2. Efficiency and Cost Impacts of Emission Control Technologies

Background

The new ultra-low-sulfur diesel (ULSD) Rule issued by the U.S. Environmental Protection Agency (EPA) requires not only that the sulfur content of transportation diesel fuel oil produced by domestic refineries be drastically reduced by 2007, but also that emission controls on heavy-duty diesel engines be imposed to dramatically reduce emissions of nitrogen oxides (NO_x), particulate matter (PM), and hydrocarbons (HC). This chapter summarizes the new heavy-duty engine emission standards, discusses the feasibility of meeting the standards based on a review of the EPA-identified emission control technology options that might be available, and assesses cost implications of the technology options.

The new ULSD standards finalized by the EPA are crucial to the successful development of emission control equipment for heavy-duty diesel engines. The catalysts to be used in meeting the emission standards can be severely damaged by sulfur contamination. For example, catalyst-based particulate filters for diesel engines have shown significant losses of conversion efficiency with fuel containing 30 ppm sulfur, particularly in colder climates. With respect to NO_x adsorbers, researchers have found that at fuel sulfur levels above 10 ppm, the heavy truck emission standard may not be attainable.

The EPA's final emission standards will affect new heavy-duty vehicles in model years 2004, 2007, and 2010. Although this study focuses on the impact of the 2007 standard, discussion of the 2004 standards and the associated impacts on technology, cost, and efficiency are relevant to the analysis. In 1997, the EPA proposed new emission standards for 2004 and later model year heavy-duty diesel engines that required a combined standard for NO_x and HC of 2.4 grams per brake horsepower-hour (g/bhp-hr).[29] The current standard for NO_x is 4 g/bhp-hr, and the standard for HC is 1.3 g/bhp-hr. The proposed standard was reviewed by industry, and in 1998 the EPA signed consent decrees with several heavy-duty engine manufacturers, stating that the 2004 emission standards would be met by October 2002.[30] The standards for new heavy-duty highway vehicles in model years 2004 and later were finalized July 2000.

In December 2000, EPA published additional standards for on-road heavy-duty diesel engines that would take effect beginning in 2007. These standards will require stricter control of PM (0.01 g/bhp-hr), NO_x (0.20 g/bhp-hr), and HC (0.14 g/bhp-hr) emissions. The new standards apply to diesel-powered vehicles with gross vehicle weight (GVW) of 14,000 pounds or more. The PM standard applies to all on-road heavy- and medium-duty diesel engines. The NO_x and HC standards are to be phased in at 50 percent of new vehicle sales in model years 2007 through 2009. In 2010, all new on-road vehicles will be required to meet the NO_x and HC standards.

For years 2007 through 2009, the EPA allows diesel engine manufacturers flexibility in meeting the NO_x and HC standards.[31] Engine manufacturers are provided the option of producing all diesel engines to meet an average of 2004 and 2007 NO_x and HC emission standards (1.1 g/bhp-hr). Engine manufacturers and EPA have confirmed that the industry intends to design and produce engines that meet the average NO_x/HC emission standard, providing engine manufacturers the ability to comply with the standards by using less stringent emission control systems.[32] If manufacturers produce low-emission engines in 2006, the number produced can be deducted from 2007 production requirements.

Emission Control Technologies

Historically, engine manufactures have met new emissions standards through modifications to engine design. The continuation of this trend is seen in the projection of technologies used to meet the EPA's 2004 emission standards for heavy-duty diesel engines. An EPA-commissioned technology study that addressed

[29]The brake horsepower of an engine is the effective power output, sometimes measured as the resistance the engine provides to a brake attached to the output shaft. A bhp-hr is that unit of work or energy equal to the work done at the rate of 1 horsepower for 1 hour.

[30]U.S. Environmental Protection Agency, *Final Emission Standards for 2004 and Later Model Year Highway Heavy-Duty Vehicles and Engines*, EPA420-F-00-026 (Washington, DC, July 2000), p. 4.

[31]U.S. Environmental Protection Agency, *Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements*, EPA420-F-00-057 (Washington, DC, December 2000), p. 2.

[32]Based on telephone interviews with engine manufacturers and the U.S. Environmental Protection Agency,

technology, availability, cost, and efficiency concerns concluded that engine manufacturers could meet the 2004 emission standards with engine control strategies—primarily, exhaust gas recirculation (EGR) and high-pressure fuel injection systems with retarded fuel injection strategies.[33] The EPA also stated that other advanced diesel engine technologies—such as waste-gated turbochargers, air-to-air after-coolers, advanced combustion chamber design, and electronic controls—could be used to help meet the 2004 emission standards.

Although the EPA states that implementation of cooled EGR will achieve most of the necessary emission reductions and that increases in fuel consumption are expected due to pumping losses, they believe that advanced turbochargers, advanced combustion chamber design, and electronic controls will also be used to overcome losses in efficiency. The EPA also mentions various catalyst technologies that might be used to meet the NO_x and PM standards but concedes that engine manufacturers will opt for engine control strategies to meet the NO_x standard, due to both economic and technological concerns regarding the catalyst technologies for NO_x reduction. The EPA concludes that particulate traps or oxidation catalysts will be used to control PM.[34] The assumptions reflected in the EPA study were recently confirmed when several engine manufacturers reported that they would implement the above-mentioned engine technologies to meet the 2004 standards.[35,36,37]

Whereas engine manufacturers have been able in the past to meet new emission standards by using advanced engine controls and technologies, they will have to rely heavily on component and system development by emission control equipment manufacturers to meet the 2007 standard. In particular, engine manufacturers must implement an exhaust after-treatment catalyst technology to control NO_x emissions.

Several NO_x control after-treatment devices are currently being investigated, including lean-NO_x catalysts, NO_x adsorber catalysts, and urea-based selective catalytic reduction (SCR) devices. Lean-NO_x catalysts have not seen significant improvement in NO_x reduction efficiency during the past 3 years and are not considered a viable option, but NO_x adsorber and SCR systems have shown potential for significant reduction of NO_x emissions.[38] The NO_x absorber catalyst works by temporarily storing NO_x during normal engine operation on the adsorbent. When the adsorbent becomes saturated, engine operating conditions and fuel delivery rates are adjusted to produce a fuel-rich exhaust, which is used to release the NO_x as N_2. The SCR process involves injecting a liquid urea solution into the exhaust stream before it reaches a catalyst. The urea then breaks down and reacts with NO_x to produce nitrogen and water. Using the SCR system, it might be possible to meet the NO_x emission standard without ultra-low-sulfur diesel fuel.

Industry experts have indicated that the SCR system shows more promise than the NO_x adsorber system for reduction of NO_x emissions in truck applications.[39] There is currently no infrastructure in place for the distribution of urea, however, and other issues remain to be addressed, including freezing of the urea solution in extreme weather conditions as well as operator compliance. Several engine manufacturers are working on infrastructure development plans for liquid urea. Although the EPA agrees that the technology is promising, it has serious concerns about compliance issues, because truck drivers may forgo refilling the urea tanks in an effort to save on operating costs. Engine manufacturers are working with the EPA to develop engine control systems to address this and other engineering issues. The SCR technology will not be viable until infrastructure plans are established and engine manufacturers can demonstrate to the EPA that compliance can be assured through reasonable engine control strategies.

Currently, the EPA expects NO_x adsorbers to be the most likely emission control technology applied by the industry.[40] Using current catalyst technology, the fuel-rich cycle reduces fuel efficiency by 4 percent.[41] The majority of the reduction in fuel efficiency comes from

[33]U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Control of Emissions of Air Pollution From Highway Heavy-Duty Engines*, EPA420-R-00-010 (Washington, DC, July 2000), p. 21.

[34]U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Control of Emissions of Air Pollution From Highway Heavy-Duty Engines*, EPA420-R-00-010 (Washington, DC, July 2000), p. 46.

[35]DieselNet, "Caterpillar Announces New Emission Technology," web site www.dieselnet.com / news / 0103cat.html (March 2001).

[36]Newport's Truckinginfo.com, "Mack To Use EGR To Meet '02 Emissions Standards," web site http: / / www.trcukinginfo.com / news / news_print.asp?news_id=42839 (March 20, 2001).

[37]DieselNet, "Cummins in Support of Cooled EGR Technology," web site www.dieselnet.com / news / 0103cummins.html (March 2001).

[38]U.S. Department of Energy, Office of Transportation Technologies, "Impact of Diesel Fuel Sulfur on CIDI Emission Control Technology" (August 21, 2000), p. 2.

[39]Based on telephone interviews with manufacturers of heavy-duty diesel engines.

[40]U.S. Environmental Protection Agency, *Technical Support Document for the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements: Air Quality Modeling Analyses*, EPA420-R-00-028 (Washington, DC, December 2000), p. V-3.

[41]U.S. Department of Energy, Office of Transportation Technologies, "Diesel Emission Control: Sulfur Effects (DECSE) Program Phase II Summary Report: NO_x Adsorber Catalysts" (October 2000), p. 21.

the reduction of sulfur in the exhaust stream. The sulfur accumulates on the NO_x adsorber catalyst, and eventually adsorber storage capability is completely lost. Even at ultra-low-sulfur levels, further desulfurization must occur to ensure that the NO_x adsorber is not "poisoned."

To date, no NO_x adsorber system has proven feasible. Although NO_x adsorbers have demonstrated compliance using ULSD (7 ppm), the systems show losses in conversion efficiency after 2,000 miles of operation.[42] Concerns have also been raised about the ability of the technology to perform over a range of operating temperatures and loads. Industry and government research efforts are seeking ways to overcome the obstacles facing the NO_x adsorber technology.

In order to meet the 2007 emission standards for heavy-duty diesel engines, the EPA makes the following assumptions regarding the performance of NO_x adsorber emission control technology:

- Conversion efficiencies will improve so that the overall loss of fuel economy will be only 2 percent: 1 percent for the fuel-rich cycle and 1 percent for pumping losses.
- EGR equipment will be optimized as a result of the improved efficiency of NO_x adsorber emission control equipment. The optimized EGR air-to-fuel mixture will provide a 1-percent increase in fuel efficiency, which will offset the 1-percent loss in efficiency from the fuel-rich exhaust cycle.
- The application of the new emission control technology will provide a 3-percent or greater increase in efficiency by offsetting the fuel efficiency reductions that were incurred to meet the 2004 standard when diesel engine manufacturers manipulated fuel injection timing to optimize for low NO_x emissions.

Based on these assumptions, EPA predicts that there will be no loss in fuel efficiency associated with the NO_x adsorber catalyst designed to meet the 2007 emission standard.[43] Although experts agree that this is possible, it has yet to be proven.[44] Current field tests reveal a 4- to 5-percent fuel efficiency loss with current state-of-the-art technology, which still requires EGR and timing control. Experts agree, however, that NO_x adsorber catalysts are expected to improve and that the associated optimization of EGR and timing control will eventually be achieved.

Technology Costs

The EPA's cost analysis of the technologies required to meet the 2004 standard assumed that fuel injection and turbocharger improvements would occur without the new emission standards. Therefore, when estimating increases in engine costs, the EPA excluded 50 percent of the technology costs in the total cost estimation. The incremental costs for medium-duty engines were estimated to be $657 in 2004, decreasing to $275 in 2009. Heavy-duty engine costs were estimated at $803 in 2004, decreasing to $368 in 2009.[45]

The EPA also estimated increases in annual operating costs of $49 for medium-duty engines and $104 for heavy-duty engines for the maintenance of the EGR system. The cost of the NO_x adsorber emission control system for medium-duty engines was estimated at $2,564 in 2007, decreasing to $1,412 in 2012. For heavy-duty trucks, the cost of control technology was estimated at $3,227 in 2007, decreasing to $1,866 in 2012.[46] Although engine manufacturers state that these costs are optimistic, no studies have been completed to dispute the EPA estimates.

Efficiency Losses

EPA assumptions for the impacts of the ULSD Rule on diesel engine fuel efficiency are used for the Regulation case in this analysis. Because the emission control technology development needed to meet the 2007 standards remains to be developed, however, a sensitivity case was analyzed to evaluate the possible impacts of fuel efficiency reductions.[47] In the 4% Efficiency Loss case for this study, it is assumed that meeting the emission standards in 2010 will reduce the average fuel efficiency of highway heavy-duty diesel engines by 4 percent, improving to no efficiency loss in 2015. It is assumed in this scenario that engine manufacturers will not be able to overcome fuel efficiency losses in order to meet the standards in 2010, but with continued improvements in NO_x adsorber efficiency and desulfurization catalysts, they will be overcome by 2015.

42 Manufacturers of Emission Controls Association, *Catalyst-Based Diesel Particulate Filters and NO_x Adsorbers: A Summary of the Technologies and the Effects of Fuel Sulfur* (August 14, 2000), p. 19.

43 U.S. Environmental Protection Agency, *Technical Support Document for the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements: Air Quality Modeling Analyses*, EPA420-R-00-028 (Washington, DC, December 2000), p. V-34.

44 Based on phone interviews with emission control equipment manufacturers.

45 U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Control of Emissions of Air Pollution From Highway Heavy-Duty Engines*, EPA420-R-00-010 (Washington, DC, July 2000), p. 88.

46 U.S. Environmental Protection Agency, *Technical Support Document for the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements: Air Quality Modeling Analyses*, EPA420-R-00-028 (Washington, DC, December 2000), p. V-38.

47 Although this case reflects a scenario in which losses in efficiency from emission contol are not overcome by new technology, the considerable time available for research and development may provide government and industry ample time to resolve the fuel efficiency loss issues associated with advanced emission control technologies.

The reference case for this analysis includes assumptions for the market penetration of advanced engine and vehicle technologies and resulting improvements in fuel efficiency. Included in the slate of technologies are low rolling resistance tires, improved aerodynamics, lightweight materials, advanced electronic engine controls, advanced turbochargers, and advanced fuel injection systems. Market penetration is estimated using a payback function in which the incremental capital cost for each technology is compared to a stream of fuel savings over a specified technology payback period (1 to 4 years), discounted at 10 percent. In the reference case it is projected that average new truck fuel efficiency will increase from 6.4 miles per gallon in 2000 to 7.4 miles per gallon in 2020.

New vehicle fuel efficiency is reduced slightly in the 4% Efficiency Loss case, but the impact on stock efficiency is marginal because the number of new vehicles expected to enter the market is small relative to the total number of vehicles on the road. Fuel expenditures for heavy trucks are projected to be $1.9 billion higher in 2007 in the 4% Efficiency Loss case than in the reference case, and the difference grows to $2.9 billion in 2011 (Table 1), an increase of $410 in average fuel expenditures per truck. Cumulative fuel expenditures from 2007 to 2015 are projected to be $17.6 billion higher in the Regulation case than in the reference case and an additional $3.0 billion higher in the 4% Efficiency Loss case. The projected cumulative increase in energy use in the 4% Efficiency Loss case is approximately 80 trillion British thermal units (Btu). Energy consumption projections are discussed in Chapter 6.

Table 1. Projected Fuel Expenditures for Heavy-Duty Diesel Vehicles, 2006-2020
(Billion 1999 Dollars)

Analysis Case	2007	2008	2009	2010	2011	2015	Total, 2007-2015
Total Fuel Expenditures							
Reference	39.45	40.46	41.46	42.19	42.98	45.96	**385.63**
Regulation	41.37	42.31	43.09	44.40	45.55	47.95	**403.24**
4% Efficiency Loss	41.37	42.31	43.09	44.58	45.92	48.44	**406.21**
Incremental Fuel Expenditures							
Regulation	1.92	1.85	1.63	2.21	2.57	1.99	**17.62**
4% Efficiency Loss	1.92	1.85	1.63	2.38	2.94	2.49	**20.58**

Source: National Energy Modeling System, runs DSUREF.D043001B, DSU7PPM.D043001A, and DSU7TRN.D043001A.