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COSTS OF EMISSION REDUCTION TECHNOLOGIES FOR HEAVY-DUTY DIESEL VEHICLES

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EXECUTIVE SUMMARY

This report presents the manufacturing costs of emission control technology used to meet recent U.S. and European emission standards for heavy-duty diesel engines and vehicles. As an update of cost forecasts done to support adoption of different stages of regulation in these regions, this assessment offers the great benefit of hindsight. Focusing on the primary technology pathway that was or is in widespread commercial use, the cost estimates can account for not only innovation and improvement in manufacturing processes over the past decades but also the unforeseen deployment of certain emission control technologies. Looking back, this analysis is able to provide reasonable cost estimates for the increasingly sophisticated technology packages used in each regulatory stage.

The current Euro VI and US 2010 standards achieve an approximately 95% reduction in emissions of the primary pollutants of concern from heavy-duty vehicles (HDVs), fine particulate matter ($PM_{2.5}$), and nitrogen oxides (NO_X), from the Euro II and US 1994 baselines. These stringent standards have been implemented even as fuel consumption and greenhouse gas emissions from heavy trucks continue to decline. Globally, HDVs are responsible for 80% of on-road transportation emissions, leading to a significant impact on local air quality and human health as well as on the global climate. This is especially true of black carbon, which is the primary constituent in diesel $PM_{2.5}$ emissions.

In addition to having the greatest impact on health, the increasingly stringent limits for particulate matter (PM) and NO_X are the key drivers of technology adoption. The costs assessed include both the in-cylinder technologies to control engine-out emissions and the aftertreatment technologies that act on the exhaust stream. Engine-out emissions are reduced by adjusting the temperature and air/fuel balance within the engine, using improvements to fuel injection and air handling and employing exhaust gas recirculation. Aftertreatment systems include selective catalytic reduction systems with ammonia as the reducing agent to control NO_X and diesel oxidation catalysts and diesel particulate filters to control PM.

This analysis assesses the itemized costs of different technologies used to meet recent standards in the European Union (Euro III, Euro IV, Euro V, and Euro VI) and in the United States (US 1998, US 2004, US 2007, and US 2010).[1] The analysis treats Euro II and US 1994 standards, the first in which 500 ppm sulfur diesel was required in each region, as the baseline for technology determination and cost estimation. In the final regulatory stage considered, Euro VI and US 2010, the two regions are well aligned in fuel sulfur levels, emissions limits, and technology pathways. In addition to the United States and Europe, Canada, Japan, South Korea, and Turkey have all begun implementing equivalent standards. Equivalent standards have been proposed or timelines published for Mexico, India, and Beijing, China, which has typically adopted emission standards ahead of the national standards.

While manufacturers occasionally differ in the layout and suite of technologies used, we focus on the prevailing compliance strategy for each regulatory step and consider the costs of technologies that were or are in widespread commercial use. New systems,

1 Heavy-duty engine standards for 2007–2010 were drafted as a single regulation, but the distinct approaches by manufacturers to meet initial requirements in 2007 and final requirements in 2010 allow us to treat them here as if they were distinct regulatory steps.

either under development or recently brought to market, are likely to further reduce costs, as well as offer other potential benefits such as increased durability or greater ease of operation. At the same time, this analysis does not incorporate discounts for process learning or volume sales; thus, cost estimates presented should be considered conservative. The current incremental costs of the prevailing technology to meet recent stages of European and U.S. standards are shown in Table ES-1.

Table ES-1. Incremental costs of emission control technology for a 12 L diesel engine under U.S. and European regulatory standards.

	Euro III	Euro IV	Euro V	Euro VI	TOTAL
European standards	$426	$3,771	$460	$2,280	**$6,937**
	US 1998	**US 2004**	**US 2007**	**US 2010**	**TOTAL**
U.S. standards	$50	$1,421	$1,650	$3,816	**$6,937**

While the incremental costs of individual regulatory steps differ, the cumulative costs for compliance with Euro VI or US 2010 (compared to Euro II or US 1994) are the same: $6,937 (in inflation-adjusted 2015 dollars). As the 2015 fleet average U.S. truck manufacturer suggested retail price was $157,000, the incremental costs of regulatory improvements over the past two decades add up to slightly over 4% of the average price to the consumer. The strong benefits of full implementation of Euro VI and US 2010 standards, along with some of the downsides and high costs of the interim standards, suggest that other regions should move as quickly as possible to harmonize with these world-class standards.

1. INTRODUCTION

Over the last two decades, many nations have adopted and implemented increasingly stringent limits on pollutant emissions from new on-road heavy-duty vehicles (HDVs). In the initial stages, compliance with HDV emission regulations primarily entailed reducing the engine-out emissions through electronic fuel injection and higher-pressure combustion. While gasoline passenger vehicles had been equipped with oxidation catalysts since the 1970s, it was not until US 2004 standards that diesel oxidation catalysts (DOCs) were required for heavy-duty diesel vehicles. In the next regulatory stages, additional aftertreatment devices were added for control of nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$).

Current U.S. and European Union (EU) standards—US 2010 and Euro VI—limit emissions of NO_X and $PM_{2.5}$ to less than a tenth of the levels allowed in 2000. Because black carbon forms the base and most important constituent of diesel particles, these standards would also reduce black carbon by more than 90%. The US 2010 and Euro VI limits have required the development and widespread deployment of advanced engine tuning and aftertreatment devices to reduce tailpipe emissions of NO_X, $PM_{2.5}$, and several other pollutants. Figure 1 shows the regulatory timeline for HDV emission standards in the world's top markets and identifies the regions that have adopted these world-class standards.

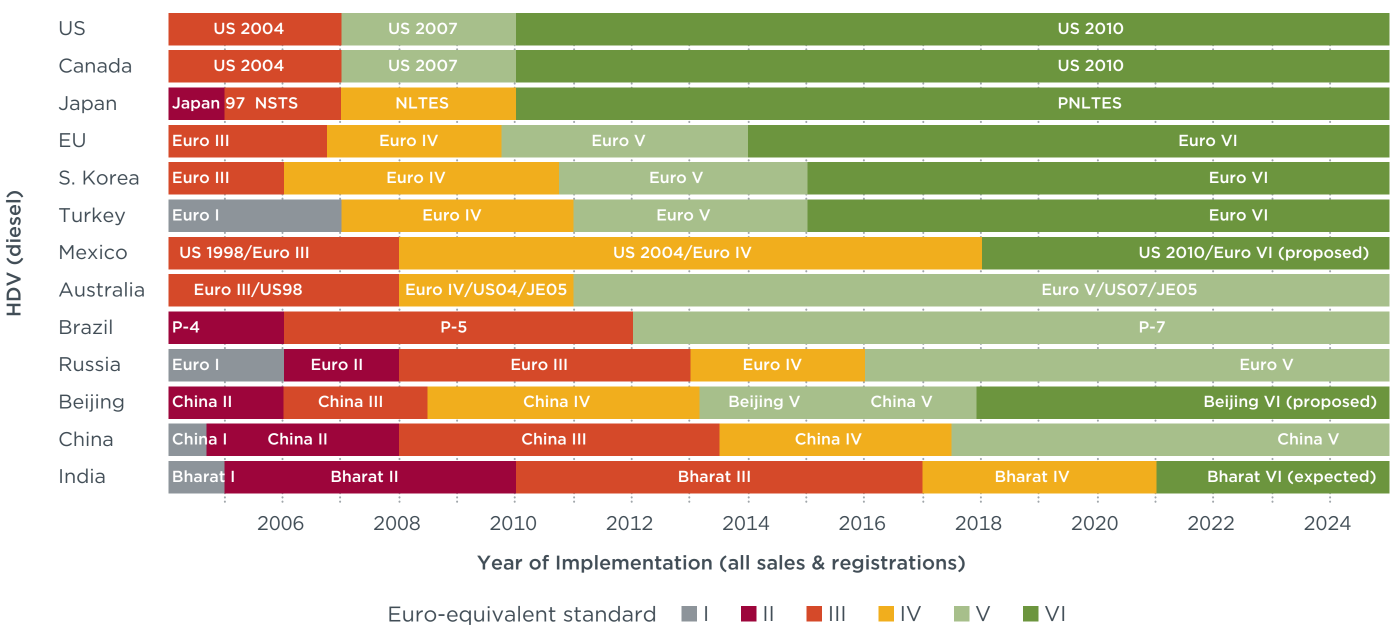

Figure 1. Major vehicle markets and national standards for all new HDVs.

The result of these advanced standards and emission control technologies has been dramatic reduction in heavy-duty emissions in the United States, the EU, Canada, Japan, South Korea, and Turkey (see Figure 2). In those regions, annual $PM_{2.5}$ emissions are projected to drop from 210,000 tons in 2000 to 8,000 tons in 2045. In all the other regions, annual $PM_{2.5}$ emissions are currently declining, from 550,000 tons in 2000 to 340,000 tons in 2015, as a result of adoption of earlier regulatory stages, but are then projected to begin increasing again to 630,000 tons in 2045 (Chambliss et al., 2013). Recent proposals from Mexico, India, and Beijing, China provide hope that this projection will never come to pass.

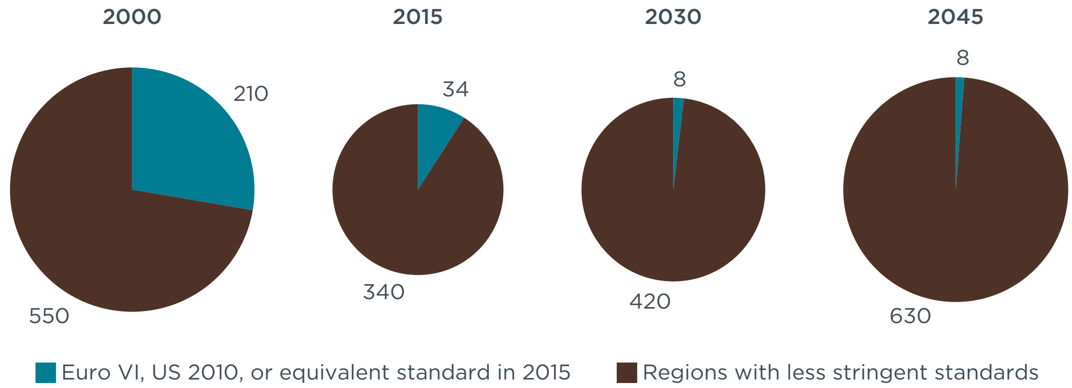

Figure 2. Historical and projected annual $PM_{2.5}$ emissions from HDVs, 2000–2045 (thousands of tons).

In 2010, HDVs contributed 80% of the global emissions of $PM_{2.5}$ and NO_X from road transportation (Chambliss et al., 2013). Adoption of advanced standards for HDVs, especially Euro VI and US 2010, offers the biggest potential to reduce health impacts from the on-road transportation sector. These standards also have the potential to greatly reduce black carbon, which is considered the second most important anthropogenic contribution to climate change after carbon dioxide (Bond et al., 2013).

While the climate, air quality, and public health benefits of adoption of advanced emission standards for HDVs have been well explored in previous studies, the incremental costs of advanced emission control technologies are less well known. Implementation of these standards in the major markets of the United States and Europe has led to dramatic improvements in vehicle technologies and substantial reductions in technology costs, such that existing U.S. and EU regulatory impact analyses do not fully reflect current costs or prevailing compliance strategies. Updated estimates of the cost of complying with the most stringent emission standards can support other major vehicle markets working toward adoption of these standards.

This analysis does not pretend to offer a consumer or price perspective, yet it can be useful to understand long-term pricing trends, both to put the incremental costs into perspective and to help provide an upper bound for the cost estimate. The average new heavy-duty truck manufacturer suggested retail price in the United States in 2015 was $157,000. Pricing strategies vary greatly between manufacturers, and over the last 15 years average prices have declined for some manufacturers and risen for others. Pricing decisions may be more closely related to macroeconomic indicators, marketing strategies, vehicle performance, comfort and fuel economy improvements, and sales incentives. Figure 3 incorporates over 4000 data points for manufacturer suggested retail price (MSRP) of heavy truck models sold in the United States from 2000 to 2015 (Truck Blue Book, 2015). Gray diamonds show MSRP for individual models (with darker gray indicating a higher number of models at that price point), and the lines represent the year-to-year average price tracking for specific manufacturers. The data are not weighted by vehicle sales and cannot provide a clear picture of the sales-weighted MSRP.

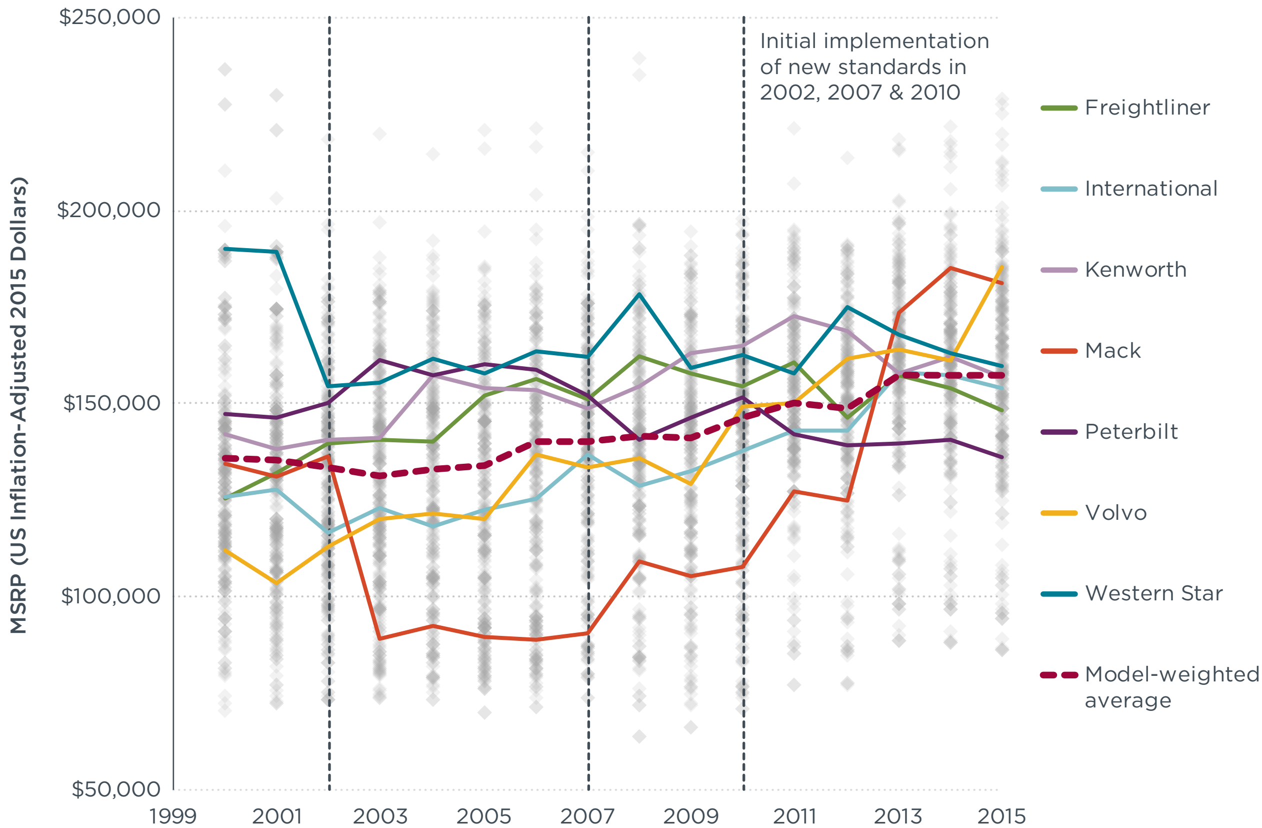

Figure 3. Manufacturer suggested retail prices for heavy truck models sold in the United States.

While corporate average price trends are highly nonlinear, overall inflation-adjusted suggested retail prices have increased by an average of 1% per year over the 15-year period. The biggest year-to-year price increases occurred in 2013 (6%), 2006 (5%), and 2010 (4%), and the biggest average price drop (−2%) occurred in 2002, the year in which engines meeting US 2004 standards were first required to be introduced.[2] The average total real MSRP increase was $6,560 (2006 to 2010), approximately 20% higher than the incremental cost attributed to the US 2007 and US 2010 regulations, presented below. Macroeconomic conditions, regulatory changes (including both exhaust and greenhouse gas emission standards), model options, and fuel efficiency changes likely all play a role in pricing trends.

This assessment does not consider the cost to consumers but instead tries to assess the per-vehicle costs of compliance for vehicle and engine manufacturers. It considers the costs of major emission control components used to meet U.S. and European emission standards and presents updated estimates of the cost of compliance for heavy-duty diesel vehicle manufacturers. The methodology for estimating heavy-duty diesel emission control technology costs follows the same steps used to assess costs for light-duty vehicles in Posada et al. (2012):

2 Manufacturers agreed to meet US 2004 standards starting in 2002 in a consent decree with the US Environmental Protection Agency (EPA) over use of defeat devices that had allowed higher NO_x emissions in real-world use conditions.

1. Detail emission control technologies and their components.
2. Identify emission control technologies used to meet each regulatory level.
3. Use publicly available information to assess the cost of each emission control system.
4. Calculate total estimated cost for each regulatory level.
5. Share preliminary technology assessment and costs data with expert reviewers and adjust original estimates based on their feedback.

This report focuses on the per-vehicle incremental costs of new vehicle emission standards, including Euro III through Euro VI and US 1998 through US 2010. The following costs are covered:

- In-cylinder technology improvement
- Aftertreatment systems
- Onboard diagnostic (OBD) systems
- Research and development (R&D) integration

The report does not consider changes to maintenance and operating costs, including changes in fuel consumption or costs of higher quality of fuels or diesel exhaust fluid. Nor does it take into account other changes to manufacturers, including warranty costs and costs for retooling and certification of new models. Finally, the report does not assess the potential for further cost reduction associated with next-generation emission control technologies, such as integrated aftertreatment systems, or process learning and production scaling.

The next section of this report describes key technologies developed to control NO_x, particulate matter (PM), and other emissions from diesel HDVs, including improved engines (in-cylinder emission controls) and aftertreatment systems. Section 3 describes the combination of these technologies that are typically used to meet Euro III, Euro IV, Euro V, Euro VI, US 1998, US 2004, US 2007, and US 2010 standards. Section 4 reviews the costs of aftertreatment system components and in-cylinder control technologies and describes the research underlying these values. The final section combines technology packages and cost estimates into a total cost package for emission standards, summarizing the incremental manufacturing cost of technology to comply with each progressive standard.

2. EMISSION REDUCTION TECHNOLOGIES

In this section the various strategies to reduce vehicle emissions are discussed (for more detail, see Johnson, 2010). The most important approaches include reducing formation of pollutants within the engine and control of emissions in the exhaust stream using aftertreatment technologies. As engines and emission control systems become increasingly complex, electronic system controls also take on a critical role.

IN-CYLINDER ENGINE CONTROLS

Pollutants like PM, hydrocarbons (HCs), and carbon monoxide (CO) are formed in diesel engines due to mixing challenges and incomplete fuel combustion, while NO_x is formed from high-temperature combustion conditions. Advanced engine design can manipulate in-cylinder combustion dynamics to minimize the formation of these pollutants, reducing engine-out emissions. The temperature, speed, and composition of the air entering the chamber influence burn conditions, as does the fuel delivery timing and strategy. Engine redesigns, which do not add significant hardware costs but do require investment in R&D, seek to improve combustion efficiency through engine geometries that improve mixing of air and fuel. Three strategies to reduce engine-out emissions do add hardware costs: improved fuel injection, improved air handling, and exhaust gas recirculation (EGR).

Fuel injection systems

Fuel injection pressure, rate, and timing are all used to control both NO_x and PM. High-pressure injection reduces the size of the fuel droplets (atomizing the fuel) and improves fuel penetration into the cylinder, resulting in better mixing of air and fuel. Fuel systems can further improve fuel mixing and the combustion process with redesigned nozzles and piston bowls. This leads to more complete fuel combustion that both reduces particle formation and improves fuel economy.

Electronic controls of injection allow precise and variable fuel timing and metering. In conventional fuel injection systems that employ a single injection event for every engine cycle, the timing of the fuel injection can favor either NO_x or PM control. Early fuel injection increases combustion pressures and temperatures, improves fuel efficiency, reduces PM, and increases NO_x emissions. Delayed injection of fuel reduces NO_x emissions due to lower temperatures, but also reduces fuel efficiency and increases PM emissions.

Reaching the desired trade-off between NO_x and PM emissions can be achieved with multiple injections of fuel, including pilot, main, and post injections. This strategy requires electronically controlled high-pressure unit injectors, or the now ubiquitous common rail fuel injectors, to minimize emissions of PM. Electronically controlled fuel metering and timing may also be used for late cycle injection for aftertreatment devices with active regeneration. HDVs can also employ active regeneration by using an extra fuel injector in the exhaust, as described in the section on diesel particulate filters (DPFs).

Air handling technology

The air management system of an engine must control the motion, temperature, and pressure of the air entering the chamber, ensure that it is clean, and ensure that it contains both sufficient oxygen for complete combustion and enough diluent to control the combustion temperature. Increasing the pressure of the air entering the chamber increases the air density, allowing better combustion in the brief time available. Tuning these parameters minimizes production of both PM and NO_x.

As part of the air handling system, turbochargers boost the intake air pressure. Traditional turbochargers achieve this at mid to low engine power ratings, but their narrow operational range leaves low-speed and high-torque operations with less air than required for the most efficient combustion. Variable geometry turbochargers (VGTs) improve upon traditional turbochargers by providing the right amount of air under a wider range of engine operating conditions, including at low speed and high torque. The availability of additional air reduces PM emissions and has positive effects on power output. In addition to allowing a higher air:fuel ratio at low engine speeds and improving vehicle acceleration, the VGT also enables several other emissions reduction technologies: It allows better control of the change in pressure between engine intake and output, which can be used to drive EGR flow, and provides the ability to raise exhaust temperatures to meet the needs of aftertreatment systems.

Exhaust gas recirculation systems

An EGR system recirculates a portion of exhaust gas back to the engine's cylinders. This provides diluent to the air handling system and reduces NO_x formation by lowering peak combustion temperature within the cylinder. Coolers are often included for further temperature control. EGR is the most widely used technology for in-cylinder NO_x reduction in diesel-powered engines. The EGR fraction (i.e., the share of recirculated exhaust gas in the total intake charge) is tailored to each engine operating condition and, in the latest systems, varies from zero to 40% of the incoming air.

EGR systems can be high-pressure or low-pressure, each with trade-offs and varying effectiveness under different operating conditions. A compromise between these is a dual-loop system, which combines a low-pressure cooled system with an uncooled high-pressure system (Kahrstedt et al., 2011). The EGR system requires a fuel sulfur level below 500 ppm to avoid pipe corrosion by sulfur compounds.

AFTERTREATMENT

Aftertreatment systems treat NO_x, PM, HC, and CO in the exhaust stream. Selective catalytic reduction (SCR), using urea as a reagent, controls NO_x emissions in the exhaust stream. The DPF and the diesel oxidation catalyst (DOC) control PM in the exhaust stream; they are also effective at reducing HC and CO emissions. These technologies can also be used in combination with other strategies to reduce other pollutant emissions. For example, DOCs can support SCR, and SCR systems enable in-cylinder strategies to reduce PM emissions.

Selective catalytic reduction systems

SCR systems introduce ammonia to react with NO_x over a catalytic surface, producing nitrogen and water. It is possible for SCR systems to achieve high NO_x conversion efficiencies over a relatively wide temperature range. Use of SCR allows the engine to be tuned for higher efficiency, generating lower PM emissions and higher engine-out NO_x levels, which can then be treated by the SCR system. Lower PM emissions are a result of reducing average particle size, thus reducing the mass of particles but not the number.

SCR systems have typically used either vanadium- or zeolite-based catalysts. Vanadium-based catalysts are less sulfur sensitive and tend to work well at the mid-temperature range, but lose NO_x conversion efficiency at both lower and higher temperatures. In addition, exposure to high temperature exhaust for prolonged periods can cause irreversible deactivation of the catalyst. Metal-exchanged zeolite catalysts are typically proprietary combinations of copper and iron that are effective at a wide temperature range and have high thermal stability but are more sulfur sensitive (Majewski, 2005). Pairing SCR systems with DPFs generally requires use of zeolite systems because of the high exhaust gas temperatures required for filter regeneration. The wider range of temperatures at which zeolite catalysts can operate effectively in turn enables NO_x control over a wider range of operating conditions (Table 1).

Table 1. Temperature range for catalysts using different materials.

Catalyst	Temperature range (°C)
Vanadium	300–450
Zeolite, high temperature (iron)	350–600
Zeolite, low temperature (copper)	150–450

In most commercial systems, ammonia is generated from the decomposition of a urea solution (commercially known by a variety of names such as Diesel Exhaust Fluid in the United States, AdBlue in Europe, and ARLA-32 in Brazil), which is introduced to the exhaust upstream of the catalyst. The urea solution is pumped into the exhaust from an onboard tank, which must be refilled periodically.[3] In regions that experience very low ambient temperatures (at or below 12 °F or −11°C), steps must be taken to make sure the urea solution does not freeze (this typically involves electric heaters for the urea tank, an additional cost). NO_x sensors are used to calibrate the dosing of urea. Excess urea injection or incomplete catalysis may cause excess ammonia emissions downstream of the SCR catalyst.[4] As an additional measure to control these toxic emissions, an ammonia slip catalyst (ASC) may be included downstream of the SCR system.

Alternative systems to deliver urea to SCR systems are under development. One company, Amminex, has developed a solid ammonia delivery system (AdAmmine) intended to replace current urea delivery systems. Among the advantages claimed by Amminex is the elimination of the need for (and expense of) a Diesel Exhaust Fluid injector and the improvement of SCR performance at low temperatures (Amminex, 2015).

Diesel oxidation catalysts

The DOC oxidizes HC, CO, and the soluble organic fraction of PM. In conventional heavy-duty diesel engines, the oxidation efficiency of these components is high due to the presence of excess oxygen in the exhaust. However, the contribution to total PM of the soluble organic fraction component is typically no more than 20–25% on a mass basis. Because DOCs are not able to control the solid carbonaceous fraction of PM, they have virtually no impact on the number of particles emitted. DOCs require 500 ppm or lower sulfur in diesel fuel. DOCs also play a fundamental role in SCR operations—they oxidize nitrogen oxide into nitrogen dioxide, leading to improved conversion rates in the SCR—and in regeneration of passive DPFs.

Diesel particulate filters

DPFs physically trap the solid carbonaceous fraction of PM, including black carbon. Wall-flow DPFs, which force the exhaust flow through a typically ceramic substrate, achieve PM reduction efficiencies higher than 95% due to their ability to accumulate the solid

3 US EPA guidelines require that the urea tank not have to be refilled more often than the fuel tank.

4 Ammonia emissions in gaseous form can have health and environmental impacts and can combine in the atmosphere with nitrogen- and sulfur-based acidic species to form particulate matter.

fraction of PM, including ultrafine particles. The process of removing the accumulated PM is called filter regeneration, and it can be passive or active. Passive regeneration burns the deposited material using nitrogen dioxide as an oxidizer. The nitrogen dioxide is formed from nitrogen oxide oxidation on an oxidation catalyst, which may be located upstream of the DPF or washcoated onto the filter itself. Active regeneration requires late fuel injections or fuel burners upstream of the DPF to regenerate the trap.

With the advent of SCR systems on DPF-equipped heavy-duty trucks, first introduced to meet US 2010 standards, manufacturers were able to calibrate their engines for improved fuel efficiency performance and high-NO_x/low-PM emissions. These lower engine-out PM levels allow passive regeneration to dominate the filter regeneration requirements. However, most US 2010–compliant heavy-duty trucks have a fuel injector in the exhaust to facilitate DPF active regeneration when it is needed. Some manufacturers of medium-duty diesel pickup trucks also use emission system designs that put the SCR catalyst upstream of the DPF. In these “reverse” configurations, active regeneration of the filter is necessary and a fuel injector is located in the exhaust upstream of the DPF to facilitate regeneration (J. Kubsh, personal communication, November 10, 2015).

In some regions, lower-cost partial-flow filters have been used in earlier regulatory stages. These filters direct the exhaust through a narrow metal channel and/or metallic fleece to facilitate contact with catalyzed surfaces. These systems have PM reduction efficiencies of 40–60%, with slightly higher efficiencies possible for smaller particles. These filters are used mostly for retrofits in applications where ultralow sulfur diesel is not available. This report does not estimate the cost of this type of technology.

System integration within the vehicle

A recent trend in emission control technology is the use of an integrated aftertreatment system that combines PM and NO_x control within a single system (e.g., Cummins, 2014). The SCR-on-filter approach is already in use for light-duty applications and is being tested for larger engines. This has the potential to reduce the size and cost of the systems, while improving functionality (Rappé, 2012; Strots et al., 2014). As canning, substrate, washcoat, brackets, and accessories make up 60% of the total cost of the DPF and SCR system, the potential for savings is significant.

In existing market solutions, the integration of EGR, air and fuel management, and multiple aftertreatment systems must be designed carefully, taking into account temperature, pressure, and the composition of the exhaust stream. Catalysts operate at highest efficiency within a temperature range determined by their materials: Catalyst efficiency is typically reduced at lower and higher temperatures, while durability can be impacted at higher temperatures. The temperature needs of all the components are a key consideration of full system design. For example, SCR systems equipped with vanadium catalysts cannot withstand the high operating temperatures required for integration with DPFs, and thus manufacturers have had to move to zeolite catalysts for the integrated systems required for compliance with Euro VI and US 2010 standards. As a result of both the wider temperature range of zeolite catalysts and the integration of DOCs, which further enhance low-temperature effectiveness, these integrated systems have offered better real-world control of NO_x as well as highly effective control of particle emissions.

A typical Euro IV or Euro V–compliant system would follow the schematic in Figure 4. A urea doser is installed upstream of the SCR system and requires some length to allow proper mixing of the urea. Due to challenges in packaging and building larger substrates, SCR catalysts are often installed in parallel, and sometimes more than one SCR catalyst is included in a series.

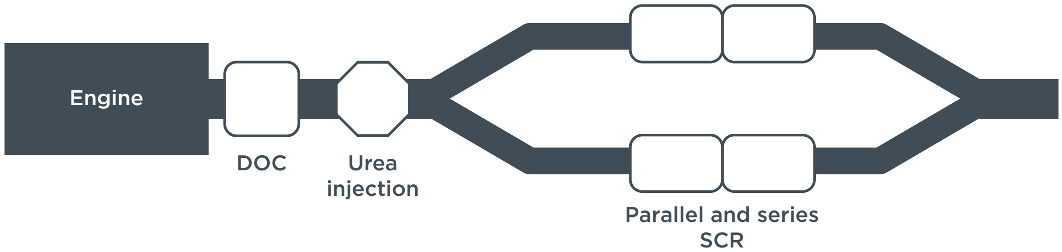

Figure 4. SCR system without DPF for Euro IV or Euro V compliance.

A US 2007–compliant vehicle follows the schematic shown in Figure 5; the DOC and DPF may or may not be combined into a single unit. In cases where fuel is directly injected for regeneration, it occurs between the engine and DOC, although most vehicles originally equipped with DPFs rely on late-cycle injections to achieve the fuel-rich exhaust required for filter regeneration.

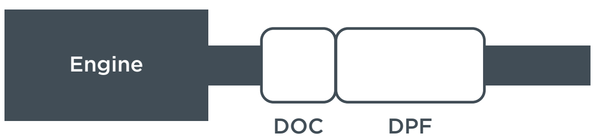

Figure 5. DPF system without SCR for US 2007 compliance.

In a Euro VI or US 2010–compliant vehicle, a typical layout follows the schematic in Figure 6. The engine-out exhaust, monitored for NO_x levels and temperature, passes through a DOC and then a DPF, followed by a urea doser, the SCR system, and the ASC. At least two temperature sensors are used between the DOC and DPF and the DPF and SCR system, and a NO_x sensor is located between the ASC and the tailpipe.

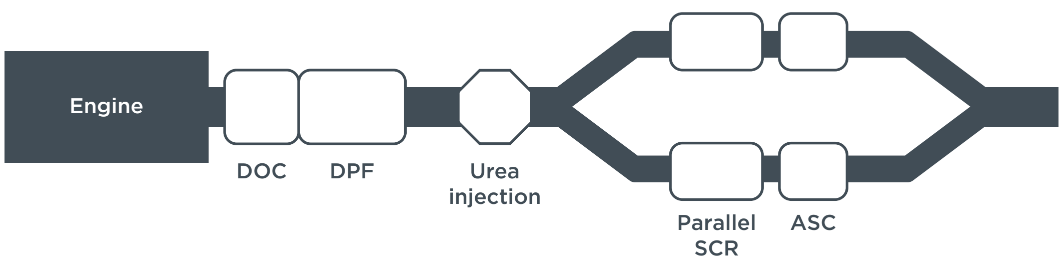

Figure 6. DPF + SCR system for Euro VI or US 2010 compliance.

SYSTEM CONTROL

The engine control unit controls the operations of many of the engine and aftertreatment systems discussed above, adjusting operations based on sensor data. Increasingly advanced vehicle standards also require increasingly advanced OBD systems. These systems gather information on engine and aftertreatment operation and alert the user when repairs are needed. OBD systems are also used by inspection and maintenance programs for light-duty vehicles, a practice that has not yet become common for HDVs. Improved engine control methods require new and more accurate sensors, many of which are then also used by the OBD system. For example, NO_x sensors are used to accurately dose urea and to monitor proper functioning of the SCR system. Manufacturers are making efforts to integrate OBD with engine control systems to provide improved tuning, fuel economy, and emission control, and are investigating more sophisticated diagnostic algorithms and wireless capabilities.

3. STANDARDS COMPARISON

The latest U.S. and European standards (US 2010 and Euro VI) both require strict control of NO_x, PM, CO, and HCs.[5] The distinct test cycles used for each program are reasonably representative of real-world conditions. Even vehicle useful life, which had been significantly less stringent in earlier Euro standards, as seen in Table 2, is reasonably well matched in the Euro VI and US 2010 standards. As a result of the similar requirements, global manufacturers follow similar compliance strategies to meet both standards: high-pressure variable fuel injection, cooled EGR (in most systems), and an aftertreatment system of DOC, DPF, SCR, and ASC in series.

Table 2. U.S. and European useful-life requirements.

Vehicle class	Euro III	Euro IV and V	Euro VI
Lightest Medium Heaviest	none	100,000 km / 5 years 200,000 km / 6 years 500,000 km / 7 years	100,000 km / 5 years 200,000 km / 6 years 500,000 km / 7 years
Vehicle class	**US 1998**	**US 2004 and more recent**	
Lightest Medium Heaviest	177,000 km / 8 years 298,000 km / 8 years 466,000 km / 8 years	177,000 km / 10 years 298,000 km / 10 years 700,000 km / 10 years / 22,000 hours	

US standards are set in miles but are given here in rounded km to enable comparison. In both standards, useful life is measured in terms of distance traveled or years of service, whichever comes first.

While Euro III and US 1998 also set similar standards and were met with similar compliance strategies, Euro IV and Euro V (the two interim steps following that stage) are not aligned in stringency or compliance strategies with US 2001 and US 2007. Euro IV requires much lower PM emissions than US 2004. Somewhat counterintuitively, manufacturers typically met Euro IV standards by introducing SCR to control NO_x, which allows control of PM through high-temperature engine tuning. The US 2004 standards are primarily met with EGR and a DOC (for more detail, see Posada & Blumberg, 2014). Euro V tightens NO_x control requirements, but leaves PM limits unchanged. On the other hand, US 2007 dramatically tightens the limits on PM emissions, leading to the use of DPFs for all new heavy-duty engines.

Recent testing on alternate test cycles revealing the loss of SCR efficiency at low-load, low-speed driving conditions means that most vehicles certified to meet Euro IV or V standards have significantly higher real-world NO_x emissions than the certification limits imply (Muncrief, 2015). Figure 7 gives both certification limits and the average, excess real-world emissions for NO_x, based on these test results. For PM emissions, both certification limits (in g/kWh on the transient test cycle) and emissions factors (in g/km) are provided.[6] The tightened PM and NO_x limits and enhanced certification procedures for Euro VI and tightened NO_x limits for US 2010 lead to the convergence of compliance strategies for the latest U.S. and EU standards, with best practice emission control systems that appear to meet certification limits in most real-world conditions for all regulated pollutants.

5 Because PM and NO_x are the technology drivers and the critical pollutants to control from diesel vehicles, only these limit values are addressed in this analysis.

6 The emissions factors are taken from the ICCT Global Transportation Roadmap model, derived from the European Environment Agency and the Joint Research Center Computer Programme to Calculate Emissions from Road Transport (COPERT) model, described in Chambliss et al., 2013.

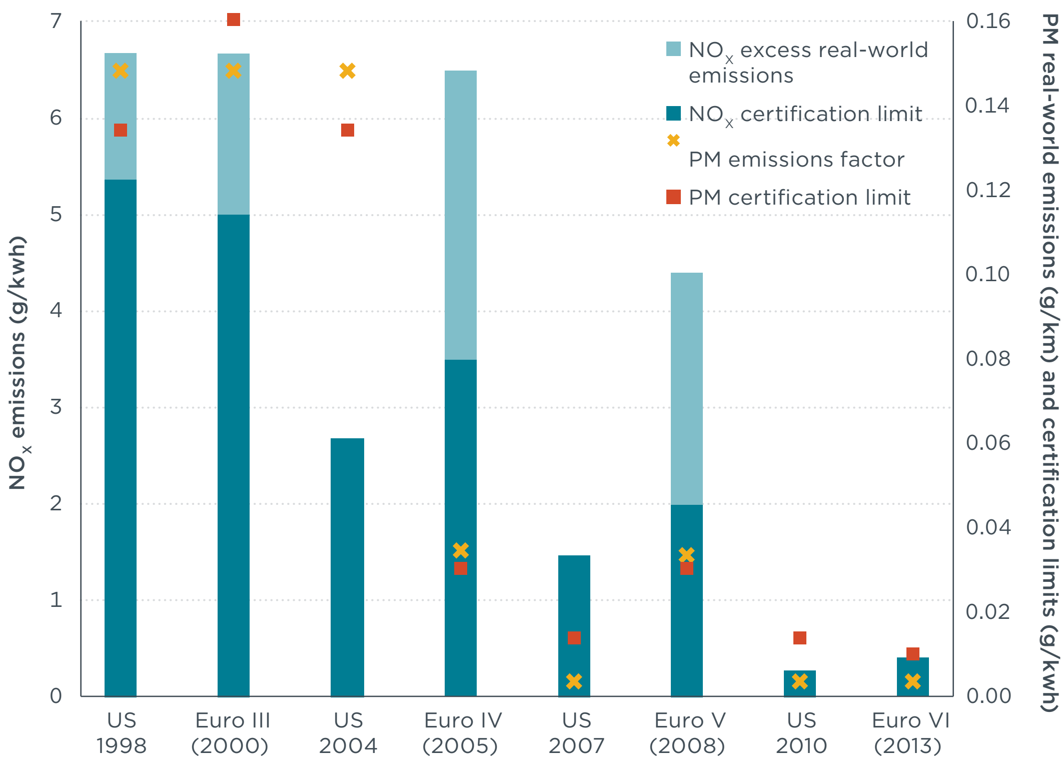

Figure 7. Emissions and limits under U.S. and European regulatory standards.

In both the United States and the EU, on-road HDV emission standards do not require the use of specific technologies. While manufacturers differ in the design parameters of the engine modifications and aftertreatment they use to meet a standard, in many cases their designs converge toward the most cost-effective option provided by current technology. This section lays out the typical compliance strategy to meet each successive standard, noting the changes with each successive standard and the cases where some manufacturers employed alternate strategies, ending with technology convergence for Euro VI and US 2010.

When estimating compliance costs in countries outside the United States and the EU that enforce equivalent standards, it may be appropriate to adjust the costs for local factors. For example, in many developing countries, average engine sizes across the heavy-duty fleet are smaller than those in the United States or Europe, which could reduce per-vehicle or per-fleet costs. In markets where there is more pressure to minimize costs, manufacturers may take additional steps to lower the costs of emission control technology, including using smaller catalyst volumes, using materials with lower tolerance for fuel sulfur content, and decreasing urea injection rates in SCR systems. While these measures could lower compliance costs, they are likely to also reduce emission control efficiency and system durability. Manufacturers who are selling advanced and advancing technologies in new markets can take advantage of the investments and learning done in the EU and the United States, effectively decreasing per-unit R&D costs. Given these factors, the incremental costs estimated in this report are expected to reflect a global perspective but may be impacted by local conditions and compliance strategies.

EUROPEAN REGULATIONS

Europe first introduced HDV emission standards in 1988. The "Euro" track was established with European Council Directive 91/542/EEC, which defined a test protocol and two sets of limits for new HDVs, Euro I and Euro II, which came into effect in 1992 and 1996. Directive 1999/96/EC introduced several stages of new standards of increasing stringency—Euro III, Euro IV, and Euro V—to be implemented in 2000, 2005, and 2008. The current Euro VI standards were introduced by Regulation 595/2009 and were implemented for new type approvals[7] in 2013. While only NO_x limits were changed in the transition from Euro IV to Euro V, Euro VI standards required significant reductions in NO_x, PM, and HC emissions. Euro VI also required a transition to the World Harmonized Test Cycle, which ensures that NO_x emissions will be controlled over a much wider range of operating conditions than the test cycle used for Euro V and earlier. As a result, and as shown in Figure 7, the real-world NO_x emissions associated with Euro IV and Euro V are significantly higher than certification limits.

Euro II, the baseline for this study, was the first standard to require a reduced-sulfur fuel at 500 ppm sulfur. Sulfur was further reduced to 350 ppm for Euro III, 50 ppm for Euro IV, and 10 ppm for Euro V. The certification limits shown in Figure 8 are for transient test cycles, except for Euro II. Euro II certification was done on a steady-state test cycle that was in use prior to adoption of the European Stationary Cycle and European Transient Cycle, which were used for Euro III through Euro V.

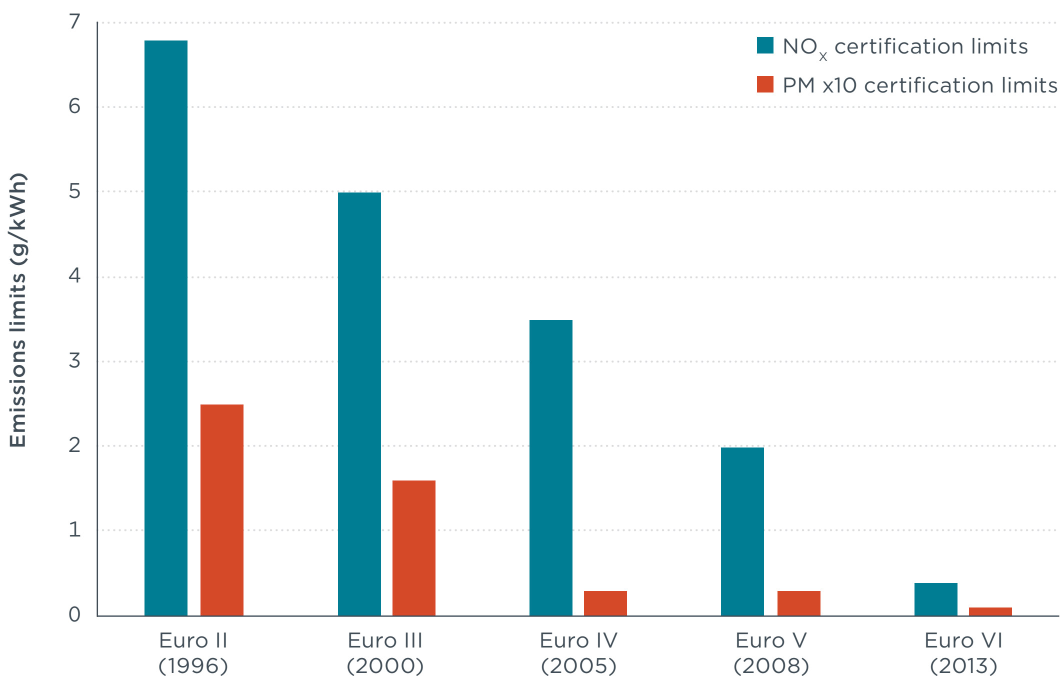

Figure 8. Emissions limits for each stage of the European standards.

Euro III is the last European heavy-duty standard that can be met without the use of aftertreatment systems. The 5 grams per kWh NO_x limit and 0.16 grams per kWh PM

7 The type approval demonstrates conformity with vehicle standards. Type approval is often required for new vehicle models earlier, and manufacturers are provided with extra time to update type approval to the latest regulations for existing models.

limit[8] are met with in-cylinder combustion improvements, including electronic control and variable injection timing.

Euro IV reduces NO_x limits by 30% to 3.5 grams per kWh and reduces PM limits by 80% to 0.03 grams per kWh. PM limits are met primarily by adjusting engine tuning to produce high-temperature conditions that minimize particulate formation. Some manufacturers also include a DOC to reduce the soluble organic fraction of PM and improve the efficiency of the SCR system. Engine tuning for reduced PM also reduces fuel consumption but results in high engine-out NO_x, which is controlled by aftertreatment. The prevailing NO_x compliance strategy analyzed here for Euro IV and beyond relies on SCR. A few manufacturers have relied solely on EGR systems, potentially with partial flow filters. Euro IV standards introduce improved durability requirements, to ensure the engine and aftertreatment do not degrade significantly during the lifetime of the vehicle, and introduce OBD requirements.

Euro V focuses on NO_x, reducing the limit by 43% to 2 grams per kWh, and maintains the Euro IV limit for PM. To meet the lower NO_x limits, those systems relying on EGR need to be supplemented with SCR. Only slight adjustments in system volume are needed for SCR systems to meet the Euro V NO_x limits. This standard augments OBD requirements.

Euro VI, the latest European standard, tightens NO_x limits to 0.4 grams per kWh and PM limits to 0.01 grams per kWh and introduces a limit of 8.0×10^{11} on the number of particles emitted.[9] On paper this is a drop of 80% for NO_x and 67% for PM. The real-world benefits are much larger, because the Euro VI limits are based on the more realistic World Harmonized Transient Cycle and World Harmonized Stationary Cycle rather than the European Transient and Stationary Cycles. As shown in Table 2, Euro VI also improves durability requirements.

To reduce NO_x emissions for Euro VI vehicles, manufacturers have relied on a combination of advanced in-cylinder controls and improvements in SCR systems. Air and fuel management technologies continue to be refined, with common rail systems now set at 2200 bar, compared to 1800 for Euro IV and Euro V, and the introduction of more complex fuel injection timing and metering algorithms and fuel injector designs. The air management system of Euro VI engines requires VGTs to match the precise timing and metering needs of the latest common rail systems. Most manufacturers still rely on SCR alone for NO_x control.[10] The switch to zeolite-based catalysts improves low temperature conversion efficiency and can tolerate the high temperatures encountered during filter regeneration. PM control is achieved with a wall flow DPF, which achieves compliance with limits on both mass and particle number Euro VI also makes significant improvements to the OBD system, adding a much more detailed list of monitoring requirements in terms of systems and conditions for monitoring, malfunction detection protocols, and management of malfunction codes. Additional OBD sensors (e.g., for NO_x) are part of the requirements.

8 These are the limits for emissions evaluated over the European Transient Cycle. PM limits are slightly lower over the European Stationary Cycle.

9 The particle number limit, new to Euro VI, regulates particle number in addition to mass of particulate matter over the engine test cycle.

10 While EGR is also common, the adoption of advanced EGR systems seems to be more widely applicable to carbon dioxide emission reduction strategies and does not imply added costs required to meet exhaust emission limits (MackAldener, 2014).

Table 3 provides an overview of the strategies for compliance with European standards.

Table 3. Strategies for compliance with recent European standards.

	Euro III	Euro IV	Euro V	Euro VI
Engine-out emissions and air/ fuel controls	• Pressure of 1500–1700 bar • Electronically controlled fueling rates • Electronic unit injectors • Variable injection	• Pressure of 1700–1900 bar • Electronic unit injectors or common rail fuel injection • Variable fuel injection (fuel timing and/or metering) • Piston redesign • Cooled EGR	No new engine technologies, only small improvements such as changes in timing strategies	• High-pressure, high-flexibility fuel injection system, with pressure greater than 2000 bar • VGT • R&D, advanced combustion, engine calibration • Sub-system integration • Cooled EGR
Aftertreatment systems	None required	• NO_x control through vanadium-based, open-loop SCR systems[a] • PM control through DOC in some vehicles, with most relying on in-cylinder control	• NO_x control through vanadium-based, open-loop SCR systems[a] • PM control through DOC in some vehicles, with most relying on in-cylinder control	• NO_x control through zeolite-based, closed-loop SCR system • ASC • PM control through DOC and DPF
OBD requirements	None	OBD stage I, including aftertreatment systems monitoring	• OBD stage II, including • Additional urea level and quality monitoring • Engine torque reduction in case of deNO_x system malfunction or low urea levels	• Additional system monitoring • Lower emission thresholds • NO_x and PM sensors

[a] Some manufacturers have chosen to control NO_x in Euro IV and V vehicles through EGR.

U.S. REGULATIONS

Federal regulation of heavy-duty engine CO, HC, and NO_x emissions in the United States began in 1974, and emissions limits were periodically tightened over the next three decades. PM limits were first implemented in 1987. Limit values were often phased in over several years. The first phase-in of more stringent NO_x and PM limits began in 1988 and was completed in 1998, comprising reductions of 62% for NO_x and 83% for PM. The next standard was required to be implemented in full in 2004. The most recent standards were phased in beginning in 2007 and came fully into force in 2010. For the purpose of this analysis, 2007 and 2010 are considered two separate stages. Limits are set in the standards in grams per brake-horsepower-hour (bhp-hr), but are converted in Figure 9 to grams per kWh. Because U.S. limits are evaluated over the transient Federal Test Procedure cycle,[11] they are not directly comparable to European limits. The US 1994

11 An additional steady-state Supplemental Emissions Test was added in a consent decree with manufacturers in 1998 and applied to the 2004 standard. This cycle was modified for the 2007–2010 standards. Supplemental Emissions Test limits have been the same as Federal Test Procedure limits for these regulatory steps.

standards, which are considered the baseline for this study, required sulfur levels in diesel to be reduced to 500 ppm. The sulfur limit was reduced to 15 ppm in 2007 as part of the US 2007/US 2010 standards.

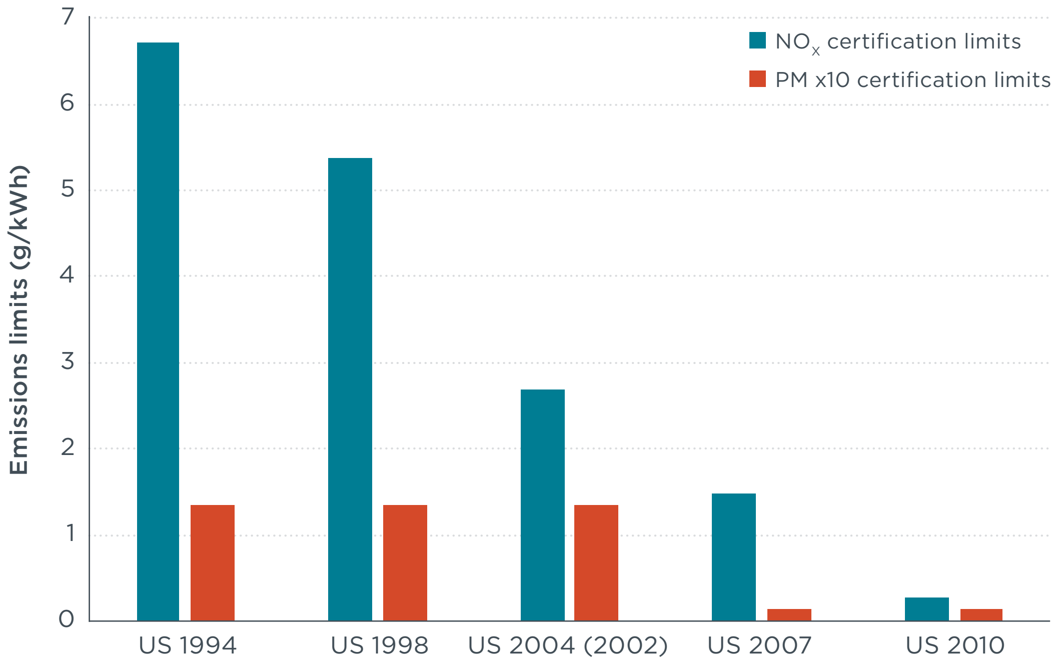

Figure 9. Emissions limits for each stage of the U.S. standards.

US 1998 is the last U.S. standard that can be met with only in-cylinder emission control, with a NO_x limit of 5.4 grams per kWh (4 grams per bhp-hr) and a PM limit of 0.13 grams per kWh (0.1 gram per bhp-hr). Combustion improvements are used to meet these standards, including electronically controlled variable fuel injection.

US 2004 limits NO_x + HC emissions to 3.2 grams per kWh (2.4 grams per bhp-hr), with an alternate NO_x limit of 2.7 grams per kWh (2 grams per bhp-hr), a reduction of 50% from US 1998 limits. It does not reduce the PM limit. Cooled EGR is used to meet NO_x standards, and DOC aftertreatment is used mainly to reduce CO and HC,[12] as well as to deal with PM emissions that can be increased with EGR.

US 2007 is the first stage of the Environmental Protection Agency's (EPA's) 2010 heavy-duty emission standards. Large reductions in both PM and NO_x are required; the PM limits took full effect in 2007, and the NO_x standards were phased in on a percent-of-sales basis from 50% in 2007 to 100% in 2010. US 2007 limits PM emissions to 0.013 grams per kWh (0.01 grams per bhp-hr), a 90% reduction from US 2004. Manufacturers complied with these limits with the use of a DPF, paired with an upstream DOC to control HC and produce nitrogen dioxide for more efficient DPF operation. Lower-cost EGR systems continued to be the primary NO_x reduction strategy for this phase of the regulation.

12 CO limits were set at 20.9 grams per kWh (15.5 grams per bhp-hr) for 1988 standards and have not been modified since. The expectations are that HC controls will also effectively control CO and separate standards will not be needed.

US 2010 is the fully phased-in stage of the 2010 standards. The NO_x limit is 83% lower than the 2004 limit at 0.27 grams per kWh (0.2 grams per bhp-hr). This stringent standard is met with a combination of in-cylinder controls and SCR. Air and fuel management primarily use common rail systems at 2200 bar along with more complex fuel injection timing and metering algorithms and fuel injector designs. The air management system of US 2010 engines requires VGTs to match the precise timing and metering needs of the latest common rail systems. To pair SCR systems with required DPFs manufacturers use zeolite-based catalysts, which are compatible with the higher temperatures associated with DPF regeneration but also cost more. Comprehensive OBD standards are required for compliance with US 2010 standards, although manufacturers were given more time to meet the full OBD requirements.

Table 4 provides an overview of the strategies for compliance with U.S. standards.

Table 4. Strategies for compliance with recent U.S. standards.

	US 1998	US 2004	US 2007	US 2010
Engine-out emissions and air/ fuel controls	• Electronic control • Electronic unit injectors • Pressure of 1500–1700 bar • Variable injection • Combustion improvements	• Electronic unit injectors or common rail • Pressure of 1700–1900 bar • Variable fuel injection • Piston redesign • Cooled EGR	• Electronic unit injectors or common rail • Pressure of 1800–2000 bar • Variable injection • Cooled EGR calibration and optimization	• High-pressure, high-flexibility fuel injection system, with pressure greater than 2000 bar • VGT • R&D, advanced combustion, engine calibration • Sub-system integration • Cooled EGR
Aftertreatment systems	None required	PM control through DOC	PM control through DOC and DPF	• NO_x control through zeolite-based, closed-loop SCR system • ASC • PM control through DOC and DPF
OBD requirements	None	None	Engine manufacturer diagnostics systems but not full OBD	• Full OBD for all models in model year 2013 • For model year 2010–2012, full OBD only for engine family with highest projected sales

4. EMISSION REDUCTION TECHNOLOGY COSTS

Based on the preceding information about emission control technology and common manufacturer compliance strategies for each emission standard, we can estimate the cost to HDV manufacturers to comply with the standards. This analysis derives the incremental costs directly from the material and manufacturing costs of major engine and emission control technologies, following the same steps employed by Posada et al. (2012) for light-duty vehicles. The following estimates include detailed information on the characteristics and costs of each technology, especially for aftertreatment systems.

METHODS

This cost assessment is necessarily indirect because total technology costs are known only to manufacturers, who are unwilling to share this information because of competitiveness concerns. Government agencies may be able to request and obtain specific cost information under confidentiality agreements for regulatory purposes. Usually the regulatory agency hires a consulting company to estimate the cost; the consulting company estimates the technology required and obtains prices from suppliers. Suppliers only know the pricing of their particular components. Beyond that, there are only a few scattered sources of information.

Initial cost values

The initial cost data for this report were found in public reports of government agencies' regulatory impact assessments (RIAs) and adjusted for inflation. For U.S. regulations, emissions reduction costs were found in the EPA RIAs for the 2004 emission standards (EPA, 1997) and the more comprehensive EPA 2010 rulemaking, which covered the regulatory stages for US 2007 and US 2010 (EPA, 2000).

A regulatory agency's technology cost assessment is a projection into the future, based on technologies that are currently available or under development, and therefore its accuracy is limited. RIAs' estimates of technology requirements may differ from the technology that is actually developed and commercialized. As an example, EPA's 2010 rule forecast that NO_x adsorbers would be applied as the primary NO_x control technology, when in fact the more costly SCR systems assessed in this report were needed to achieve the regulatory requirements. While not always accounted for in this analysis, manufacturers also often find unexpected ways to reduce compliance costs. This is especially true for catalyst technology, in which improvements have resulted in substantial savings in terms of precious metals use.

Cost adjustments and other assumptions

The initial cost values, and the technical parameters that affect the cost of emission control technologies, were adjusted after a comprehensive review of available publications (principally SAE International technical papers) and presentations. Additional adjustments followed from direct expert consultations. As an example, the swept volume ratio (SVR) parameter, used to relate the size of a particle filter or catalyst to the engine size, as well as platinum group metal (PGM) loading and washcoat loading, were updated for most of the catalytic systems from the initial values to better reflect the current status of emission control technologies.

The cost figures obtained from such a wide spectrum of sources were condensed into a table, which was reviewed by a small group of representatives of emission control industries and vehicle manufacturers at the request of the ICCT. Adjustments of those costs were made based on their input, resulting in the final values presented in this report.

Cost values for certain emission control technologies were not available in the literature, so an alternative approach was taken. Average commercial prices were obtained from several auto-parts and supplier websites and then corrected by dividing the number by a fixed factor that scales the commercial price to manufacturer cost. The fixed factor used in this cost assessment, 2.5, closely matched the costs of some technologies listed in RIAs with commercial prices cited on auto-parts retailers' websites. The same 2.5 value was used in the non-road diesel engines impact assessment to set the warranty cost (commercial value) of spare parts based on direct manufacturing costs (EPA, 2004).

Another important methodological issue is the treatment of technologies that are used not only for emission control but also for vehicle operation or performance, such as fuel injectors and turbochargers. For those technologies, half their corrected costs were assumed to go to emission control and the other half to improving performance and fuel economy.

Cost inputs were corrected for inflation and total costs are presented in 2015 USD. This assessment does not include discounts for technologies that have undergone cost reductions due to process learning and volume sales; thus, cost estimates presented here are conservative.[13]

COSTS OF EMISSION CONTROL TECHNOLOGIES

Assumptions are described below for technology costs to the manufacturer for development and use of systems that contribute to emission control, including in-cylinder controls, OBD, aftertreatment systems, and R&D.

In-cylinder controls

Proper fuel injection control (timing and metering), adequate air induction management (to properly match the fuel quantity), and mixing, as discussed earlier, are the most important aspects of controlling in-cylinder emissions from diesel-powered vehicles. Besides air and fuel control, the in-cylinder control also involves NO_x control using cooled EGR.

Fuel injection systems

The main fuel injection systems currently used in heavy-duty applications are the unit injector, unit pump, and common rail systems. These replaced the in-line pump, used widely in Euro I diesel vehicles.

Modern fuel injection systems generally consist of one pump, an injector for each engine cylinder, and an electronic control unit for fuel timing and metering. The use of electronically controlled fueling strategies (multiple, variable timing and metering) may require a number of sensors in addition to the electronic control unit. The fuel injection system does not change much with engine size, although larger engines use larger rails in a common rail system, up to 60 cubic centimeters.

The cost to upgrade a fuel system from rotary to common rail fuel injection is estimated as $750. This estimate comes from extrapolating the cost of non-road engines as

13 It is widely accepted that as new technologies enter the market, manufacturing costs tend to drop quickly due to increased production volume and improved production processes. In its cost analysis, the US EPA estimates 10% reduction per doubling of production volume and 1–3% reduction per year from process improvements (EPA, 2010).

described in the RIA prepared by ICF International for EPA's Tier IV non-road diesel engines standards (2004). In that report, the engines have 2 and 3 cylinders. Thus, a linear extrapolation was developed for each cost item (injector, pump, electronic control system, sensors and wiring) based on cylinder count. It is evident that the baseline non-road engine used for our injector system cost estimate is technically less complex than the baseline Euro III injector system defined in this report, which is a unit injector system. Thus, $750 is considered a conservative estimate. The cost assigned to emission control technologies is 50% of that, $375, as the fuel injection system has other functions besides emission control. The other 50% is allocated to engine operation and performance.

The Euro IV, Euro V, and Euro VI fuel injection system costs were estimated by correcting the Euro III proportionally based on injection pressure, which increased from 1,300 bar to 2,200 bar. A 10% increase in cost with respect to the previous technology was applied for Euro IV, Euro V, and Euro VI; the cost of US 2010 technology was assumed to be equal to Euro VI. This cost increase estimate is conservative, as in many cases technology tends to provide better performance at the same cost over time.

Variable geometry turbochargers

For diesel engines, turbochargers are key elements for achieving high performance and low emission levels. The first turbochargers commercially offered were wastegate turbochargers, limited to operating properly at mid-loads. These turbos were the prevailing strategy for compliance with baseline regulatory limits for this study and dominated HDV markets for most vehicles until the advent of Euro V and US 2010. Variable geometry turbochargers (VGTs), which include a mechanism for varying the turbine geometry, allow for better PM and NO_x control and increased fuel economy due to proper air delivery during most of the operating engine envelope (the range of engine speed to load that is encountered).

A VGT is made from stainless steel and has much more complex geometry, mechanisms, and electric actuators than a fixed geometry turbocharger made from galvanized steel with no actuation except the wastegate valve. The size of the air handling system scales up with larger engines.

An electrically actuated VGT is estimated to add $370 to the cost of the traditional wastegate turbocharger and cooler. As with fuel injection system costs, only 50% of the cost of the VGT is counted toward emission standard compliance, as these systems also provide performance benefits.

Exhaust gas recirculation valve and cooling

The EGR system consists of piping, flanges, gaskets, one or more EGR control valves, and one or more EGR coolers. It may also include a heater plate for use at low ambient temperatures. The EGR system is estimated to cost $439, with an additional $108 (ranging from $85 to $130) for a cooling system.[14] In recent years, several manufacturers have introduced systems that do not include an EGR system, but EGR remains a prevailing technology for compliance with current European and U.S. standards.

14 For light-duty diesel vehicles meeting Euro 6 standards, it is expected that those that will not use SCR for NO_x control will require dual loop EGR systems, which in turn require a double set of EGR valves (high and low pressure) and a low-pressure loop cooler (Johnson, 2011). Dual EGR systems are not required for US 2010 or Euro VI compliance, although it is likely the greenhouse gas and fuel economy regulations and goals would result in adopting this technology.

Onboard diagnostic systems

The cost of an OBD system was estimated to range from $350 to $500. This analysis uses a value of $425 for a full OBD system. As OBD systems are further integrated with engine control units, compliance costs will drop further and be increasingly difficult to distinguish. The estimate here includes the cost of R&D and demonstration for an entire engine family, spread across the total number of units produced in the primary regulatory market. While other OBD sensors are included in this estimate, the costs of NO_x sensors and others required by the inclusion of SCR aftertreatment systems are included as a line item for the aftertreatment systems rather than within this estimate.

Table 5 summarizes in-cylinder control and OBD costs.

Table 5. In-cylinder control and OBD costs.

Technology	Cost
Fuel system, common rail or extra with respect to unit injector systems	$750 + 10% for each successive standard
VGT (extra cost with respect to turbocharger)	$370
EGR system	$439
EGR intercooler	$108 ($85–130)
Full OBD	$425 ($350–$500)

Aftertreatment systems

The cost structure of the three aftertreatment systems considered—DOC, catalyzed DPF, and SCR—includes the catalyst itself, composed of the substrate, washcoat, and precious metal loading; a stainless steel can for structural support; and various system accessories. The SCR system costs also include the urea storage and dosing system.

An important cost for both the DOC and the DPF are the precious metal loading on the catalyst. The DOC includes the precious metals platinum and palladium in a ratio that can vary from 1:1 to 5:1 platinum:palladium, with a typical ratio of 2:1 and total precious metal loading of 0.2 g per liter. DPF platinum:palladium ratios can vary from 5:1 to 1:1, with a typical ratio of 2:1. Total precious metal loading can be as low as 0.4 g per liter, but more typically ranges from 1.0 to 1.4 g per liter. Catalyst costs were taken as the average three-month price in the commodity market, at $30/g for platinum and $18/g for palladium.[15] The size of the catalyst depends on the engine displacement.

The other components for both DOCs and DPFs are substrate, washcoat, canning, and accessories. In addition, DPFs require a regeneration system, which includes a differential pressure sensor, temperature sensor, wiring, additional electronic control unit processing capabilities, and in some cases an oxygen sensor; an injector is also used in most HDV applications.

The cost for the SCR catalyst is split between the catalyst system (the substrate, washcoat, and canning) and the urea system. Many components of the urea system scale by the urea tank volume. The urea tank volume scales by engine displacement but does not vary between regulatory standards, as better NO_x conversion efficiencies are

15 Three-month average, rounded prices in grams were used for platinum and palladium, covering the November 2015 through January 2016 time frame (Apmex, 2016a, 2016b; Palladiumpriceoz.com, 2016; Platinumpriceoz.com, 2016).

gained over time through increased catalyst volume, better catalysts, and better control (NO_x sensor).[16] The urea system includes a tank and tank accessories (brackets, bolts, and spacer), urea pump and injector, tubing, heating system, sensors (one for urea level, two for temperature, and one for NO_x), and a dosing control unit. Euro VI and US 2010 systems typically include an ASC.

All of the catalyst system costs scale directly with catalyst volume, which is again scaled to engine displacement volume, and with the loading of precious metals in the catalyst. Industry research has led to reductions in cost by lowering the ratio of catalyst volume to engine displacement volume, the SVR, and reducing the per-volume loading of precious metals. Much of the literature on SVR and precious metal loading refers to laboratory results rather than commercially deployed technology, so there were limited reference points to adjust the values presented here. The relevant sources are noted in Table 6.

Table 6. Literature values referenced for aftertreatment costs.

Technology	Parameter	Value	Source
DOC	Catalyst loading	1.4 g/L	Desai et al., 2010; Glover, 2011
	SVR	0.5–0.75, 0.83	Johnson, 2011; Folic et al., 2010
Catalyzed DPF	Catalyst loading	0.18 g/L–0.7g/L	Voss, 2011; Xu, 2009
	SVR	1.42, 2	Folic et al., 2010; Voss, 2011
Euro IV SCR	SVR	1.7–2.5	Arrowsmith et al., 2006; Cho et al., 2008
Euro V SCR	SVR	1.4–2.8	Blakeman, 2009; Johnson, 2002
Euro VI SCR	SVR	1.8–2.8	Folic et al., 2010

An average of values found in the literature for SVR and catalyst loading (adjusted and confirmed through consultation with industry experts) was used to adjust the estimated costs of aftertreatment technologies. The final cost estimates are presented below for DOCs (Table 7), DPFs (Table 8), and SCR systems (Tables 9, 10, and 11).

Table 7. Diesel oxidation catalyst costs.

Engine displacement	9.0 L	12.0 L	15.0 L
Catalyst volume (SVR = 0.75)	**6.8 L**	**9.0 L**	**11.3 L**
Platinum 0.94 g/L × CV × $30/g	$190	$254	$317
Palladium 0.47 g/L × CV × $18/g	$57	$76	$95
Substrate ($6 × CV)	$41	$54	$68
Washcoat ($6 × CV)	$41	$54	$68
Total PGMs + substrate + washcoat	**$329**	**$438**	**$548**
Canning ($5 × CV)	$33	$45	$56
Accessories	$15	$15	$15
Total manufacturing	**$377**	**$498**	**$619**

CV = catalyst volume.

16 The urea tank volume was assumed to be 12 × engine displacement volume: 108 L for the 9 L engine, 144 L for the 12 L engine, and 180 L for the 15 L engine.

Table 8. Catalyzed diesel particulate filter costs.

Engine displacement	9.0 L	12.0 L	15.0 L
Catalyst volume (SVR = 2.0)	18 L	24 L	30 L
Platinum 2/3 × 0.2 g/L × CV × $30/g	$72	$96	$120
Palladium 1/3 × 0.2 g/L × CV × $18/g	$22	$29	$36
Substrate ($30 × CV)	$540	$720	$900
Washcoat ($13 × CV)	$234	$312	$390
Total PGMs + substrate + washcoat	**$868**	**$1,157**	**$1,446**
Canning ($5 × CV)	$90	$120	$150
Accessories—brackets	$40	$40	$40
Regeneration system	$81	$81	$81
Total manufacturing	**$1,079**	**$1,398**	**$1,717**

CV = catalyst volume.

Several components of future SCR systems are not required and thus not included in Tables 9 and 10. Precious metals are not required for either Euro IV or Euro V SCR system, and base metal costs are negligible. An ASC is also not used in either regulatory stage. NO_x sensors are not required for Euro IV systems but are included in Table 10 for Euro V systems.

Table 9. Costs of vanadium-based SCR system used for Euro IV.

Engine displacement	9.0 L	12.0 L	15.0 L
Catalyst volume (SVR = 2)	18 L	24 L	30 L
Substrate and washcoat cost (vanadium: $12 × CV)	$216	$288	$360
Canning cost ($30 × CV)	$540	$720	$900
Total PGMs + substrate + washcoat	**$756**	**$1,008**	**$1,260**
Urea tank cost	$338	$409	$474
Urea level sensor cost	$48	$48	$48
Urea tank accessories cost (brackets, bolts, spacers)	$33	$36	$40
Urea pump cost	$85	$94	$101
Urea injector cost	$56	$62	$67
Stainless steel tubing cost	$140	$140	$140
Urea injection pipe section cost (6 cm in diameter × 38 cm long)	$112	$112	$112
Urea injection mounting cost (brackets, bolts, gaskets, spacers, etc.)	$33	$36	$40
Urea heating system cost (200 W, 12 V DC)	$66	$72	$78
Temperature sensor cost (4 sensors per system)	$84	$84	$84
Mixer cost	$100	$115	$149
Dosing control unit cost	$170	$170	$170
Total urea system cost	**$1,265**	**$1,378**	**$1,503**
Total manufacturing cost	**$2,021**	**$2,386**	**$2,763**

Vd = engine displacement; CV = catalyst volume.

Table 10. Costs of vanadium-based SCR system used for Euro V.

Engine displacement	9.0 L	12.0 L	15.0 L
Catalyst volume (SVR = 2.5)	22.5 L	30 L	37.5 L
Substrate and washcoat (vanadium: $12 × CV)	$270	$360	$450
Canning ($30 × CV)	$675	$900	$1,125
Total PGMs + substrate + washcoat	**$945**	**$1,260**	**$1,575**
Urea tank cost	$337	$409	$474
Urea level sensor cost	$48	$48	$48
Urea tank accessories cost (brackets, bolts, spacers)	$33	$36	$40
Urea pump cost	$85	$94	$101
Urea injector cost	$57	$62	$67
Stainless steel tubing cost	$140	$140	$140
Urea injection pipe section cost (6 cm in diameter × 38 cm long)	$112	$112	$112
Urea injection mounting cost (brackets, bolts, gaskets, spacers, etc.)	$33	$36	$40
Urea heating system cost (200 W, 12 V DC)	$66	$72	$78
Temperature sensor cost (4 sensors per system)	$84	$84	$84
Mixer cost	$100	$115	$149
Dosing control unit cost	$170	$170	$170
NO_x sensor cost ($170 × 1 per system)	$170	$170	$170
Total urea system	**$1,435**	**$1,548**	**$1,673**
Total manufacturing	**$2,380**	**$2,808**	**$3,248**

Vd = engine displacement; CV = catalyst volume.

Table 11. Costs of zeolite-based SCR system used for US 2010 and Euro VI.

Engine displacement	9.0 L	12.0 L	15.0 L
Catalyst volume (SVR = 2.5)	22.5 L	30 L	37.5 L
ASC (CV [SVR = 0.2 × Vd] × 0.2 g/L × $28/g)	$11	$14	$18
Substrate and washcoat (copper/iron zeolites: $18 × CV)	$405	$540	$675
Canning ($30 × CV)	$675	$900	$1,125
Total PGMs + substrate + washcoat	$1,091	$1,454	$1,818
Urea tank cost	$337	$409	$474
Urea level sensor cost	$48	$48	$48
Urea tank accessories cost (brackets, bolts, spacers)	$33	$36	$40
Urea pump cost	$85	$94	$101
Urea injector cost	$57	$62	$67
Stainless steel tubing cost	$140	$140	$140
Urea injection pipe section cost (6 cm in diameter × 38 cm long)	$112	$112	$112
Urea injection mounting cost (brackets, bolts, gaskets, spacers, etc.)	$33	$36	$40
Urea heating system cost (200 W, 12 V DC)	$66	$72	$78
Temperature sensor cost (4 sensors per system)	$84	$84	$84
Mixer cost	$100	$115	$149
Dosing control unit cost	$170	$170	$170
NO_x sensor cost ($170 × 2 per system)	$340	$340	$340
Total urea system	$1,605	$1,718	$1,843
Total manufacturing	$2,696	$3,172	$3,661

Vd = engine displacement; CV = catalyst volume.

Research and development

R&D costs are accrued by manufacturers for improving engine-out emissions while integrating the aftertreatment system with the engine and powertrain system. Cost data on R&D for engine and aftertreatment integration can only be found in RIAs. For this analysis, we used the values provided by the EPA in its impact analysis of the US 2010 emissions regulation (EPA, 2000). According to the EPA, R&D aftertreatment integration costs are incurred for engineers' and technicians' time, plus the cost for engine test cell time and prototype system fabrication. These costs are split by emissions target, PM and HC control and NO_x control. EPA-estimated integration R&D costs are presented in Table 12. The values for medium heavy-duty engines are higher than those for heavy heavy-duty engines due to the larger market size of the HDV sector, which makes it possible to spread R&D costs over a larger number of units.

Table 12. Estimated R&D costs for integrating emission control technology.

	Light heavy-duty diesel engines	Medium heavy-duty diesel engines	Heavy heavy-duty diesel engines and urban buses
PM/HC control	$37	$86	$79
NO_x control	$81	$213	$178

These values are required for each regulatory step where DPF and SCR are introduced for emission control. As a result, R&D integration costs for PM/HC control are applied here only to US 2007, US 2010, and Euro VI; R&D costs for NO_x control integration are applied to US 2010 and Euro IV.

5. INCREMENTAL COSTS OF RECENT EMISSION STANDARDS

The final step in the analysis focuses on Euro III through Euro VI and US 1998 through US 2010.[17] For each regulatory stage, the total incremental costs are estimated by matching the technologies required for that stage (Tables 3 and 4) with their costs (Tables 5 and 7 through 12). Because the same compliance strategies and technologies are used to meet Euro VI and US 2010, the cumulative cost of compliance with these final, aligned standards is the same: $6,937 per 12 L engine.

The costs presented here represent updated estimates of manufacturer compliance costs. These include costs for materials and R&D but not for manufacturers' certification or warranty. They also do not include the operational costs or savings incurred by vehicle owners—including improved fuel economy, added cost of diesel exhaust fluid and low- or ultralow-sulfur fuel, and any adjustments in maintenance costs. As noted in the introduction, pricing strategies are not necessarily aligned with manufacturer costs, and this analysis does not attempt to estimate consumer impacts.

These estimates improve on past assessments that projected the technology needs to meet upcoming regulatory stages. The analysis is informed by publicly available data on in-cylinder and aftertreatment technologies that are in widespread commercial use, and cost factors have been adjusted based on industry review. Nonetheless, these values are only approximations, as information on the exact costs of most engine and aftertreatment technology is protected as a trade secret. Where cost data are available only for consumer prices for parts and technologies, the analysis uses a standard factor to estimate the much lower cost to manufacturers operating at scale. Whenever more concrete data are not available, we generally over- rather than underestimate the potential costs. Significant savings are expected from ongoing technology improvements, such as the combined SCR and DPF aftertreatment systems now entering the market, and further process learning and production scaling. As a result, we expect that the cost estimates given here will continue to decline in the coming years.

Tables 13 and 14 list the incremental cost of each component, compared with its cost under the previous standard. For components that, in addition to emission control, serve other purposes such as performance improvement or basic functioning, only 50% of the cost is considered in this analysis.

17 As mentioned above, the Euro III and US 1998 regulatory stages only accounted for the major technologies that would be carried into future standards and may have underestimated the total cost of the transition from the Euro II and US 1994 baselines.

Table 13. Technology costs to meet European standards at different stages for a 12 L engine.

	Euro III	Euro IV	Euro V	Euro VI
Hardware				
Air/fuel control and engine-out emissions				
Fuel system—50% of total cost	$376	—	$38	$41
VGT (extra cost)—50% of total cost	—	—	—	$185
EGR system	—	$439	—	—
EGR cooling	—	$108	—	—
Total for air/fuel control and engine-out emissions	*$376*	*$547*	*$38*	*$226*
Aftertreatment systems				
DOC	—	$498	—	—
DPF	—	—	—	$1,398
SCR	—	$2,386	$422	$364
Total for aftertreatment systems	—	*$2,884*	*$422*	*$1,762*
Total for hardware	$376	$3,431	$460	$1,988
OBD and sensors	—	$212	—	$213
R&D	$50	$128	—	$79
Incremental cost (compared to the previous standard)	**$426**	**$3,771**	**$460**	**$2,280**
Cumulative incremental cost (compared to Euro III)	**$426**	**$4,197**	**$4,657**	**$6,937**

Table 14. Technology costs to meet U.S. standards at different stages for a 12 L engine.

	US 1998	US 2004	US 2007	US 2010
Hardware				
Air/fuel control and engine-out emissions				
Fuel system—50% of total cost	—	$376	$38	$41
VGT (extra cost)—50% of total cost	—	—	$185	—
EGR system	—	$439	—	—
EGR cooling	—	$108	—	—
Total for air/fuel control and engine-out emissions	—	*$923*	*$223*	*$41*
Aftertreatment systems				
DOC	—	$498	—	—
DPF	—	—	$1,398	—
SCR	—	—	—	$3,172
Total for aftertreatment systems	—	*$498*	*$1,398*	*$3,172*
Total for hardware	—	$1,421	$1,621	$3,213
OBD and sensors	—	—	—	$425
R&D	$50	—	$29	$178
Incremental cost (compared to previous standard)	**$50**	**$1,421**	**$1,650**	**$3,816**
Cumulative incremental cost (compared to US 1998)	**$50**	**$1,471**	**$3,121**	**$6,937**

Because the final standards are similar and based on reasonably representative use cycles, the compliance strategies and thus the final cumulative incremental costs of the US 2010 and Euro VI standards are the same. The costs estimated here are slightly lower than estimates in earlier ICCT analyses but somewhat higher than estimates in the EPA's RIAs (Blumberg et al., 2014; EPA, 2000). On the other hand, a 2006 assessment by TNO Science and Industry for the European Commission projected that costs for moving from Euro IV to Euro VI would be two and a half to three times higher than the estimate given here (Gense et al., 2006). Unfortunately, the modeling approach used makes it difficult to compare specific technology costs. A backward-looking assessment such as the one presented here has the benefit of clear understanding of the most common compliance strategies and commercially available technologies.

Figure 10 provides a comparison of costs, juxtaposed with PM emissions factors. The Euro VI and US 2010 standards offer very good benefits compared to their incremental costs. The costs and benefits of interim steps, however, vary widely. From an emission control perspective (both PM and NO_x), US 2007 had the lowest cost and highest benefit. This interim regulatory stage is, however, no longer commercially available, nor was it favored by consumers because it did not offer the fuel efficiency benefits of Euro VI or US 2010. Euro IV and Euro V did offer PM benefits, although in the form of a reduction in particle size, not particle number, reducing the mass but doing less to affect the overall health impacts of the vehicles. These lesser benefits also came at a higher cost than the US 2007 regulatory stage.

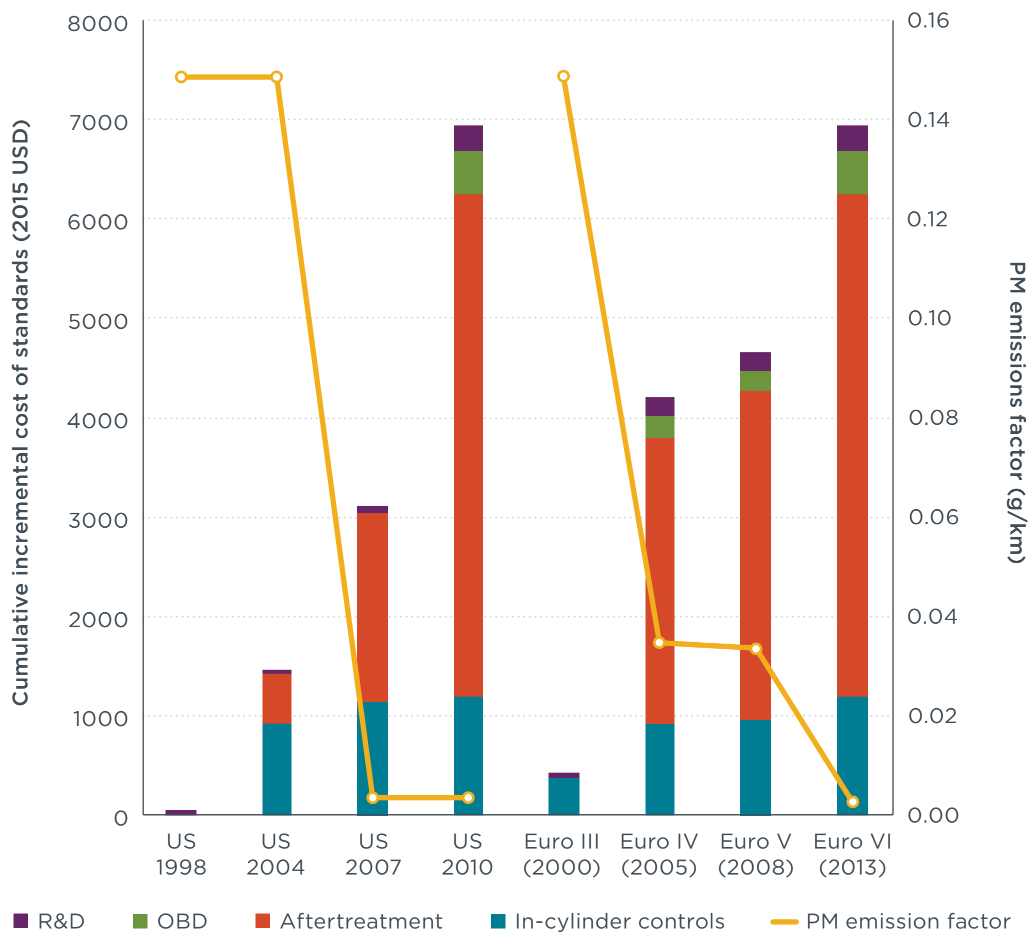

Figure 10. Cumulative costs and PM emissions factors for each regulatory stage.

The final regulatory steps to date in both regions are well aligned. At approximately $7,000 per vehicle (assuming a 12 L engine) compared to US 1994 or Euro II standards, these standards offer approximately a 95% reduction in real-world NO_x emissions and a 98% reduction in PM emissions. And these stringent standards have been implemented as we continue to see significant reductions in fuel consumption and greenhouse gas emissions from heavy trucks. The strong benefits of full implementation of Euro VI and US 2010, along with some of the downsides and high costs of the interim standards touched upon in this report, suggest that other regions should move as quickly as possible to harmonize with these world-class standards.

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