include those associated with noise, congestion, and increased dependence on foreign oil. The external costs of emissions associated with the vehicle arise from three different processes: vehicle production, vehicle operation, and fuel production. On the other hand, the benefit of a given vehicle is assumed to be strictly private and falls on the user of the vehicle. This benefit is a function of the services provided by the vehicle to that user. Some of these costs and benefits will vary across alternative versions of some vehicle, while others are constant.

When it is some new emission standard that forces the transition from one version of a vehicle to another, it is important to differentiate between the benefits and costs of the vehicle itself and the benefits and costs of the policy. As described above, there are benefits and many different types of costs associated with each version of some vehicle.

[16] See, for example, Keefe et al. 2007, Lave et al. 2000, and Lave and Maclean 2003.

The policy-driven transition from one version of the vehicle to another will lead to changes in these benefits and costs. Therefore, the benefits of the policy itself are any decreases in costs associated with the vehicle or any increase in the benefits realized by the user of the vehicle. Likewise, the costs of the policy are any increases in the costs associated with the vehicle or any decrease in the benefits realized by the user.

In this analysis, there are three versions of a relevant heavy-duty diesel truck: a 2004-compliant truck, a 2007-compliant truck, and a 2010-compliant truck. These versions will only differ in the emission control technology used and the effects of those different controls. It should be made clear that the year designation attached to each version does not refer to the production year of the vehicle. Rather, it refers to the emissions performance of that version. The 2004-compliant truck is equipped with emission control technology that allows it to meet 2004 standards. The 2007-compliant truck is equipped with technology that allows it to meet standards during the phase-in of the 2007 standards, while the 2010-compliant version is equipped with technology that allows it to meet the full 2007 standards.

It is assumed that the benefits of each of these versions are equal. This is a reasonable assumption to make because emission control technologies used on these vehicles do not significantly impact vehicle performance or durability. Each version will provide the same services and last about the same amount of time. Therefore, the evaluation of the policy that forces the purchase and use of one version of the vehicle rather than some other is dependent only on the costs of each version of the vehicle. The benefits of the policy are any decreases in those costs, and the costs of the policy are any increases in those costs. Table 5.1 provides a summary of the benefits and costs of the emission standards.

Table 5.1 - Summary of Benefits and Costs to be Included

Benefits	Costs
Decreases in Private Costs of Vehicle Production	Increases in Private Costs of Vehicle Production
Decreases in Private Costs of Operation	Increases in Private Costs of Operation
Decreases in External Costs of Vehicle Operation	Increases in External Costs of Vehicle Operation
Decreases in Private Fuel Costs	Increases in Private Fuel Costs
Decreases in External Fuel Costs	Increases in External Fuel Costs

5.2 Mathematical Representation

The full lifecycle cost of version *v* of the vehicle is given by

(4) $$lifecycle\ cost_v = VC_v + PVEC_v + PVOC_v + PVDC_v,$$

where VC_v is the total production cost of version *v* of the vehicle, $PVEC_v$ is the present value of all external costs resulting from operation of the vehicle, $PVOC_v$ is the present value of all non-fuel operating and maintenance costs occurring over the life of the vehicle, and $PVDC_v$ is the total cost of diesel fuel used by the vehicle. Total production cost of the vehicle is given by

(5) $$VC_v = PVC_v + EVC\ ,$$

where PVC_v is the private cost of producing the vehicle and *EVC* is the external cost of vehicle production. Note that *EVC* is constant across versions of the vehicle. This is a reasonable assumption because the external cost of vehicle production is unlikely to be changed to any significant degree by the addition of the control technologies used for heavy-duty trucks.

The present value of the external cost of vehicle operation is calculated according to the following

(6) $$PVEC_v = \sum_{0}^{T} \frac{VMT_t \left(\sum_{p}^{P} md_p * emission\ rate_{v,p} + other\ external\ costs\ per\ mile \right)}{(1+r)^{t/12}},$$

where VMT_t is the number of miles traveled in month t, md_p is the marginal damages per-gram of pollutant p, $emission\ rate_{v,p}$ is the per-mile emission rate of p by some version v of the vehicle, and r is the annual rate of discount. There are several things to note about this construction of $PVEC_v$. First, *VMT* is constant across vehicle versions. The validity of this assumption depends on how responsive demand for miles is to operating costs. Also note that *other external cost per mile* is constant across versions of the vehicle. This is a reasonable assumption to make if *VMT* is constant across versions.

The present value of the operating costs of the vehicle are calculated according to

(7) $$PVOC_v = \sum_{0}^{T} \frac{OC_{v,t}}{(1+r)^{t/12}},$$

where $OC_{v,t}$ is the operating costs of vehicle version v in month t. These costs exclude the present value of diesel fuel costs that are calculated according to

(8) $$PVDC_v = {}_{0}^{T} \frac{\frac{VMT_t}{MPG_v} \; MC_v + \; {}_{p}^{P} fuel\ emission\ rate_p * md_p}{(1+r)^{t/12}},$$

which accounts for both private fuel costs as well as external costs associated with emissions produced during production and distribution of diesel fuel. The private cost of diesel fuel production is given by $MC_{v.}$ This is dependent on v because the 2007-compliant and 2010-compliant vehicles require the use of diesel fuel with lower sulfur content than the 2004-compliant vehicle requires.

The change in lifecycle costs that result from purchasing and operating a different version of the vehicle are then given by

(9) $$\Delta lifecycle\ costs_{\Delta v} = \Delta PVC_{\Delta v} + \Delta PVEC_{\Delta v} + \Delta PVOC_{\Delta v} + \Delta PVDC_{\Delta v}\ .$$

Because it is a new set of emission standards that is causing the change in v, any decreases in the terms on the right side of equation (9) are the benefits of the standards. Likewise any increases are interpreted as costs of the standard. The net benefit of the standards is the given by the negative of $\Delta lifecycle\ costs_{\Delta v}$.

These benefits and costs of the standards as described here are not the total benefits and costs of the policy. They are per-vehicle in the sense that they are the benefits and costs of the policy that result when a single vehicle meeting a new standard is purchased and operated instead of a similar vehicle meeting the previous standard. To obtain the total benefits and costs of the new standards over some time period, the number of vehicles sold over that time period must be estimated.

Without new standards, some number of new vehicles would be purchased each year, and some number of older vehicles would be removed from service. New standards affect this process because they increase the purchase price of new vehicles. Specifically, the standards result in increased vehicle sales before the standards are implemented and decreased sales for some period of time after implementation. The decrease in sales after implementation results from several factors. Much of the decrease is likely due to the fact that some older vehicles were replaced before than they would have been in the years prior to the new standards. The decrease in sales could also result from delayed retirement of some older vehicles, or a shift to other forms of transportation.

If fleet turnover is assumed to be unaffected by new standards, it is unclear in which direction this will bias the estimated total net benefit of the standards. Increased sales before implementation implies a higher net benefit because older vehicles are replaced before they otherwise would be. However, the decrease in sales after implementation implies a lower net benefit. This is complicated by the fact that there may be a shift to other forms of transportation that are now relatively less costly. These other forms of transport may be more or less polluting than transportation by truck. Quantifying these effects on fleet turnover is beyond the scope of this analysis, and it will be assumed that fleet turnover is independent of the standards.[17] The effects described above tend to offset each other, and as the time frame of analysis is extended, this assumption will matter less. Although the standards may delay the replacement of some older vehicles, these vehicles must be replaced eventually. This delay actually implies an eventual faster rate of turnover when these vehicles are replaced. Given this assumption, the total net benefit of the standards is given by

[17] NERA (2008) claims the standard's impact on fleet turnover tend to lower the net benefit of the standards. This tends to reinforce the results from this analysis.

(10) $$total\ net\ benefit = \ {}_{0}^{M} \frac{sales_m * \Delta lifecycle\ costs_{\Delta v}}{(1+r)^{m/12}},$$

where $sales_m$ is the number of new vehicles sold in month *m*.

Chapter Six: Parametric Calibration

6.1 Truck Class

Calculating the total net benefit according to the above equations requires the calibration of a number of parameters. It should be pointed out that the heavy-duty diesel vehicle class is not a homogenous class. It includes eight sub-classes of vehicles with gross weight ratings ranging from 8,500 lbs to more than 60,000 lbs. This makes parametric calibration difficult because many of the parameters depend on the sub-class of the vehicle being considered. An analysis using all heavy-duty vehicle sub-classes is beyond the scope of this research, although the methodology would be the same. The approach taken here is to focus on a single sub-class of heavy-duty trucks. The result of this approach is that the calculated net benefit will be the net benefit of the standards applied to that sub-class alone. While not a complete analysis, it illustrates the method and allows one to judge the efficiency of the standards applied to the sub-class considered.[18]

The sub-class used in this analysis will be class 8 trucks. These are trucks with gross weight ratings of more than 33,000 lbs and are powered nearly exclusively by diesel engines. Most of the trucks in this subclass are tractor-trailers typically used to transport goods over long distances. This sub-class was chosen because of the large number of these trucks in use, the large number of miles they travel, the amount of

[18] This is also valuable information given there is no reason identical standards must be applied across sub-classes and fuel types.

information available about the trucks and their use, and the fact that substitution into gasoline vehicles is unlikely.

6.2 Production Costs

There is no need to estimate total production costs of these trucks. It is only the change in private production cost due to the standards that matters. 2007 emissions achieved by the 2007-compliant trucks required several changes relative to the 2004-compliant trucks. The primary technology used to achieve 2007 emissions was the catalyzed diesel particulate filter (DPF). This device reduces PM emissions by trapping the PM and periodically or continuously burning it off through a process called regeneration. Retarded injection timing and increased rates of exhaust gas recirculation (EGR) were also used to address NOx emissions. NOx emissions are dependent on combustion temperatures, which are reduced by both of these changes (Majewski and Khair 2006). The costs associated with retarded injection timing and increased EGR rates are relatively small since they are modifications to already existing systems. Cooled-EGR had been in use since 2002 and retarded injection timing was accomplished with existing fuel injection systems (Moore 2003).

Estimates of the cost of these changes are based on statements from industry sources regarding price increases associated with 2007 emissions. A cost estimation approach based on price increases is valid because the changes made to the vehicle have not increased demand for the trucks. DPF technology, in particular, increases maintenance costs and was viewed with uncertainty by consumers. Additionally, changes made to lower combustion temperatures typically result in a fuel economy penalty. Any negative impact on fuel economy is a major concern for consumers in this market due to the already high fuel costs. Given that the technologies do not increase demand, the price increase is actually a lower bound for the production cost increase. No manufacturer would increase price by more than the cost increase if the cost increase results from technology that makes the truck less desirable. Price increases reported by five major manufacturers are given in Table 6.1. The average of the reported values is $7,410, which

Table 6.1 - Price Increases from 2007 Emissions

Source	Low	Central	High
Isuzu (FleetOwner 2008)	$3,000		$10,000
International (Kilcarr 2006)	$7,000		$10,000
Detroit Diesel (Kilcarr 2006)		$6,638	
Volvo (Kilcarr 2006)		$7,500	
Mack (Kilcarr 2006)		$7,000	

will be the estimate used here. This cost, however, is likely to fall over time. Primary results will be based on the assumption that it falls by 50% after five years, which is roughly consistent with US EPA (2000). Results of alternative assumptions will be presented in the sensitivity analysis.

2010 emissions achieved by the 2010-compliant trucks relied on several other changes. The challenge of 2010 emissions is achieving a significant reduction in NOx emissions while maintaining the ultra-low PM emission levels achieved by the 2007-compliant trucks. Meeting this challenge has required the use of selective catalytic reduction (SCR) technology. The technology consists of a catalyst located in the exhaust system downstream of the DPF, as well as an injection system for the urea and water solution consumed as a reductant (Majewski 2005). SCR systems are so effective at controlling NOx emissions that EGR-rates can be reduced and injection timing advanced relative to 2007-compliant truck levels (Sturgess 2008a). Again, the cost of these changes is based on reported price increases. Kilcarr (2007) reports that DaimlerChrysler claims an increase in price of $4,000, while Carretta (2009) reports that Volvo estimates a $9,600 increase in price. Sturgess (2009) believes that 2010 trucks will be between $6,000 and $10,000 more expensive due to the improved emission performance. The average of the estimates is $7,400 which will be the estimate used in this analysis. Again, it will be assumed that this cost falls by 50% after five years, although results of alternative assumptions will also be examined.

6.3 Annual Miles Traveled and Useful Life

In order to calculate total fuel consumption and emissions over the life of a vehicle, the miles of travel each year and the number of years it is in use must be estimated. Knowing the average number of miles traveled and average age when scrapped is not sufficient. When benefits and costs are calculated for future years, those values must be discounted. Therefore, it is preferable to know the number of miles traveled in each year. Unfortunately, lack of data prohibits precise estimation of this.

Miles traveled by a vehicle typically decline over the course of its life. Additionally, there is some probability that the vehicle will be taken out of service during any year due to accidents or expensive repairs. Data is available that describes how miles of travel per year decline as a vehicle ages. Given this data and information on survival rates, it would be possible to derive the expected value for miles travelled each year over some period of time. Unfortunately, the data that would allow derivation of survival rates is not sufficient. Estimation of survival rates requires data on sales for past years as well as current registration data that indicates how many of those older vehicles are still in use. This data is available, but it in recent years, reported registrations for some model years exceed new sales of that model year. This makes use of such data highly questionable. Therefore, no attempt is made to estimate survival rates.

This analysis will make use of the data on miles travelled by different ages of vehicles in a different way. The EPA has estimated average annual miles travelled for different ages of vehicles for use in their MOBILE 6 model. This data is available for different classes of heavy-duty trucks. The time series is 30 years long. Concluding that this represents the annual miles of travel for the average vehicle is implicitly making the assumption that average survival rates are 100% for all years. Most class 8 vehicles do not last 30 years. The time series does, however, give a good indication of the expected lifespan of a vehicle in terms of miles, if it does survive for a long period of time. Therefore, the sum of the time series will be used to calculate a useful life estimate for the various classes. Table 6.2 shows the estimated average annual miles of travel by vehicle year as well as the expected useful life of each class of vehicle. It will then be assumed that the typical class 8 vehicle travels 120,000 miles per year (Sturgess 2008b). This leads to a lifespan of 8.5 years based on the average useful life of 1,019,623 miles for class 8 trucks. This estimated travel of 120,000 miles per year is also consistent with most other industry estimates. For example, most literature that calculates annual operating costs of class 8 vehicles does so based on 120,000 miles travelled each year.[19]

6.4 Location of Vehicle Use

[19] An example is Cummins (2009).

The area in which a vehicle is used is important because damages from emissions will vary across areas. Damages in urban areas will be high due to large populations and high population densities. Additionally, the ambient levels of pollutants may be higher in

Table 6.2 - Estimated Miles Traveled by Age

Vehicle Age	Class 8B	Class 8A	Class 8 Average	Class 6 and 7	Class 2B
1	124208	87821	106014.5	40681	27137
2	112590	78257	95423.5	36872	24831
3	102060	69735	85897.5	33420	22721
4	92514	62141	77327.5	30291	20791
5	83861	55374	69617.5	27455	19024
6	76017	49343	62680	24885	17407
7	68907	43970	56438.5	22555	15928
8	62462	39181	50821.5	20443	14575
9	56620	34915	45767.5	18529	13336
10	51324	31112	41218	16795	12203
11	46523	27724	37123.5	15222	11166
12	42172	24705	33438.5	13797	10217
13	38228	22015	30121.5	12505	9349
14	34652	19617	27134.5	11335	8555
15	31411	17481	24446	10273	7828
16	28473	15577	22025	9312	7163
17	25810	13881	19845.5	8440	6554
18	23396	12369	17882.5	7650	5997
19	21208	11022	16115	6933	5488
20	19224	9822	14523	6284	5021
21	17426	8752	13089	5696	4595
22	15796	7799	11797.5	5163	4204
23	14319	6950	10634.5	4679	3847
24	12979	6193	9586	4241	3520
25	11765	5518	8641.5	3844	3221
26	10665	4918	7791.5	3484	2947
27	9667	4382	7024.5	3158	2697
28	8763	3905	6334	2862	2468
29	7944	3480	5712	2594	2258
30	7201	3101	5151	2352	2066
Total	1,258,185	781,060	1,019,623	411,750	297,114

urban areas implying higher marginal damages. Unfortunately, there is no data available which indicates the proportion of urban or rural travel by heavy-duty vehicles. Some vehicles, especially class 8 vehicles, are used to transport goods over long distances. This seems to imply that the majority of their travel takes place in rural areas. However, some class 8 vehicles may spend the majority of their time in urban areas (e.g. some fuel tanker trucks). Because there is nothing to base an assumption on, a variety of scenarios will be examined. However, as a starting point, a “best guess” of 75% rural and 25% urban travel will be used.

6.5 Fuel Economy and Carbon Emissions

The fuel economy estimate used here is based on two sources. The EPA reports an estimate of 7.3 MPG for 2010 (US EPA 2000). This is based on a linear extrapolation of data prior to 2000. Huai et al. (2006) reports an estimate of 6.6 MPG based on data downloaded from vehicles sold between 1995 and 2000. It will be assumed here that the 2004-compliant vehicle achieves 7.0 MPG. Estimates for the other two versions of the vehicle are based on the effects of methods used to reduce emissions from these vehicles. Most manufacturers are reporting 3% to 5% better fuel economy for 2010 trucks. Table 6.3 presents these estimates. This fuel economy improvement is a result of the adoption of SCR. SCR systems are very effective at controlling NOx emissions which has allowed manufacturers to reverse some of the changes made to 2007 trucks. Specifically, the fuel economy improvement observed for 2010 trucks results from the ability to reduce EGR rates, advance injection timing, and reduce or eliminate active regeneration of the DPF

(Leavitt 2009). Reduced EGR rates and advanced injection timing allow for more complete combustion which improves fuel economy and increases NOx emissions. The

Table 6.3 - Industry Statements about 2010 Fuel Economy

Brand	Fuel Economy Improvement in 2010 Vehicles Relative to 2007-2009 Vehicles	Source
Volvo	5%	Kilcarr (2007)
All EU Trucks	<7%	Kilcarr (2007)
Volvo and "other" brands	>3%	Mele (2009)
All	3%	Sturgess (2009)
Detroit Diesel	<5%	Detroit Diesel (2009b)
Cummins	<5%	Cummins (2009)

increase in NOx emissions increases passive regeneration of the DPF and, therefore, reduces the need for active regeneration. Active regeneration increases fuel use because it requires the injection of additional fuel (Majewski and Khair 2006). The increase in NOx emissions is then addressed downstream of the DPF by the SCR system.

Manufacturers did not want to advertise the fact that 2007 trucks achieved lower fuel economy than previous trucks, so there are no statements from these manufacturers available on which to base an estimate of the decrease in fuel economy for 2007-compliant trucks. The approach used here will be to assume the improvement in 2010-compliant trucks exactly offsets the loss in 2007-compliant trucks. This is a reasonable assumption given the way in which the gain was achieved in 2010. The factors that led to the gain in 2010 were reversals of changes that caused the loss of fuel efficiency in 2007. As a starting point it will be assumed the loss in 2007-compliant trucks and the improvement in the 2010-compliant trucks is 4%. This is based on the median of the range of reported improvements in 2010 trucks. This assumption yields a fuel economy of 6.731 MPG for the 2007-compliant truck and 7.0 MPG for the 2010-compliant truck.

Carbon dioxide (CO_2) emissions are almost strictly a function of fuel consumption, so these fuel economy estimates yield estimated CO_2 emissions of 1440.571 grams per mile for the 2004- and 2010-compliant trucks and 1498.143 grams for the 2007-compliant trucks based on the carbon content of one gallon of diesel.

6.6 Emission Rates

Regulated pollutant emission rates of the three versions of the trucks are based on certification data provided by the EPA (US EPA 2009a). This certification data is emission test results reported to the EPA by manufacturers in order to prove their engine or truck meets current standards. Table 6.4 presents the emission rates for each version of

Table 6.4 - Average Emission Rates for Regulated Pollutants for Class 8 Heavy-Duty Diesel Vehicles (g/mi)

Version	NOx	PM	NMHC	VOC
2004-compliant	6.657	0.211	0.287	0.300
2007-compliant	3.508	0.009	0.061	0.065
2010-compliant	0.533	0.009	0.061	0.065

the vehicle. Emission rates for the 2004- and 2007-compliant vehicle are based directly on certification data. Certification data for 2010-compliant vehicles is not yet available, so these emission rates are assumed to be equal to those for 2007-complaint vehicles with the exception of NOx emissions. 2010 emissions require full compliance with the new NOx standard, and it is assumed this will be achieved with an eight percent margin of compliance[20]. Reported PM emission rates are the sum of emissions of $PM_{2.5}$ (particles less than 2.5 μm in diameter) and PM_{10} (particles less than 10 μm in diameter but excluding $PM_{2.5}$). US EPA (2000) estimates that greater than 90% of PM emissions from

[20] This is consistent with US EPA (2000)

diesel vehicles are $PM_{2.5}$. For the purposes of this analysis it is assumed to be 95%. It should be noted that certification data is expressed in g/bhp-hr, and the estimated rates in Table 6.4 have been converted according to conversion factors reported by US EPA (2002b). Additionally, volatile organic compound (VOC) emission rates have been derived from reported non-methane hydrocarbon (NMHC) according to conversion factors reported by US EPA (2005a).

Several types of non-regulated emissions also need consideration. These include black carbon (BC), sulfur dioxide (SO_2), and ammonia (NH_3). Although black carbon emissions have not typically received attention in discussion of emission standards, interest has increased in recent years due to black carbon's significant climate change impacts. Historically, diesel vehicles have been major emitters of black carbon. US EPA (2002a) estimates that 75% of $PM_{2.5}$ emissions from diesel trucks are black carbon. This will be the estimate used in this analysis. Although not a regulated pollutant from on-road mobile sources, SO_2 emissions have been affected by the standards and should be included in the analysis. SO_2 emission rates are based on the calculation method used in US EPA (2000), but adjusted for different fuel economy estimates.[21] They are primarily a function of the sulfur content of the fuel as well as the presence of a DPF.

NH_3 emissions should be included in the analysis because a by-product of the process used by SCR to reduce NOx emissions is NH_3.[22] NH_3 emission rates are based on results from Block et al. (2005), in which the authors calculated emission rates for a diesel truck without a DPF or SCR system, with a DPF only, and with a DPF and SCR system. It is assumed that the NH_3 emission rate for the truck with neither technology is

[21] See Appendix D for more details.
[22] This undesirable result is commonly called ammonia slip.

indicative of NH_3 emissions from a 2004-compliant truck. Likewise, the other two results are assumed to be indicative of emissions from a 2007-compliant and 2010-compliant truck. Table 6.5 summarizes the estimated emission rates of non-regulated pollutants.

Table 6.5 - Average Emission Rates for Non-Regulated Pollutants for Class 8 Heavy-Duty Diesel Vehicles (g/mi)

Version	BC	SO_2	NH_3
2004-compliant	0.150	0.888	0.491
2007-compliant	0.006	0.014	0.095
2010-compliant	0.006	0.013	0.263

6.7 Marginal Damages

Assumptions made about marginal damages are critical to this analysis. The purpose of any new set of emission standards is to reduce pollution. This benefit will be monetized according to the assumed marginal damages. As used here, the term "marginal damages" refers to the external cost associated with an additional unit of some pollutant. These assumed values are multiplied by the per-mile emission rates, which yields per-mile external costs. The assumed values will be based on estimates reported in the literature.

It should be pointed out that any true marginal damage function is likely to indicate that marginal damages increase as emissions increase. However, this analysis will assume that marginal damages are constant. This is not an unreasonable assumption. The change in emissions that results from any new standard applied to heavy-duty vehicles is probably quite insignificant relative to the total emissions from all sources. This implies that any new standards would represent a small movement along the marginal damage curve. Thus, assuming constant marginal damages over the range of emissions considered here would not significantly affect the results.

Within the literature, there are various terms that refer to marginal damages. These include unit damages, emission values, marginal external costs of emissions, and pollution costs. Two general approaches have been used by studies that estimate marginal damages of non-greenhouse gas emissions. The first is based on estimation of abatement costs. As emissions increase, marginal damages increase and marginal abatement costs fall. The increase in marginal damages is primarily due to some level of tolerance that human and ecosystems typically have for pollution. Thus, a small amount of pollution will not have much effect, but as pollution increases, that tolerance is exhausted and the damages increase. Marginal abatement costs fall as emissions increase because it is reasonable to expect lowest-cost means of abatement to be implemented first. Theoretically, the ideal emission standard for some pollutant is set where marginal damages equal marginal abatement costs. The resulting level of emissions will be the level that minimizes the sum of abatement costs and damages. Note, however, that at any alternative standard the marginal abatement cost and marginal damage will not be equal.

The control cost approach estimates abatement costs in order to estimate marginal damage.[23] The implicit assumption is that the standards are set at the ideal level. While it might be hoped that policy makers would set standards in such a way, it is highly unlikely. Even if the policy maker's objective was to set the standard in such a way, it would require large amounts of information including, ironically, the damage costs. Regardless, setting an efficient standard is rarely the objective. The process is usually

[23] See, for example, Bernow and Marron (1990) and Schilberg et al. (1989).

political in nature and is therefore influenced by many interests. For these reasons, this approach is inadequate.

The alternative to the abatement cost approach is to directly estimate the costs of the various types of damage. There are many types of damages that result from the pollutants of concern in this analysis. These damages include impacts on human health, decreased crop and forest yields, degradation of recreation sites, visibility impacts, and materials damage. The basic steps involved in this approach are as shown in Table 6.6.

Table 6.6 - Steps to Estimating Marginal Damages[24]
1. Identify emission sources
2. Estimate emissions from sources
3. Model impact of emissions on ambient concentration
4. Estimate human and non-human exposure based on ambient concentration
5. Determine effects of exposure
6. Assign Costs to effects

Several can be problematic. The effect that emissions have on ambient concentrations is difficult to determine. The relationship depends on many factors, including weather conditions, geographical location, air pollutant dispersion, reaction, and residence. Additionally, the relationship is often non-linear. In practice, complex computer models are used to model this relationship as well as predict human exposure (Wang and Santini 1994).

The effects of human exposure to some of the pollutants may include premature death, disability, medical expenses, and discomfort. These are estimated by various means. Medical expenses are often relied on because they are actually observed, but are

[24] These steps are based loosely on those reported in Wang and Santini (1994).

insufficient when used alone. The value placed on human life (value of statistical life or VSL) often makes up a large portion of the damages and its estimation and use can be quite controversial. Decreases in agriculture and forest yields are fairly straightforward to estimate. Typically, statistical analysis is used to determine how ambient concentrations effect yields. These products have a market price, which makes assigning monetary values to the lower yield simple. Damages due to degradation of recreation sites may be estimated by contingent valuation or the travel cost method. Materials damages may also be relevant and can be estimated based on increased maintenance costs or the cost of avoidance behavior.

While the damage estimation approach to estimating damages is theoretically more sound than approaches based on estimation of abatement costs, it is not without problems. In each of the steps above, additional uncertainty is introduced. Compounded, the uncertainty can lead to inaccurate results or low-confidence in reported results. Nevertheless, this is the approach used by the estimates relied on in this analysis.

There have been many studies that attempt to estimate marginal damages based on direct estimation of the damages. The remainder of this section will provide an overview of the various estimates while providing justification for those chosen to be used here. An often cited study is Wang and Santini (1994). The authors do not actually conduct their own analysis, but instead extend the results of previous work.[25] They use regression analysis to determine the link between marginal damages, ambient concentrations, and population. The dependent variable in their regression was marginal damages as estimated by previous studies for specific areas. Ambient concentration and

[25] These studies were Eco Northwest (1987), Regional Economic Research, Inc. (1990, 1991, 1992a, 1992b), National Economic Research Associates (1993), and Ottinger et al. (1991)

population were the dependent variables. Separate regressions were run for the various pollutants, and the estimated functions were then used to predict damages for areas of the country for which no damage estimates existed.

The results from Wang and Santini (1994) have since been modified by Victoria Transport Policy Institute (2005). In this study, the results from Wang and Santiti (1994) were adjusted for inflation and then used to estimate rural marginal damages according to an adjustment process based on Holland et al. (2005).

Despite their acceptance in the literature, estimates based on Wang and Santini (1994) are not used in this analysis for several reasons. First, the original studies are from the early 1990's. Since that time, there have been considerable changes in ambient air quality and population size. Significant changes in these can impact marginal damage estimates. Specifically, improvements in ambient air quality should lower marginal damages, while increases in population should increase those damages. An update of the original studies based on these changes is beyond the scope of this analysis. Additionally, it is unclear how the estimates should be adjusted for use in rural areas. While such an adjustment was made by Victoria Transport Policy Institute (2005), the method of adjustment is questionable. Holland et al. (2005) calculated the difference between their urban marginal damage estimates and rural estimates from Holland and Watkiss (2002). These calculated differences were then used by Victoria Transport Policy Institute to adjust the Wang and Santini (1994) estimates. Given the significant variation among all estimates of marginal damages, it seems unlikely that the calculated difference between one set of urban estimates and one set of rural estimates would be representative of the true relationship. Additionally, Holland et al. (2005) and Holland and Watkiss (2002) produce estimates for European areas. Given Europe's greater population densities, it is unclear if these results, or the urban/rural differences they indicate, would apply to the U.S.

A more recent estimation of marginal damages comes from a line of work by Mark Delucchi at the University of California's Institution of Transportation Studies. The damages estimated include those related to human health, crop damage, and visibility degredation. The methodology used to value health impact of emissions in McCubbin and Delucchi (1999) is generally based on the approach described in Table 6.6.

The authors first estimated emissions using the EPA's MOBILE model for vehicle emissions as well as stationary source models. Next, data from previous years on emissions and ambient concentrations was used to estimate the relationship between those two variables. This made it possible to predict how a proposed change in emissions will impact ambient concentrations. An advantage of this approach is that it is less reliant on complex air quality models such as those used by the EPA in their impact analyses on new emission standards.

Exposure-impact functions are then estimated which express the health effects of air pollution as functions of ambient concentrations, a change in ambient concentrations, and population size and location. The authors constructed these exposure-impact functions based on a review of clinical, animal, and epidemiological studies that linked pollution with negative health effects. The last step is the monetization of the negative health effects. The authors base health values on previous studies and construct ranges for each health characteristic. These health values were then used to calculate total and marginal health costs resulting from motor vehicles.

Murphy et al. (1999) employs a methodology similar to McCubbin and Delucchi (1999) to estimate agriculture-related damages. This study indicates that virtually all crop damage due to pollution is due to ozone or some combination of pollutants including ozone. Emissions are estimated and the link between emissions and ambient concentrations established. Instead of estimating impact-response functions, yield-response functions are estimated which link ambient concentration to yields. This is typically done using regression analysis on past data. Market prices of the commodities are then used to value changes in yields that result from changes in emissions.

Delucchi et al. (1996) estimates damages from reduced visibility. To estimate these damages the authors of that study determined how emissions affected visibility and then valued those reductions using hedonic prices. Specifically, they estimated willingness-to-pay for improved visibility was based on Smith and Huang (1995) which was a meta-hedonic price analysis.

The results of McCubbin and Delucchi (1999), Murphy et al. (1999), and Delucchi et al. (1996) were not used in this analysis for several reasons. First, while each study estimates marginal damages, the results are very uncertain. This leads to a wide range of estimates. Constructing a range for the full marginal damages by summing the individual marginal components then gives an extremely large range. This level of uncertainty is clearly undesirable. A second reason these studies were not utilized is their age. They are from more than ten years ago, and it is unclear how marginal damages may have changed since that time. Third, marginal damages associated with human health are not broken down into separate urban and rural marginal damages. Although estimates are provided specifically for urban areas, it would be more desirable to have both.

Marginal damage estimates used in this analysis come from Muller and Medelsohn (2007), which applies a new integrated assessment model to estimate damages. The air quality model links 2002 county-level emission inventories of NH_3, NOx, $PM_{2.5}$, PM_{10}, SO_2, and VOC with county level ambient concentrations of NOx, $PM_{2.5}$, PM_{10}, SO_2, VOC and ozone (O_3). County level inventories of crops, trees, people, materials, visibility resources, and sensitive ecosystems are used to estimate exposure. Concentration-response functions from peer-reviewed studies are used to estimate physical impacts of the exposure, which are then monetized to obtain a total damage estimate.

Emissions are then increased one source at a time and total damages recalculated. This provides a marginal damage estimate for each source. To obtain a general rural marginal damage estimate, the marginal damages for all sources in rural counties are averaged. The general urban marginal damage estimate is calculated using the same method. Table 6.7 presents the resulting marginal damage estimates. These marginal

Table 6.7 - Marginal Damages ($/kg)

	NOx	$PM_{2.5}$	PM_{10}	VOC	SO_2	NH_3
Urban	0.413469	4.548154	0.689114	0.689114	2.067343	5.788559
Rural	0.413469	1.516051	0.275646	0.413469	1.240406	1.516051

damage estimates are the most desirable for several reasons. First, they incorporate many types of damages and all are estimated using a consistent methodology. They also provide damage estimates for all of the relevant air pollutants, while breaking down damages into urban and rural components. Furthermore, they are recent estimates from a study published in a leading journal and appear to be well accepted in the literature.

The marginal damages of CO_2 and BC are based on an estimate from Tol (2009) of $0.078 per kilogram CO_2. This is the mean estimate at a 3% discount rate that results from a meta-analysis of 232 different estimates[26]. Reynolds and Kandlikar (2008) estimate that the global warming potential (GWP) of BC is 455.[27] This estimate is roughly consistent with estimates from Hansen et al. (2007), Bond and Sun (2005), and Berntsen et al. (2006). This implies that a single kilogram of BC has about 455 times the impact that a single kilogram of CO_2 has. Thus, the marginal damage estimate for BC will be 455 times that of CO_2.

6.8 Operating and Maintenance Costs

As with vehicle production costs, the total operating costs of the vehicle do not need to be estimated. It is only the difference in operating costs across the versions of the vehicle that is needed. The 2007-compliant trucks have higher operating costs than the 2004-compliant trucks due to maintenance of the DPF. This cost is assumed to be $367 per year based on an estimate reported by Kilcarr (2006). The 2010-compliant trucks will, in addition to the DPF maintenance, require replenishing of the urea and water solution consumed by the SCR system. It has been estimated that the cost of this will remain between $2 and $3 per gallon, while estimates of consumption rates range from 1% to 3% of fuel consumption (Sturgess 2008b, Cummins Filtration 2009).

6.9 Emissions from Fuel Production and Distribution

Vehicle exhaust is not the only source of emissions resulting from vehicle operation. Production and distribution of diesel fuel also causes pollution in the form of a

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[26] Also see Tol (2005) and Tol (2008).
[27] GWP of CO_2 is one.

variety of air pollutants. These emissions occur during the extraction and transport of crude oil, the refining of diesel fuel, and the distribution of that fuel to retail outlets.

To estimate the emission rates that result from these processes, this analysis relies on the GREETUI program developed at the Argonne National Laboratory.[28] GREETGUI combines the GUI (graphical user interface) program with the underlying GREET model.

The GREET (greenhouse gases, regulated emissions, and energy use in transportation) model is a spreadsheet based simulation that calculates emissions of various pollutants and energy use for various scenarios of energy production and transportation methods. For a given scenario, it calculates energy use at every step. The fuel cycle is broken down into two parts: well-to-pump and pump-to-wheels. The well-to-pump component calculates the energy used to produce the various fuels and transport them to the end user. The use of energy to produce fuel results in emissions from the production and combustion of the various fuels that provide this energy. The pump-to-wheels component calculates emissions that come from the vehicle itself. Users can specify various mixes of transportation methods such as different mixes of fuels and vehicle types. This allows the evaluation of alternative mixes in terms of total emissions and energy use.

This analysis makes use of the well-to-pump component of the model. It relies on the default production assumptions in order to calculate the well-to-pump emissions of ULSD. Table 6.8 describes these assumptions. These assumptions as well as others that are embedded in the model are used to arrive at the emission rates shown in Table 6.9. GREET breaks the emissions down by urban and rural categories, which proves

[28] This model is available for download at http://www.transportation.anl.gov/modeling_simulation/GREET/index.html.

useful in this analysis because damages are likely to be greater in urban areas.

Table 6.8 - Description of Key GREET Assumptions

Diesel Fuel Type	ULSD
Crude Recovery Efficiency	98.0%
LSD Refining Efficiency	89.30%
Residual Oil Utility Boiler Efficiency	34.8%
NG Utility Boiler Efficiency	34.8%
NG Simple Cycle Turbine Efficiency	33.1%
NG Combined Cycle Turbine Efficiency	53.0%
Coal Utility Boiler Efficiency	34.1%
Electricity Transmission and Distribution Loss	8.0%
Energy intensity in HTGR reactors (MWh/g of U-235)	8.704
Energy intensity in LWR reactors (MWh/g of U-235)	6.926
Electricity Use of Uranium Enrichment (kWh/SWU): Gaseous Diffusion Plants for LWR electricity generation	2,400
Electricity Use of Uranium Enrichment (kWh/SWU): Centrifuge Plants for LWR electricity generation	50.0
Electricity Use of Uranium Enrichment (kWh/SWU): Gaseous Diffusion Plants for HTGR electricity generation	2,400
Electricity Use of Uranium Enrichment (kWh/SWU): Centrifuge Plants for HTGR electricity generation	50

Table 6.9 - Emissions from Diesel Production and Distribution (g/gal)

Pollutant	Total	Urban	Rural
NOx	5.945	1.283	4.661
$PM_{2.5}$	3.470	0.932	2.538
PM_{10}	8.676	1.603	7.073
VOC	1.081	0.416	0.665
SO_2	20.615	6.588	14.027
GHG (g CO_2 equivalents)	2,526.309	N/A	N/A

6.10 Production Cost of Diesel Fuel

The production cost of diesel fuel is relevant to this analysis because methods used to comply with new emission standards may affect fuel economy. The Energy

Information Administration (EIA) reports that the average price of ULSD over the past year has been approximately $2.694.[29] Estimation of production costs based on this price uses information from the EIA regarding the relative contribution to the retail price of diesel fuel of factors affecting those prices. In May of 2008, the EIA reported a national average retail price of $4.43 for diesel fuel. It estimates that 10% of this price can be attributed to taxes, 21% to refining costs, 64% to crude oil, and 5% to distribution and marketing (EIA 2008).

To derive a production cost estimate from this information, two reasonable assumptions are made. It is assumed that any profit is accounted for in the distribution and marketing category. It is also assumed that the actual size of the distribution and marketing category is not a function of price. Thus, based on the above information, distribution and marketing accounted for 22.15 cents of the total price. Taxes currently total 47.02 cents based on the national average of current state taxes and the current federal tax (EIA 2009). This yields a price net taxes of 222.4 cents. It is unknown how much of the 22.15 cents per gallon is attributable to price exceeding production and distribution costs. Therefore, it will be assumed that the difference could be as low as zero or as high as 22.15 cents.[30] Based on the average price over the last year, this yields an estimated production cost of $2.002 to $2.224 per gallon. As a starting point, this analysis will make use of the midpoint of this range: $2.113. Given that these values were based on a time series that started in 2008, it is assumed that these values are expressed in 2008 dollars.

[29] This is based on national averages reported by EIA from the first week of each month beginning in August 2008. See http://tonto.eia.doe.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm.
[30] Obviously, distribution costs must be non-zero, but allowing them to take that value avoids making an arbitrary assumption about their value.

The above applies to ULSD, but an estimate is also needed for LSD. This is because the 2007 standards force the adoption of ULSD, so accounting for the full costs of these regulations will require estimates of production costs for both types of diesel.

There are two sets of estimates that can be used to calculate the cost of LSD. In their regulatory impact analysis of the 2007 standards, the EPA concluded that in the short run ULSD will cost about 6.3 cents more per gallon, while in the long run the cost increase will fall to 5.6 cents per gallon. Alternatively, EIA places the cost increase at 6.6 to 9.2 cents per gallon (EIA 2001).[31] Based on these two sources, it will be assumed that the cost increase will fall between 5.6 and 9.2 cents. A middle-of-the-road value of 7.4 cents will be used as a starting point.

[31] Both sets of estimates have been corrected for inflation and are expressed in 2008 dollars.

Chapter Seven: Results

The results presented in this section are calculated using "best guess" parameter estimates. When there is a range of possible values for some parameter, the midpoint of the range is used. Location of vehicle use is assumed to be 75% rural, 25% urban and the discount rate is set at 2.5%. There are two per-vehicle net benefit results to be presented. The first is the net benefit of purchasing and operating a 2007-compliant truck rather than a 2004-compliant truck. The second is the net benefit of purchasing and operating a 2010-compliant truck rather than a 2004-compliant truck. Table 7.1 presents the changes

Table 7.1 - Costs Relative to 2004-Compliant Truck

	ΔPVC (Tech.)	ΔPVEC (External)	ΔPVOC (Operating)	ΔPVDC (Fuel)	Δ Lifecycle Cost
2007-Compliant Truck	$7,410	-$4,385	$2,817	$22,008	$27,850
2010-Compliant Truck	$14,810	-$9,247	$9,395	$9,736	$24,695

in the costs that appear in Equation (9). The change in the present value of the total lifecycle cost is the negative of the net benefit of purchasing and operating that truck relative to the 2004-compliant truck. It can be seen that there is a substantial negative net benefit associated with the transition from a 2004-compliant truck to a 2007-compliant truck. The result is similar when comparing the 2004-compliant truck to the 2010-compliant truck, although the 2010-compliant truck does have a small positive net benefit over the 2007-compliant truck. It should be noted that these results are not applicable in the long-run because *ΔPVC* will fall as technology costs fall. Given that the focus of emission standards is reducing the external cost of emissions, it is interesting to examine this in more detail. Table 7.2 lists the external cost associated with each pollutant that

Table 7.2 - External Cost per Vehicle

	NOx	$PM_{2.5}$	PM_{10}	SO_2	NH_3	VOC	BC	$C0_2$
2004-Compliant	$2,535	$420	$4	$1,184	$1,169	$133	$4,905	$103,309.17
2007-Compliant	$1,336	$18	$0	$18	$226	$29	$209	$107,437.85
2010-Compliant	$203	$18	$0	$17	$626	$29	$209	$103,309.17

occurs over the life of a single vehicle. It can be seen that the cost of carbon emissions dominates the other external costs. Thus, the expectation that future regulations in the heavy-duty market will target fuel economy is a reasonable one. These results also point to the need to minimize ammonia slip given it is the single largest non-carbon source of external costs from current trucks.

To obtain a present value of all future benefits and costs, the per-vehicle net benefits reported in Table 7.1 are used in Equation (10) along with estimated vehicle sales for those future years. It should be remembered that these results are for class 8 truck sales only. Therefore, the total net benefit reported here is only the net benefit of the new standards applied to class 8 trucks. The American Trucking Association (2007) reported that annual class 8 sales have been between 150,000 and 300,000 over the last decade. For the purposes of this research, it will be assumed that annual sales will remain constant at 225,000. The calculation of total benefits depends on the range of years considered. Table 7.3 presents results for several different time periods because it is

Table 7.3 - Primary Results

Time Period	Discounted Net Benefit
2007 through 2010	-$18,137,744,728
2007 through 2015	-$43,455,894,014
2007 through 2030	-$82,543,824,033

unclear how many years should be considered. As the analysis is extended into the future, the discounted net benefit would approach some limit. However, this would occur so far into the future that the result would have little meaning because parameter values and vehicle technology may be radically different.

Even for the three time periods considered, there is a tradeoff as the analysis is extended into the future. Although the 2007 through 2030 result is the most comprehensive, it also introduces the most uncertainty. This is because many of the parameter estimates are based on current and historical values. The way these parameters will change over time is uncertain, and the assumptions and predictions about the various parameters may prove inaccurate. It should also be noted that the benefits and costs used to arrive at the above results are the benefits and costs that are created by trucks sold in each time period. Some of these benefits and costs therefore occur in years after the time period because trucks sold during the time period remain in operation after the time period ends. It is necessary to include these to ensure that benefits and costs are correctly matched.

Chapter Eight: Sensitivity Analysis

The net benefits reported in Table 7.3 are sensitive to the parameter estimates used. There is uncertainty associated with all parameter estimates, and the probability of alternative values occurring is unknown. Table 8.1 presents the results of alternative

Table 8.1 - Sensitivity Analysis Results
(change relative to primary results - millions US dollars)

Change	2007-2010	2007-2015	2007-2030
50% change NOx md	±$388 (2.1%)	±$1,748 (4.0%)	±$4,384 (5.3%)
50% change $PM_{2.5}$ md	±$124 (0.7%)	±$359(0.8%)	±$813 (1.0%)
50% change PM_{10} md	±$2 (0.0%)	±$0 (0.0%)	±$4 (0.0%)
50% change VOC md	±$34 (0.2%)	±$94 (0.2%)	±$212 (0.3%)
50% change SO_2 md	±$351 (1.9%)	±$1,032 (2.4%)	±$2,350 (2.9%)
50% change NH_3 md	±$307 (1.7%)	±$623 (1.4%)	±$1,237 (1.5%)
50% change CO_2 md	±$152 (0.8%)	±$2,587 (5.6%)	±$7,895 (9.6%)
0% urban travel	-$465 (2.6%)	-$1,095 (2.5%)	-$2,318 (2.8%)
100% urban travel	$1,394 (7.7%)	$3,286 (7.6%)	$6,954 (8.4%)
no ULSD premium	$6,595 (36.4%)	$17,951 (41.3%)	$39,963 (48.4%)
high ULSD premium	-$1,604 (8.8%)	-$4,366 (10.0%)	-$9,721 (11.8%)
high/low SCR operating costs	$0 (0.0%)	±$6,139 (14.1%)	±$18,037 (21.9%)
75% drop in technology costs	$0 (0.0%)	$1,742 (4.0%)	$10,113 (12.3%)
25% drop in technology costs	$0 (0.0%)	-$1,742 (4.0%)	-$10,113 (12.3%)
50% increase in truck life	-$6,656 (36.7%)	-$12,420 (28.6%)	-$23,594 (28.6%)
best case scenario	$9,347 (51.5%)	$35,561 (81.4%)	$91,962 (111.6%)
worst case scenario	-$10,083 (55.5%)	-$26,066 (59.5%)	-$62,641 (76.1%)

assumptions. It can be seen that no single parameter change affects the sign of net benefit although several of the changes have a significant impact on the results. In particular, fuel costs and SCR operating costs have the largest impact. If the increase in the refining cost of diesel fuel due to the ULSD requirement is less than expected, the net benefit of the standard will be significantly higher. Likewise, if the urea solution consumed by the SCR system is less costly or consumed at a slower rate than expected, the net benefit will again be significantly higher. It should be noted that incorporating all of the positive effects listed above (except a change in truck life) to produce a best case scenario for the 2007-2010 and 2007-2015 time periods is not enough to produce a positive net benefit. For the 2007-2030 time period the same parameter value changes produce only a very small positive net benefit. It can therefore be concluded that the probability of the true net benefit being positive is very low. Unfortunately the probability distributions of the parameter estimates are unknown and it is therefore impossible to accurately assign a probability to such an outcome.

Chapter Nine: Comparison to Results Based on EPA Methodology

The EPA analysis of 2007 standards calculated a net benefit based on the benefits and costs of the standards in the year 2030 only. This section will calculate a net benefit based on this method. However, the parameter estimates used will be those used in this analysis rather than those from the EPA analysis. This makes it possible to compare the methodology used by this analysis and that used by the EPA. The benefits that occur in 2030 as a result of the policy depend on the size of the fleet in that year. Equation (11)

$$fleetsize = \frac{lifespan\ in\ miles}{miles\ per\ month} * sales\ per\ month\ . \tag{11}$$

calculates the size of the vehicle fleet given the average lifespan of class 8 trucks, the number of miles they travel each month, and the number of trucks sold each month. Based on the previous assumptions an average lifespan of 1,019,623 miles, 120,000 miles traveled each year, and 225,000 trucks sold each year, the fleet size in 2030 will be about 1,911,793 trucks. Total emissions from these vehicles will be reduced significantly if these trucks are 2010-compliant trucks instead of 2004-compliant trucks. Table 9.1

Table 9.1 - Benefits and Costs of 2007 Standards Realized in 2030

ΔPVC (Tech.)	ΔPVEC (External)	ΔPVOC (Operating)	ΔPVDC (Fuel)	Total Net Benefit
$1,666,125,000	-$3,501,976,393	$2,340,307,898	$2,425,246,136	-$2,929,702,641

displays the benefit of the reduced emissions as well as the increases in various costs. The increase in fuel costs and operating costs are a function of the per-vehicle cost increases and the total number of trucks on the road in 2030. Consistent with the EPA approach, the change in vehicle production costs is calculated by multiplying the per-vehicle cost increase by the number of new trucks sold in 2030. It can be seen that the net benefit for the year 2030 is much smaller in absolute value than any of the primary results from the methodology developed in this analysis. It is also much different than the EPA result ($85 billion) for several reasons. First, the parameter estimates are different. Second, there are some types of damages included here that were not included in the EPA analysis. Finally, the result presented here is only for class 8 diesel trucks while the EPA analysis included all heavy-duty trucks.

More importantly, there are significant differences in the benefit-cost ratios provided by the different methods. This is a critical result because it shows that the different results are not just a result of different parameter estimates. Table 9.2

Table 9.2 - Benefit-Cost Ratios

single-year (2030)	0.544
2007-2010	0.131
2007-2015	0.215
2007-2030	0.226

displays the benefit-cost ratios calculated according to the single-year method and the method developed in this analysis. The single-year approach yields a much higher ratio because it fails to consider short run impacts of the policy. Annual net benefits are lower in early years of the policy due to higher costs. Additionally, the higher future net benefits are discounted which gives them less weight in the results. The implication of this is that the EPA analysis would have resulted in a much lower net benefit if the benefits and costs in earlier years had been included in the analysis. It is also possible that the inclusion of gasoline vehicles in the EPA analysis had a significant positive effect on the resulting net benefit.

Chapter Ten: Conclusion

The methodology developed here provides several advantages over the methodology used by the EPA to conduct benefit-cost analyses of vehicle emission standards. Importantly, it considers short-run and long-run benefits and costs. The results given in the previous section show that failure to consider short-run impacts of standards can have a significant positive impact on the benefit cost-ratio. This implies an analysis that fails to consider short-run effects will provide an estimate of the net benefit which is overly optimistic.

From a practical standpoint it may also be important to consider short-run impacts. Historically, emission standards have been revised frequently implying the short-run impacts are perhaps the only impacts that will actually be realized. Additionally, as any benefit-cost analysis is extended into the future, the results become less certain. Assumptions must be made regarding the changes in many parameters. An analysis that relies only on these long-run assumptions will provide results that are more uncertain than an analysis that is based at least in part on short-run assumptions.

Another key advantage of the approach developed here is that it relies on marginal damage estimates from the peer-reviewed literature. While these estimates are not necessarily based on a methodology superior to that used by the EPA, they do at least provide more transparency and accountability. This reliance also makes it easier to adapt the methodology here to other emission standards or to modify it in this application. This is because there is no need to model air quality changes and responses for every change in emissions considered. The links between emissions, ambient concentrations, and responses are implicit in the marginal damage estimates and do not need to be reestablished for different emission standards.

The evaluation of the 2007 standards presented here incorporates several other improvements besides the new methodology. First, correct assumptions about the control technologies are made. The EPA analysis was conducted about seven years before the standards were implemented, which resulted in cost estimation based on incorrect assumptions about which control technologies would be used. Specifically, the EPA expected NOx adsorbers to be used to control NOx emissions. Development of this technology has not proceeded at the expected rate, and SCR technology will instead be the technology of choice to control NOx emissions in 2010. The analysis conducted here can also make use of better information about technology costs, because the price increases associated with the technologies are known. The focus here on a single type of heavy-duty vehicle is also important. Although the standards for all heavy-duty vehicles were changed at the same time, there is no reason different types of heavy duty-vehicles must be evaluated together. It is possible that the EPA analysis would have found results more similar to this analysis if the focus had been limited to class 8 trucks powered by diesel engines. However, the benefit-cost ratios provided by the different methods imply that this differing focus is not the sole contributor to the different results.

An additional improvement is the incorporation of damages from black carbon and ammonia emissions from the SCR systems. Black carbon is an important contributor to climate change and the standards have a significant impact on these emissions. Ammonia emissions have been a concern with SCR systems due to ammonia slip. This analysis shows that these two pollutants do not have a significant effect on the overall results, but that they are a significant contributor to the external cost of emissions from these trucks.

This analysis is not without its shortcomings. While changes in vehicle sales resulting from exogenous factors can easily be accounted for, it is unclear how to handle changes in sales that result from the standards. In the long-run, this omission probably has little impact on the results. In the short-run, however, the impact could be significant. Uncertainty surrounding the parameter estimates is also a problem. Despite the inclusion of short-run impacts, the results provided by this analysis remain uncertain as a result. While the sensitivity analysis shows how this uncertainty can affect the results, the probability of alternative results being realized is unknown.

The basic result of this analysis is that the standards provide a net benefit of about -$82.5 billion when they are left in place until the end of 2030. This is a large number, but should not be too surprising given the long time frame, large number of vehicles in operation, and number of miles traveled by each vehicle. This estimate is sensitive to the parameter estimates. Despite this, and given the results of the sensitivity analysis, it can be concluded with reasonable certainty that the net benefit is negative. This has obvious implications in terms of the desirability of the standards, but it also points to the need for more careful analysis in the future. The benefit-cost ratios given by the different methodologies imply that short-run impacts are important and can have a significant impact on the outcomes of benefit-cost analyses. Careful consideration should also be given to the group of vehicles considered. When multiple sets of standards are implemented at the same time, there is no reason they must be evaluated together. Separate analysis of gasoline and diesel trucks, for example, would provide useful information to policy makers and allow for more careful construction of standards applied to those vehicles.

The US 2007 standards have already been implemented, and the results of this particular application of the methodology developed have little direct use as a result. However, the results of this analysis do have important implications for several other sets of emissions standards and for diesel emission standards in general. In the US, PM and NOx aftertreatment technologies are appearing on light-duty vehicles. The use of these technologies on light-duty vehicles is driven by current Tier II standards and California LEV II standards. While Tier II and LEV II standards have been in place for several years, coming (in 2014) Euro 6 light-duty standards in Europe have given manufacturers the incentive to develop vehicles for both markets that incorporate the new technologies. US Tier 4 off-road standards, Japan 2009 heavy-duty standards, and Euro 6 heavy-duty standards will also require both aftertreatment technologies. [32]

While the results of this analysis do not provide definitive evidence that the net benefit of these other standards is negative, it seems probable that this is the case. There may be slight differences in the benefits of the standards due to small differences in required emission rates, but the costs will likely be very similar because the technologies used are the same. Thus, the results of this analysis point to the need for careful consideration of diesel emission standards that have not yet been implemented. This applies to standards that are already scheduled to be implemented (e.g Euro 6), as well as standards that have yet to be written. It appears that diesel emissions reduction, given current technology, has reached a point from which further reduction will not yield a positive net benefit. From a social standpoint, it may therefore be desirable to channel

[32] See Appendix E and F for a detailed discussion of other emission standards.

resources into research that leads to less costly means of emissions reduction before that reduction is required.

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Appendix A: Heavy-Duty Vehicle Classes

Table A.1 - Heavy-Duty Vehicle Classes

Description	Class	Gross Weight Rating (GWR) (lbs)
Light Heavy-Duty Diesel	2B	8,500-10,000
Light Heavy-Duty Diesel	3	10,001-14,000
Light Heavy-Duty Diesel	4	14,001-16,000
Light Heavy-Duty Diesel	5	16,001-19,500
Medium Heavy-Duty Diesel	6	19,501-26,000
Medium Heavy-Duty Diesel	7	26,001-33,000
Heavy Heavy-Duty Diesel	8A	33,001-60,000
Heavy Heavy-Duty Diesel	8B	>60,000

Appendix B: Construction of Table 3.4

Table 3.4 was constructed based on data on emission test results provided by the EPA. Referred to as certification data, these are the results of tests carried out by the manufacturers and then reported to the EPA. The purpose is to ensure compliance with emission standards. The data is available for download from the EPA's website. Table 3.3 reports results for 2005 and 2007. These years were selected to show the effect US 2007 emission standards had on actual emissions. 2005 was selected instead of 2006 to avoid the risk of contaminating the data with engines that may have been intended for sale in 2007.

Construction of Table 3.4 proceeded by first selecting certain engines based on several criteria. First, engines from smaller manufacturers were eliminated. Second, light-duty, non-diesel, and off-highway engines were eliminated. The remaining observations constitute the data used to construct the table. Some of the test results were incomplete, which requires making certain assumptions. In the following tables, the emission rates that are italicized have been estimated. This was done in several ways. If an engine did not have a test result for NOx, NMHC, or NMHC+NOx, but has two of the three reported, the missing data is estimated according to the relationship between the two reported and the missing data. Some engines were missing both NMHC and NOx. For these, the NMHC results reported for the same manufacturer's other engines were averaged and used in place of the missing NMHC result. The NOx data was then calculated based on that NMHC average and the reported NMHC+HC number. If none of a manufacturer's engines had reported NMHC or NOx results, the average of all manufacturers' reported NMHC results was used.

Table B.1 - 2005 EPA Certification Data

Manufacturer	Model	Displacement (L)	NOx	PM	NOx+NMHC	NMHC	CO
Caterpillar	C15	15.2	2.3	0.07	2.4	0.1	1.6
Caterpillar	C13	12.5	2.1	0.1	2.2	0.1	2
Caterpillar	C9	8.8	2.2	0.08	2.3	0.1	1.8
Caterpillar	C9	8.8	2.3	0	2.4	0.1	0.6
Caterpillar	C7	7.2	2.3	0.01	2.4	0.1	0.3
Caterpillar	C7	7.2	2.2	0.1	2.4	0.2	5.2
Caterpillar	C11	11.1	2.3	0.09	2.4	0.1	1.6
Cummins	ISM 500	10.8	2.3	0.1	2.4	0.1	1
Cummins	ISL 330	8.8	*2.942857*	0.01	3.1	*0.157143*	0
Cummins	ISC 280	8.3	*2.142857*	0.01	2.3	*0.157143*	0
Cummins	ISB 260H	5.9	*2.342857*	0.04	2.5	*0.157143*	0.6
Cummins	ISM 450	10.8	2	0.1	2	0	0.6
Cummins	ISM 330ST	10.8	1.8	0.1	2	0.2	0.8
Cummins	ISM 330	10.8	*2.042857*	0.04	2.2	*0.157143*	0.6
Cummins	ISX 500	14.9	2.1	0.08	2.2	0.1	1
Cummins	ISX 450	14.9	2.1	0.08	2.3	0.2	0.8
Cummins	ISB 230	5.9	*1.942857*	0.1	2.1	*0.157143*	1.3
Cummins	ISB 300	5.9	*2.142857*	0.1	2.3	*0.157143*	1.3
Cummins	ISL 280	8.3	*2.542857*	0.07	2.7	*0.157143*	0.5
Cummins	ISC 315	8.3	2.6	0.08	2.7	0.1	1
Cummins	ISB 275	5.9	2.1	0.09	2.2	0.1	1.1
Cummins	ISC 330	8.3	2.7	0.1	3	0.3	2
Cummins	ISL 400	8.8	*2.942857*	0.09	3.1	*0.157143*	4.1
Cummins	ISB 325	5.9	2.3	0.09	2.4	0.1	1.4
Cummins	ISC 260	8.3	*2.642857*	0.09	2.8	*0.157143*	2.2
Cummins	ISL 400	8.9	*2.542857*	0.1	2.7	*0.157143*	2
Cummins	ISC 330	8.3	*2.542857*	0.08	2.7	*0.157143*	1.1
Cummins	ISL 350	8.8	*2.542857*	0.1	2.7	*0.157143*	2.6
Detroit Diesel	Series 60	12.7	*2.282353*	0.081	2.4	*0.117647*	0.72
Detroit Diesel	Series 60	14	*2.282353*	0.08	2.4	*0.117647*	0.5
International	D300	7.6	2.4	0.09	2.4	*0*	
International	D340	9.3	2.3	0.08	2.3	*0*	0.7
International	DG285	7.6	2.3	0.002	2.3	*0*	0
Volvo	VE D12D465	12.1	*2.282353*	0.085	2.4	*0.117647*	0.7

Table B.2 - 2007 EPA Certification Data

Manufacturer	Model	Displacement	NOx	PM	NMHC+NOx	NMHC	CO
Caterpillar	C9	9.3	1	0	1	0	0.4
Caterpillar	C13	12.5	1	0	1	0	1.6
Caterpillar	C15	15.2	0.8	0.01	0.9	0	1.4
Caterpillar	C7	9.3	0.8	0	0.9	0.1	0.8
Cummins	ISB 305	6.7	*1.89*	0	1.9	*0.01*	0.1
Cummins	ISB 350	6.7	*1.6*	0	1.6	0	0
Cummins	ISC 360	8.3	1	0	1	0	0.3
Cummins	ISC 330	8.3	1.14	0	1.1	0	0.1
Cummins	ISL 425	8.8	*1.6*	0	1.6	0	0.2
Cummins	ISL 365	8.8	1.1	0	1.1	0.02	0.1
Cummins	ISM 450	10.8	*2.3*	0	2.3	0	0.1
Cummins	ISM 330	10.8	*2.2*	0	2.2	0	0
Cummins	ISM 500	10.8	*2.3*	0.1	2.4	0.1	1
Cummins	ISM 330ST	10.8	*2.3*	0	2.3	0	0
Cummins	ISM 370	10.8	*2.3*	0	2.3	0	0
Cummins	ISX 435ST	14.9	1.18	0	1.2	0.0038	0.2
Cummins	ISX 500	14.9	1.1	0.01	1.1	0	1.1
Cummins	ISX 600	14.9	*1.9*	0	1.9	0	0
Detroit Diesel	OM460LA	12.8	1.07	0.004	1.08	0.014	0.08
Detroit Diesel	Series 60, 14L	14.0	1.095	0.006	1.11	0.01	0.23
Detroit Diesel	OM926LA	7.2	1.1	0.001	1.12	0.02	0.32
International	GDT300	7.6	1.394	0.001	1.39	*0*	0.34
International	GDT230	7.6	1.018	0.001	1.08	*0.062*	0.94
International	GDT350	9.3	1.626	0.001	1.63	*0.004*	0.51
International	GDT310	9.3	1.596	0.001	1.6	*0.004*	0.52
Volvo	MP7 - 395C	10.8	0.964	0.001	1	*0.036*	0
Volvo	MP8 - 485M	12.8	0.868	0.003	0.91	*0.042*	0
Volvo	D16F-600	16.1	1.019	0.002	1.053	*0.034*	0

Appendix C: Diesel Engine Basics

C.1 Diesel Engine Design and Operation

The diesel engine was invented by a German engineer named Dr. Rudolph Diesel. The first prototype was operated successfully in 1893 and patents for the design were granted in 1895 and 1898 in Germany and the US respectively. The first example deemed commercially viable was built in 1897. These early examples used peanut oil for fuel. Development continued, and it was not until the 1920's that versions sufficiently small for mobile use were developed.[33]

Diesel engines are reciprocating internal combustion engines. Virtually all on-road diesel engines are four-stroke and resemble gasoline engines in basic design. This design consists of an engine block, which houses the crankshaft and contains the piston bores. Pistons reside within the piston bores and are attached to the crankshaft via connecting rods. The top of the piston forms the bottom of the combustion chamber. The cylinder head is attached to the engine block and forms the top of the combustion chamber. Intake and exhaust valves are also contained within the cylinder head(s) and control the flow of air and exhaust to and from the cylinders. These valves are timed according to lobes on the camshaft(s), which may also be contained within the cylinder head(s). The crankshaft is rotated by the pistons and the camshafts are rotated by the crankshaft.

The four-stroke designation refers to the number of strokes made by each piston per complete combustion cycle. Starting with the piston at top-dead-center (TDC), the intake stroke begins with the rotating crankshaft pulling the piston downward to bottom-

[33] Information on the history of the diesel engine comes from www.dieselenginemotor.com.

dead-center (BDC). As the piston moves downward, the intake valve opens allowing air to be drawn into the cylinder. As the intake stroke completes, the intake valve is closed and the piston is forced upward by the crankshaft. As it moves upward towards TDC, the volume of the combustion chamber decreases and the air within it is compressed. The compression of the air raises its temperature above the auto-ignition temperature of the fuel. In a modern diesel engine, fuel is injected directly into the combustion chamber as the piston nears TDC. This injection is accomplished via a fuel injector housed in the cylinder head. Once the fuel is injected, it evaporates and then combusts due to the high temperature within the cylinder. At this point the third stroke, often called the power stroke, begins. The ignition of the fuel within the cylinder produces heat, which increases pressure within the cylinder, driving the piston downward. This is known as the power stroke because this is the stroke that forces the crankshaft to rotate. When the piston reaches BDC the exhaust stroke begins. The piston is driven up by the rotating crankshaft and the exhaust valve opens. As the piston moves upward, it pushes exhaust gases out of the cylinder. This completes the combustion cycle and it repeats as long as the engine continues to operate.

The size and layout of a diesel engine depends on the desired application. Engine layout refers to the number and arrangement of the cylinders. Diesel engines used in on-road transportation typically use either an inline layout or a V layout. An inline engine has all of the cylinders arranged in a single row, while a V engine has two rows of cylinders arranged in two lines such that the two rows form a V. In a V engine, each row (or bank) of cylinders contains half of the cylinders. Passenger car diesel engines usually contain four or six cylinders and range in displacement from around 1 liter to 5 liters.

Diesel engines found in SUV's and pickup trucks usually contain 6 or 8 cylinders and range in displacement from 4 to 8 liters. Heavy-duty diesel engines typically contain 6 cylinders and may have displacements exceeding 15 liters.

Although the basic design of diesel engines is similar to gasoline engines, the primary difference is the way in which the fuel is ignited. Diesel engines are compression-ignited (CI) in the sense that heat produced from compression within the cylinder causes the fuel to auto-ignite. This differs from gasoline engines, which are spark-ignited (SI). This leads to other changes in the design on diesel engines. Diesel engines are typically built more robustly than their gasoline counterparts due to their need to cope with greater pressures within the cylinders. While this may lead to greater weight, it often leads to greater longevity compared to gasoline engines.

C.2 Major Advances in Diesel Engine Technology

Two of the most important advances in diesel technology have been the application of turbochargers and recently improved methods of fuel injection. Both of these developments have significantly improved the performance of diesel engines in mobile applications. The use of turbocharged diesel engines in vehicles started in the late 1930's when Swiss Machine Works Saurer offered a turbocharged diesel engine for use in trucks. Despite this early introduction, it was not until the high fuel prices of the 1970's that diesel turbochargers became more common. This was due the modest fuel economy improvements that turbochargers offered as well as the improved performance. Today, nearly all diesel engines used in mobile applications are turbocharged.[34]

[34] Information on the history of turbo diesel engines is sourced from www.turbodriven.com.

Turbochargers are devices that force more air into the cylinders, a process known as forced induction. In a naturally-aspirated (non-forced induction) engine, air is drawn into the cylinders by the intake stroke of the pistons. Forced induction is typically achieved by using either a turbocharger or supercharger. These devices compress the inducted air, increasing its density. Increasing the density of inducted air allows more fuel to be injected into the cylinder, which leads to greater power output. Both superchargers and turbochargers are essentially air compressors. The difference lies in how they are powered. A supercharger is typically belt-driven by the crankshaft, while a turbocharger is powered by exhaust gases. Although both devices can increase power output, turbochargers are generally preferred due to their fuel economy advantage over superchargers. This is because turbochargers utilize some of the wasted exhaust gas energy (Khair 2004a).

A turbocharger is typically bolted to the exhaust manifold. Engine exhaust flows through the device and spins a turbine at high speed. The turbine powers the compressor wheel, or impeller, which compresses the inducted air. Due to the increase in pressure, the inducted air increases in temperature. To address this increase in temperature, most modern turbo diesel engines incorporate an intercooler (aftercooler). Intercoolers can use either air or liquid to remove heat from the compressed air. These devices increase power output because they increase the density of the air entering the cylinders, allowing more fuel to be injected.

In addition to modest gains in fuel economy, turbocharging a diesel engine can lead to large gains in both horsepower and torque. According to Nice (2009), typical power increases are in the 30-40% range. Recent advances in turbocharger design have lead to even greater benefits. One of the most critical challenges of turbocharger design is achieving constant charge-air pressure, regardless of operating conditions. Two technologies that have improved the control of charge air pressure are waste-gating and variable turbine geometry (VTG). Waste-gated turbochargers provide a bypass around the turbine for exhaust gases. This bypass is activated when intake pressure rises beyond some specified value. This design element allows the turbo to be designed such that it responds well to lower flows of exhaust without building excessive pressure at higher flows. The end result is that power and response are greater at lower engine speeds and loads.

Variable turbine geometry technology addresses the same problem waste gates address, but in a way that is more efficient. In a waste gated turbo, the air that bypasses the impeller is directed to the atmosphere, which is seen as a waste. A variable geometry turbo operates by changing the position of the turbine vanes according to operating conditions. At low exhaust flows, the flow area between two consecutive vanes is reduced, causing the turbo to rotate at higher speeds. As exhaust flow increases, the flow area between two consecutive vanes is increased so that the turbo does not rotate too fast. This maximizes engine power and response at different engine speeds by better controlling charge-air pressure.

There are also other benefits of VTG technology. One problem with turbocharging is a phenomenon known as turbo lag. Turbo lag occurs when a driver demands an abrupt increase in power. When the driver pushes on the accelerator pedal, more fuel is injected into the cylinders. However, there is a short period of time after this when the turbo has not yet responded. When this occurs, the air-fuel ratio temporarily drops. This leads to poor response and visible smoke. VTG technology minimizes turbo lag because the vanes can be positioned such that the turbo reaches sufficient speed in less time (Khair 2004b).

A second major improvement in diesel engine technology has been advances in fuel injection. Fuel injection is extremely important in diesel engines and can influence performance, fuel economy, emissions, and noise. Precise timing and metering of the injection is necessary as well as good fuel atomization and air utilization. Injection timing refers to when the injection takes place during the compression stroke. Injection metering refers to the quantity of fuel that is delivered when injection occurs. Fuel atomization refers to fuel delivery in the form of very small particles, while air utilization is a measure of how well the fuel penetrates the combustion chamber and how uniform the delivery is across cylinders. A system which achieves precision at these tasks is very costly and may account for 30% of an engine's cost.

A major improvement in fuel injection was the introduction of direct injection (DI). In a DI engine fuel is injected directly into the combustion chamber. This is in contrast to traditional indirect-injected (IDI) engines which inject fuel into a pre-chamber. This pre-chamber is designed to ensure adequate mixing of the air and fuel. Advances in engine and fuel injection technology allowed for the introduction of direct-injection and elimination of the pre-chamber. The most significant advantage of DI over IDI is an improvement in fuel economy.

Injection technology itself has also gone through several major changes. Historically, mechanically-controlled pump-line-nozzle systems were the primary method of injection. These systems generally consist of a single, engine driven, high-pressure pump, high pressure lines, and the fuel injectors. Fuel delivery into each high pressure line is mechanically timed. Each high pressure line is exactly the same length and delivers fuel to fuel injectors above each cylinder. When the pressure rises at the injector a needle valve opens and fuel is injected. One downside to the various pump-line-nozzle systems is that fuel pressure is dependent on engine speed. This makes precise control and metering difficult, and may decrease atomization performance. The mechanical nature of these systems also constrains engineers' ability to incorporate more complex injection functions.

The unit injector (UI) system is generally regarded as an improvement over the pump-line-nozzle systems. UI systems incorporate a pumping device in each fuel injector. The primary advantage of this system is it can achieve very high fuel pressure, which is essential for good fuel atomization. Elimination of the high pressure fuel lines allows this increase in pressure. The pumps themselves are typically camshaft-driven. Although UI achieves higher pressure it shares a disadvantage with the pump-line-nozzle systems: fuel pressure remains dependant on engine speed.

Another fuel injection system regarded as an improvement over the pump-line-nozzle system, and possibly the UI systems, is common rail fuel injection. In these systems an engine-driven high pressure pump supplies fuel to the rail. A pressure regulator keep pressure in the rail from rising too high, while the volume of fuel contained by the rail is sufficient to damp changes in pressure caused by operation of the pump or injectors. High pressure fuel lines provide fuel to each injector which can be mechanically or electronically controlled. The primary advantage of this system is that constant pressure is maintained. Combined with electronic control of injectors, this system is a particularly elegant solution and is quite similar in general concept to modern gasoline fuel injection systems.

Finally, electronic controls have contributed to the performance of all the previously mentioned fuel injection systems. Electronic control combined with either UI systems or common rail systems has increased power and drivability, while at the same time decreasing emissions. In fact, increasingly strict emission standards have been a large driver of the progression and adoption of these systems. Electronic control of diesel engines began in the late 1970's and was generally complete for on-road vehicles by the mid 1990's. Electronic control of the fuel injection systems allowed engineers more precise control over injection. Timing and metering could be more precisely controlled and tailored to varying conditions. Multiple injections per combustion cycle could be implemented, and the systems could be designed to account for the various needs of emission control equipment. [35]

[35] Information on fuel injection systems is based on Khair (2003), while information regarding the development of DI technology is based on Khair (2000).

Appendix D: SO_2 Emission Rates

SO_2 emission rates are calculated according to

(D1) $$grams\ SO_2\ per\ mile = D \times SUL \times F \times MCF \times CF \times K \times MPG^{-1},$$

where

$$D \equiv \text{density of fuel} = 7.1\ \text{lb gal}^{-1},$$

$$SUL \equiv \text{fuel sulfur concentration} = \begin{matrix} 3.4 \times 10^{-4}\ \text{for 2006 and earlier} \\ 0.07 \times 10^{-4}\ \text{for 2007 and later} \end{matrix},$$

$$MCF \equiv \text{molar conversion factor} = 2\ \text{lb per lb sulfur},$$

$$CF \equiv \text{engine conversion factor} = 2.897\ \text{bhp-hr/mi},$$

$$K \equiv \text{mass conversion factor} = 453.59\ \text{g/lb}.$$

Appendix E: Impact on the US Light-Duty Diesel Market

The aftertreatment technologies pioneered by US 2007 heavy-duty standards are now being seen in the US light-duty market. Adoption of these technologies has been driven by US Tier II standards, California LEV II standards, and the coming Euro 6 standards. Availability of diesel light-duty vehicles in the US has been severely limited in recent years by Tier II and LEV standards. Table E.1 presents recent PM and NOx

Table E.1 - US and European Union Light-Duty Emission Standards

Standard	Phase-in Period	PM (mg/km)	NOx (mg/km)	Aftertreatment
Tier I (US)	1994-1997	62.1	776.7	None
Tier II Bin 2	2004-2007	6.2	12.4	PM, NOx[36]
Tier II Bin 5	2004-2007	6.2	43.5	PM, NOx
Tier II Bin 8	2004-2007	12.4	124.3	PM
LEV II (CA)	2004	6.2	43.5	PM, NOx
Euro 3	2000-2001	50	500	None
Euro 4	2005-2006	25	250	None
Euro 5	2009-2011	5	180	PM
Euro 6	2014-2015	4.5	80	PM, some NOx[37]

standards in Europe and the US. Current US emission standards are known as Tier II. Under these standards, manufacturers can certify vehicles to different bins, although each manufacturer must achieve a fleet average NOx emission rate equal to Bin 5 levels. This means a diesel vehicle could be certified to Bin 8, but this requires offsetting vehicles certified to levels cleaner than Bin 5. It should also be noted that California has separate standards. These are relevant because California represents a significant part of the US vehicle market, and many other states have adopted or are considering adoption of these standards.

[36] Johnson (2009) claims that achieving this standard is a stretch for current aftertreatment technology.
[37] Larger vehicles are likely to require NOx aftertreatment (Johnson 2008).

Careful examination of US and EU standards shows US standards have forced adoption of both aftertreatment technologies before adoption in the EU. Particulate filters to control PM emissions were forced by Tier II standards and LEV II standards which were implemented in 2004. In Europe it was not until Euro 5 standards in 2009 that particulate filters became necessary. Additionally, 50-state legal diesel vehicles in the US market have required NOx aftertreatment since 2004. It is not until Euro 6 standards in 2014 that similar technology will be forced in Europe. However, it should be noted that NOx aftertreatment may appear in Europe prior to 2014 due to early adoption incentives. As a result of these differences in emission standards, manufacturers have been forced to develop diesel vehicles specifically for the US market. This is a costly endeavor given the technologies required. There is also considerable risk because manufacturers cannot be sure how well these diesel vehicles will be accepted in the US market.

Due to these issues, there were no 50-state legal light duty diesel vehicles available in the US from 2004 to 2008. In 2009 there were eight 50-state models available, and in 2010 there are ten. It seems likely that the heavy-duty standards played an important role in this recent availability by forcing the development of the necessary technology at a speed that would not have otherwise occurred.

Several other factors that have reduced availability of diesel vehicles in the US, and which are affected by the heavy-duty standards, should be mentioned. One is the availability of ultra low sulfur diesel (ULSD). Vehicles equipped with diesel particulate filters and NOx adsorbers require the use of ULSD. This fuel was not widely available in the US until it became required as part of US 2007 Heavy-Duty Vehicle emission standards. Lack of this fuel before this date made it very difficult to sell a 50-state legal diesel in the US. Another factor that has reduced supply of diesel vehicles has been lack of a distribution network for the urea solution consumed by SCR systems. Given that this solution needs periodic replenishment, availability of it is a legitimate concern. However, with the adoption of SCR by virtually all heavy-duty trucks in 2010, there is now widespread distribution of the fluid.

Appendix F: Implications for Other Standards

The basic result of this analysis is that the current US heavy-duty emission standards have a very large negative net benefit. This has important implications for several other sets of emission standards. First, US Tier II and California LEV II light-duty standards have led to the adoption of both PM and NOx aftertreatment technologies. Based on the result here, it seems likely that there is also a negative net benefit of these standards when applied to light-duty diesel vehicles.

There are a number of other standards that affect the heavy-duty diesel market. These include US Tier 4 off-road standards, as well as Euro 6 and Japan 2009 on-road standards. Table F.1 presents NOx and PM components of these standards. All have been

Table F.1 – Heavy-Duty PM and NOx Limits (g/bhp-hr)

Standard	Phase-in Period	NOx	PM	Aftertreatment
US 2007	2007-2010	0.2	0.01	NOx, PM
US Tier 4	2011-2014	0.4	0.02	NOx, PM
Euro 5	2008-2009	1.5	0.015	NOx
Euro 6	2013-2014	0.3	0.007	NOx, PM
Japan 2009	2009	0.52	0.007	NOx, PM

converted to g/bhp-hr to make comparison easy. It can be seen that by 2014, heavy-duty trucks sold in all three markets will require aftrertreatment of both NOx and PM. Again, the results of this analysis imply a negative net benefit associated with Euro 6 and Japan 2009 standards. This implication, however, should be viewed with caution. External costs are likely to be different in Japan and Europe. Additionally, the standards are not identical so production costs may vary if manufacturers choose to tailor vehicles to the specific market.

The question of whether vehicles will be tailored to the market they are sold in is an important one. From a production cost standpoint, it would be most efficient if a vehicle did not have to be tailored to the specific market it is sold in. This gain in efficiency must be weighed against the fact that different abatement benefits and costs imply different optimal standards. However, policy makers in no area are currently setting standards in such a way. Additionally, it seems unlikely that abatement benefits and costs would vary to a large extent. This generates two questions. First, are manufacturers likely to produce a single version of a truck that meets both US 2007 and Euro 6 standards? Second, would the adoption of some type of global standard be preferable.

The answer to both questions probably depends on fuel economy. A Euro 6 truck must emit slightly less PM than a US 2007-compliant truck, but can emit slightly more NOx. Higher NOx emissions typically imply a fuel economy advantage. Given that fuel economy is highly valued by consumers in this market, it is likely that manufacturers would tune Euro 6 trucks to achieve slightly better fuel economy at the cost of greater NOx emissions than a US 2007-compliant truck.

The desirability of a single standard for both the US and EU would depend on the answer to the first question. If manufacturers do not produce separate vehicles for US 2007 and Euro 6 standards, then the standards are essentially equivalent, and there would be little incentive for the US to adopt EU standards, or for the EU to adopt US standards. However, if manufacturers do choose to produce different vehicles for the US and EU market after Euro 6 takes effect, it is possible that considerable cost savings could be realized by moving toward a single standard. Which standard, then, would be preferred?

Unfortunately, it is impossible to answer this without knowing the exact relationship between NOx emissions, PM emission, and fuel economy. The external cost resulting from US 2007 and Euro 6 levels of NOx and PM emissions could be valued easily, but valuing the change in fuel economy requires knowing exactly how much it will change when moving from one standard to the other.