

# Costs of Emission Reduction Technologies for Diesel Engines Used in Non-Road Vehicles and Equipment

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## 1. Introduction

### BACKGROUND

Diesel engines used to power non-road equipment and vehicles, such as agricultural tractors and construction equipment, are a significant source of air pollutant emissions, especially particulate matter (PM) and nitrogen oxides (NO<sub>x</sub>).<sup>1</sup> These emissions have significant societal impacts, contributing to poor air quality, negative human health impacts, and climate change.

Recognizing the importance of controlling emissions from this source category, several regions around the world, led by the United States and the European Union, have implemented performance-based emission standards for non-road diesel engines. Standards were first introduced by the United States in 1996, followed by the EU in 1999. In subsequent years, each region has advanced its non-road engine control program through increasingly

stringent standards, including reduced emission limits and more challenging certification test procedures. This regulatory progression has been instrumental in the technological development of non-road diesel engines. These engines now incorporate improved emission control technologies and produce less than 10% of the pollutants emitted by their predecessors.

Regulatory programs developed in the United States and Europe historically have served as the model for programs adopted in other regions. Some countries, such as Japan, South Korea, and Canada, generally have kept pace with developments in the United States and the EU. Others, like India and China, remain 5–10 years behind. For countries where standards lag behind international best practices or where no standards are in place, there is a significant opportunity to reduce emissions of harmful air pollutants from non-road engines through further regulatory action.

The costs of non-road engine emission regulations are an important consideration for policymakers when evaluating new standards. In this paper, we look at one component of the cost of non-road emission control regulations—the costs incurred by engine manufacturers for emission reduction

technologies needed to meet more stringent standards. This analysis builds upon similar assessments conducted in support of U.S. and EU rulemaking, with updated cost estimates reflective of prevailing compliance strategies. Results will be useful to countries and regions considering further development of their non-road engine emission control programs.

### SCOPE

This paper aims to quantify the per-engine costs incurred by non-road engine manufacturers to comply with U.S. and European emission standards. We consider the direct material and manufacturing costs of major emission reduction technologies and fixed costs related to research and development, tooling, and certification. The total cost of emission reduction technologies is evaluated for each regulatory step, from Tier 2/3 to Tier 4f standards in the United States and from Stage II/IIIA to Stage V standards in the EU. The methodology used here follows previous studies of manufacturing costs of emission control technologies for on-road light- and heavy-duty vehicles (Posada-Sanchez, Bandivadekar, & German, 2012; Posada, Chambliss, & Blumberg, 2016).

<sup>1</sup> For the purposes of this paper, the term non-road engine will refer solely to engines used in non-road vehicles and equipment, such as those common in the agricultural and construction sectors. This definition excludes other non-road sources—locomotives, marine vessels, and aircraft—which are beyond the scope of this paper.

In this analysis, we do not assess the operational costs incurred by equipment owners, including the cost of diesel exhaust fluid and low- or ultralow-sulfur fuel as well as any change in maintenance costs. Nor do these estimates include costs incurred by equipment manufacturers for equipment redesign, new hardware, and increased equipment assembly time, as equipment manufacturers purchase a complete engine and emission control package from engine manufacturers. Pricing strategies are not necessarily aligned with manufacturer costs, and this analysis does not attempt to estimate consumer impacts.

Section 2 presents an overview of the evolution of non-road engine emission control programs in the EU and United States. Section 3 includes a general discussion of technologies used to reduce emissions from diesel engines, including in-cylinder controls and exhaust aftertreatment systems. Section 4 identifies emission control technologies typically used by manufacturers at each regulatory step. Section 5 details our methodology for calculating the costs of these emission control technologies. In the final section of the paper, engine technology pathways are combined with emission control technology costs to evaluate the total cost of

compliance for engine manufacturers at each regulatory step.

## 2. Standards comparison

The U.S. Environmental Protection Agency first promulgated emission standards for non-road diesel engines in 1994, followed by the European Union in 1997. In order to avoid disparity between engines sold in both regions, standards adopted in the two generally parallel each other. U.S. and EU regulatory programs have served as models for other countries establishing programs to control emissions from non-road diesel engines. Successive, more stringent U.S.

		UNITED STATES																									
Engine Rating kW	Engine rating hp	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	
P < 8	P < 11										8.0 / (10.5) / 1.0																8.0 / (7.5) / 0.4 <sup>a</sup>
8 ≤ P < 19	11 ≤ P < 25										6.6 / (9.5) / 0.8																6.6 / (7.5) / 0.4
19 ≤ P < 37	25 ≤ P < 50																										5.5 / (4.7) / 0.03
37 ≤ P < 56	50 ≤ P < 75																										5.0 / (4.7) / 0.03
56 ≤ P < 75	75 ≤ P < 100																										5.0 / (4.7) / 0.03
75 ≤ P < 130	100 ≤ P < 175																										5.0 / 0.19 / 0.40 / 0.02
130 ≤ P < 225	175 ≤ P < 300																										3.5 / 0.19 / 0.40 / 0.02
225 ≤ P < 450	300 ≤ P < 600																										3.5 / 0.19 / 2.0 <sup>a</sup> / 0.02
450 ≤ P < 560	600 ≤ P < 750																										3.5 / 0.4 / 3.5 / 0.10 <sup>a</sup>
P ≥ 560	P ≥ 750																										3.5 / 0.19 / 3.5 / 0.04 <sup>a</sup>

		EUROPEAN UNION Tier 3 / Stage IIIA																									
Engine Rating kW	Engine rating hp	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	
P < 8	P < 11																										8.0 / (7.5) / 0.4
8 ≤ P < 19	11 ≤ P < 25																										6.6 / (7.5) / 0.4
19 ≤ P < 37	25 ≤ P < 50																										5.0 / (4.7) / 0.015 <sup>f</sup>
37 ≤ P < 56	50 ≤ P < 75																										5.0 / (4.7) / 0.015 <sup>f</sup>
56 ≤ P < 75	75 ≤ P < 100																										5.0 / (4.7) / 0.015 <sup>f</sup>
75 ≤ P < 130	100 ≤ P < 175																										5.0 / 0.19 / 0.4 / 0.025
130 ≤ P < 225	175 ≤ P < 300																										3.5 / 0.19 / 0.4 / 0.025
225 ≤ P < 450	300 ≤ P < 600																										3.5 / 0.19 / 0.4 / 0.025
450 ≤ P < 560	600 ≤ P < 750																										3.5 / 0.19 / 3.5 / 0.045
P ≥ 560	P ≥ 750																										3.5 / 0.19 / 3.5 / 0.045

Pollutant key (g/kWh)	Unregulated	Tier 1 / Stage I	Tier 2 / Stage II	Tier 3 / Stage IIIA	Tier 4i / Stage IIIB	Tier 4f / Stage IV	Stage V
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Figure 1. Emission standards for non-road engines in the United States and European Union

(Dallmann & Menon, 2016)

<sup>a</sup> For air-cooled, hand-startable direct injection engines, manufacturer may certify engines to Tier 2 PM standard through 2009 and demonstrate compliance with 0.6 g/kWh PM limit in 2010.

<sup>b</sup> Manufacturer can alternatively certify to Tier 2 PM limit and demonstrate compliance with Tier 4f limit in 2012.

<sup>c</sup> For NO<sub>x</sub> compliance, manufacturers may a) If banked Tier 2 credits are used for compliance, certify to an alternate NO<sub>x</sub> standard of 2.3 g/kWh or 50% of engines must demonstrate compliance with Tier 4f standard from 2012-2013, or b) If no banked Tier 2 credits are used for compliance, certify to an alternate NO<sub>x</sub> standard of 3.4 g/kWh or 25% of engines must demonstrate compliance with Tier 4f standard from 2012-2014.

<sup>d</sup> Manufacturer may certify to an alternate NO<sub>x</sub> standard of 2.0 g/kWh or 50% of engines must demonstrate compliance with the Tier 4f standard through 2011-13.

<sup>e</sup> Tier 4i NO<sub>x</sub> emission limit for generator sets rated at > 900 kW is set at 0.67 g/kWh. Tier 4f NO<sub>x</sub> and PM emission limits for generator sets rated at ≤ 560 kW are 0.67 and 0.03 g/kWh, respectively.

<sup>f</sup> A particle number emission limit of 1x10<sup>12</sup> #/kWh is introduced in Stage V standards for engines between 19 and 560 kW.

Environmental Protection Agency (EPA) emission standards are divided into tiers, whereas EU emission standards progress in stages. Non-road emission standards are defined according to engine power class, and the implementation year of emission standards for different engine power classes can vary within a given regulatory tier or stage. Regulated pollutants include NO<sub>x</sub>, PM, hydrocarbons (HC), and carbon monoxide (CO). The EPA also regulates smoke emissions from non-road diesel engines, and ammonia emissions have been regulated in the EU beginning with Stage IIIB standards. To date, no fuel efficiency or carbon dioxide emission standards have been promulgated for non-road engines in the United States or the EU. A detailed discussion of the progression of regulatory emission control programs in the United States and the EU is included in a companion publication (Dallmann & Menon, 2016). Timelines and details for the implementation of non-road engine emission standards in both regions are illustrated in Figure 1.

In general, U.S. and EU emission standards have been harmonized with similar limits applying at parallel regulatory Tiers/Stages. The correspondence between U.S. regulatory Tiers and EU regulatory Stages is shown in Table 1.

**Table 1.** Comparison of regulatory Tiers (U.S.) and Stages (EU) for non-road diesel engines

U.S. regulatory Tier	EU regulatory Stage
Tier 1	Stage I
Tier 2	Stage II
Tier 3	Stage IIIA
Tier 4i	Stage IIIB
Tier 4f	Stage IV
No corresponding standard	Stage V

Although the standards in the two regions have been largely harmonized, there are several key differences for certain power classes that are worth noting:

- **Engines with rated power < 19 kW and ≥ 560 kW:** Engines in these power classes have been subject to emission standards since 2000 in the United States. In contrast, these power classes have not been subject to emission regulation in the EU. Stage V standards will introduce emission limits for these engines for the first time.
- **Engines with rated power (P) 19 kW ≤ P < 37 kW:** No Stage IIIB or IV emission limits were set for this power class in the EU. Emission limits for these engines remain at Stage IIIA levels, which are equivalent to those of U.S. Tier 2. The United States has subsequently implemented more stringent emission limits through the Tier 4 regulation. The European Stage V regulation includes new, more stringent limits for this power class.
- **Engines with rated power 37 kW ≤ P < 56 kW:** The EU did not set Stage IV emission standards for this power class. However, Stage IIIB standards are of similar stringency to emission limits defined for this power class in the U.S. Tier 4f program.

Today, non-road engines in the United States and the EU are subject to Tier 4f and Stage IV emission standards, respectively. In September 2016, the EU adopted Stage V emission standards, which will be phased in beginning in 2018 for new type approvals (European Commission, 2016). Stage V standards introduce particle number (PN) limits for non-road engines for the first time. Emission standards for

engines below 19 kW and above 560 kW also will be included in the EU regulatory program for the first time. Stage V standards for these power classes are set at levels equivalent to U.S. Tier 4f standards. Stage V PM limits for engines between 37 kW and 560 kW will see a 40% reduction from Stage IV levels, while NO<sub>x</sub> limits remain unchanged (International Council on Clean Transportation, 2016). There has, to date, been no public action taken by the U.S. EPA to introduce similarly stringent Tier 5 emission standards.

For non-road engine cost modeling, we have selected Tier 3/Stage IIIA engines as the baseline.<sup>2</sup> This is reflective of the current level of emission control programs in countries such as India, China, and Brazil, where results presented in this paper will be most useful as the countries work to strengthen their non-road engine regulatory programs. The progression of PM and NO<sub>x</sub> emission limits from this baseline through the most stringent Stage V standards is shown in Figure 2 for four engine power classes. These power classes were selected to illustrate how emission limits have progressed differently for different engine sizes.

### 3. Emission reduction technologies

In this section, the various strategies to reduce emissions from non-road diesel engines are discussed. The most important approaches include reducing formation of pollutants within the engine and control of the emissions in the exhaust stream through use of aftertreatment technologies. As

<sup>2</sup> For power classes where no Tier 3 standards were set (< 19 kW) or where Tier 3 standards were superseded by Tier 4i standards (19–75 kW), Tier 2 engine configurations are used as the baseline for cost modeling.

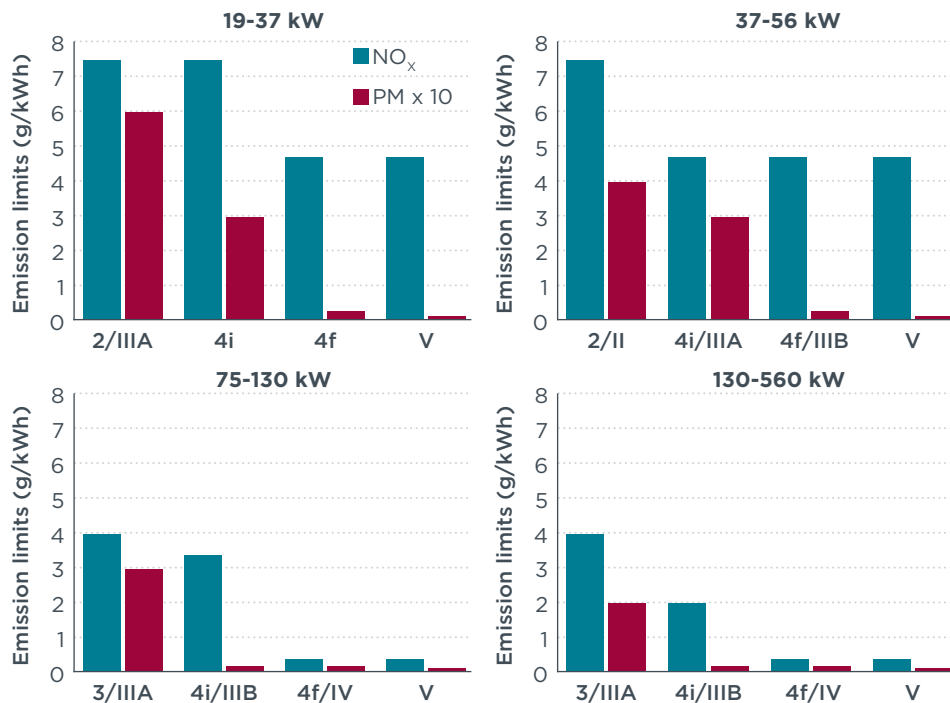
engines and emission control systems become increasingly complex, the electronic system controls also take on a critical role.

## IN-CYLINDER ENGINE CONTROLS

Pollutants like PM, HC, and CO are formed in diesel engines due to air and fuel mixing challenges and incomplete fuel combustion, whereas NO<sub>x</sub> 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 amount, temperature, and composition of the air entering the chamber influence combustion conditions, as do the fuel delivery timing and strategy and the use of exhaust gas recirculation (EGR). Engine redesigns that do not add significant hardware costs but do require investment in research and development (R&D) seek to improve combustion efficiency through engine calibration and redesigned component 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 EGR.

### Fuel injection systems

Fuel injection pressure, rate, and timing all are used to control both NO<sub>x</sub> and PM. Increasing injection pressure reduces the size of the fuel droplets in 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 injection nozzles and piston bowls. This leads to more complete fuel combustion that both reduces particle formation and improves fuel efficiency.



**Figure 2.** PM and NO<sub>x</sub> emission limits for select non-road engine power classes. NO<sub>x</sub> + HC emission limits shown for 19-37 kW and 37-56 kW classes.

Electronic control of fuel injection allows precise and variable fuel timing and metering. In traditional mechanically operated fuel injection systems that employ a single injection event for each engine cycle, the timing of the fuel injection can favor either NO<sub>x</sub> or PM control. Early fuel injection during the combustion cycle increases combustion pressures and temperatures, improves fuel efficiency, reduces PM, but increases NO<sub>x</sub> emissions. Delayed injection of fuel has the opposite effect. The improvement on one pollutant and deterioration on the other is known as the PM and NO<sub>x</sub> trade-off.

Reducing the trade-off between NO<sub>x</sub> 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. Diesel powered engines 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, and ensure that it contains both sufficient oxygen for complete combustion and enough diluent (excess air or recirculated exhaust gas) to control the combustion temperature. Increasing the amount of the air entering the chamber increases the pressure and air density, allowing better combustion in the brief time available. Tuning these parameters minimizes production of both PM and NO<sub>x</sub>.

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 engine rotational speeds and low load. The availability of additional air reduces PM emissions and has positive effects on power output. In addition to allowing a higher air-to-fuel ratio at low engine speeds and improving vehicle acceleration, the VGT also enables several other emission reduction technologies: It allows better control of the change in pressure between engine intake and outlet manifolds, 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  $\text{NO}_x$  formation by lowering peak combustion temperature within the cylinder. EGR coolers often are included for further temperature control aiming at keeping the density of the mixture high. EGR is the most widely used technology for in-cylinder  $\text{NO}_x$  reduction in diesel-powered engines. The EGR fraction, which is to say the share of recirculated exhaust gas in the total intake charge, is tailored to each engine operating condition as part of engine calibration and, in the latest systems, may vary from 0% 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. The most common is the high-pressure EGR system, which draws in exhaust gases before the turbocharger and mixes them with the compressed air before the intake valves. The low-pressure system is more complex and requires drawing in the exhaust stream after the turbocharger, preferably after the aftertreatment system, and mixing it back with air before entering the turbocharger. The high-pressure EGR system is simpler and less expensive but it requires a cooling system and constant maintenance; the low-pressure EGR system is more complex but maintenance is less strenuous as the EGR is cleaner when taken after the DPF. 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 SYSTEMS**

Aftertreatment systems reduce  $\text{NO}_x$ , PM, HC, and CO in the exhaust stream. The DPF and the diesel oxidation catalyst (DOC) control PM in the exhaust stream; the DOC is also effective at reducing HC and CO emissions. Selective catalytic reduction (SCR), using urea as a reagent, controls  $\text{NO}_x$  emissions in the exhaust stream. Lean  $\text{NO}_x$  trap technologies, used in some light-duty vehicle applications, are not used either in the non-road or the heavy-duty vehicle sector due to sulfur tolerance and high costs associated with high platinum loading demand, which makes the system uncompetitive with SCR. These technologies also can be used in combination with other strategies to reduce other pollutant

emissions. For example, DOCs can support SCR operation, and SCR systems enable in-cylinder strategies to reduce PM emissions.

### **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 (SOF) 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 solid 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 (NO) into nitrogen dioxide ( $\text{NO}_2$ ), leading to improved conversion rates in the SCR—and in regeneration of passive DPFs.

### **Selective catalytic reduction systems**

SCR systems introduce ammonia to react with  $\text{NO}_x$  over a catalytic surface, producing nitrogen and water. It is possible for SCR systems to achieve high  $\text{NO}_x$  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 high engine-out  $\text{NO}_x$  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 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  $\text{NO}_x$  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 over a wide temperature range and have high thermal stability but are more sulfur sensitive. Copper zeolites have better NO<sub>x</sub> conversion at lower temperature ranges than iron zeolites (Narula, Yang, Bonnesen, & Hagaman, 2011). 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<sub>x</sub> control over a wider range of operating conditions (Table 2).

**Table 2.** Temperature range for catalysts using different materials

Catalyst	Temperature range (°C)
Vanadium	300–450
Zeolite, high temperature (iron)	200–650
Zeolite, low temperature (copper)	180–600

Note. Data from Majewski (2005), Chen (2014), and Narula et al. (2011).

In most commercial systems, ammonia is generated from the decomposition of a urea solution. These are commercially known by a variety of names such as Diesel Exhaust Fluid or DEF in the United States, AdBlue in Europe, and ARLA-32 in Brazil. The urea solution is pumped into the exhaust upstream of the catalyst from an onboard tank, which must be refilled periodically.<sup>3</sup>

In regions that experience very low ambient temperatures—at or below 12 °F or –11°C—steps must be taken to ensure the urea solution does not freeze. This typically involves electric heaters for the urea tank, which is an additional cost. Urea dosage has been approached by simple system look-up table operation or by adding NO<sub>x</sub> sensors. NO<sub>x</sub> sensors are used to calibrate the dosing of urea on the latest and more stringent standards for on-road applications, such as Euro V, Euro VI, and U.S. EPA 2010. Excess urea injection or incomplete catalysis may cause excess ammonia emissions downstream of the SCR catalyst.<sup>4</sup> As an additional measure to control these toxic emissions from on-road vehicles, an ammonia slip catalyst (ASC) may be included downstream of the SCR system.

**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% through their ability to accumulate the solid 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 on a DOC, which may be located upstream of the DPF or washcoated onto the front section of 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 diesel vehicles, manufacturers were able to calibrate their engines for improved fuel efficiency performance and high-NO<sub>x</sub>/low-PM engine-out emissions. These lower engine-out PM levels allow passive regeneration to dominate the filter regeneration requirements. However, most on-road and off-road diesel technology has a fuel injector in the exhaust to facilitate DPF active regeneration when it is needed. The literature shows that 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 to achieve temperatures necessary for regeneration and a fuel injector is located in the exhaust upstream of the DPF to facilitate regeneration (J. Kubsh, personal communication, November 10, 2015). Reverse configurations for off-road applications were not found in technical literature.

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**

The integration of EGR, air and fuel management, and multiple aftertreatment systems must be designed with temperature, pressure, and the composition of the exhaust stream in mind. Catalysts operate at highest efficiency

3 US EPA guidelines require that the urea tank not have to be refilled more often than the fuel tank. They also require measures to ensure that the urea tank is refilled and is refilled with urea.

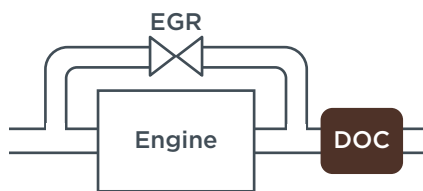
4 Ammonia emissions in gaseous form can have health and environmental impacts and can combine in the atmosphere with nitrogen- and sulfur-based acidic species to form particulate matter.

within a temperature range determined by their materials: Catalyst efficiency typically is reduced at lower temperatures, and durability can be affected 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 traditionally 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 and which may be required in non-road standards that require the use of DPFs. 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  $\text{NO}_x$  as well as highly effective control of particle emissions.

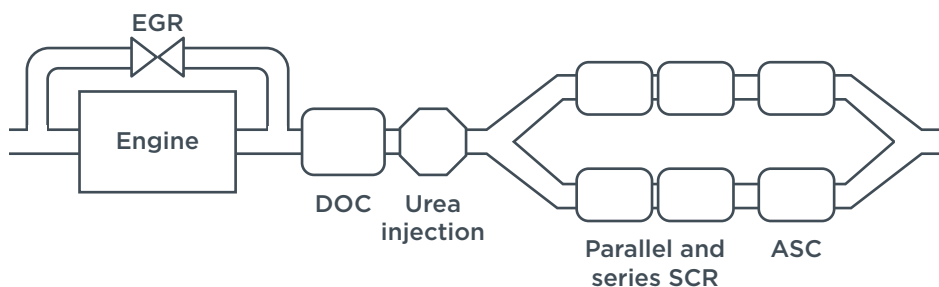
The most basic system integration solution required for emission control in low-power engines combines engine-out control for  $\text{NO}_x$  emissions with DOCs for PM-soluble phase control. An example Tier 4f compliant engine follows the schematic shown in Figure 3.<sup>5</sup>

A solution found in some of the higher power engines ( $P > 56$  kW) certified to Tier 4f/Stage IV standards 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 often are installed in parallel, and sometimes more than one SCR catalyst is included in a series.

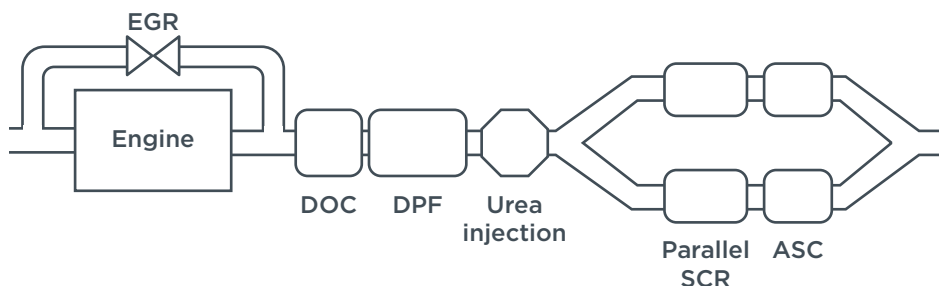
For Stage V-compliant engines, a typical layout is projected to follow



**Figure 3.** DOC system applied for PM control in low-power Tier 4f/Stage IV compliant non-road engine.



**Figure 4.** One common solution for Tier 4f or Stage IV compliance for engines rated between 56 and 560 kW: DOC+SCR system without DPF.



**Figure 5.** Projected aftertreatment system architecture for Stage V compliance (56-560 kW engines).

the schematic in Figure 5. The engine-out exhaust, monitored for  $\text{NO}_x$  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  $\text{NO}_x$  sensor is located between the ASC and the tailpipe.

One recent trend in emission control technology is the use of an integrated aftertreatment system that combines PM and  $\text{NO}_x$  control within a single system such as that described by Cummins (2014). The SCR-on-particulate filter (SPF) approach is already in use for light-duty

applications and is being tested for larger engines. Although the authors found some examples of commercial applications for SPF (FPT Industrial, 2016), this technology was not costed; it is assumed to offer a cost benefit due to having fewer components and reduced volume.

## 4. Technology Pathways

### APPROACH

The non-road engine cost modeling presented in this paper requires, as a first step, the definition of engine and aftertreatment technologies employed by manufacturers to meet pollutant emission limits at each

<sup>5</sup> System architecture shown for engine with rated power between 19 and 37 kW meeting Tier 4f emission standards.

regulatory Tier or Stage. We have previously reviewed the technological progression of non-road diesel engine designs in a companion publication (Dallmann & Menon, 2016). In the following sections, we provide a brief overview of this assessment, including the approach and information sources used to define technology pathways for non-road engines. We also describe how specific technology packages were defined by power class and emission control tier/stage for cost modeling.

A number of sources were used to determine key technologies and engine modifications incorporated into non-road engine designs in response to increasingly stringent regulatory programs in the United States and the European Union. On-road diesel engine technology developments provide a starting point for the assessment of non-road engine technology pathways. Further information specific to non-road diesel engines was obtained from a number of different sources. Key among these sources is the EPA's engine certification database, which compiles engine data submitted by engine manufacturers to the EPA during the certificate of conformity application process (U.S. Environmental Protection Agency [EPA], 2018). This database contains detailed information for non-road diesel engines beginning with the implementation of U.S. Tier 1 standards in 1994 and continuing through 2018 model year engine families.

We considered a number of engine design parameters that are reported in the database in order to track non-road engine technology developments over time. These include fuel system type, method of aspiration, engine modifications for emission control (e.g., variable injection timing), electronic engine controls,

exhaust gas recirculation, and the use of aftertreatment devices. This approach enables the tracking of changes in the use of specific engine technologies (e.g., electronic engine controls) over time, and forms the basis for the technology pathways presented here. Key insights from this analysis will be discussed in subsequent sections.

The European Union does not compile similar data for non-road diesel engines approved for sale in Europe. However, due to the high degree of harmonization between U.S. and EU standards and the international nature of the non-road engine market, general engine technology pathways are expected to be similar in the two regions. With few exceptions, engine designs and technology applications for U.S. and European markets are similar within corresponding regulatory tiers/stages. Unless otherwise noted, technology pathways presented below will be assumed to be common to the U.S. and European markets.

Information contained in the EPA engine certification database was supplemented with engine data from a number of other sources, including government regulatory documents, academic literature, conference materials, industry reports, and publicly available literature from engine manufacturers.

Results from the non-road engine technology assessment are summarized in Figure 6, which shows technology packages by emission control level and engine power category. The figure has been updated to incorporate recently released information on planned Stage V engine designs. For example, Deutz recently received Stage V certification for a 6.1 L, 180 kW rated engine (Prandi, 2017). The engine employs both SCR and DPF

technologies to meet Stage V PM and  $\text{NO}_x$  emission limits. Other non-road engine manufacturers, such as John Deere and Caterpillar, also have announced Stage V engine designs (John Deere, 2016; SAE International [SAE], 2016). Common among these approaches is the inclusion of a DPF for engines between 19 and 560 kW in order to meet tightened PM emission limits and new particle number emission limits. Others, like FPT Industrial, have adopted a SCR-on-filter approach, which combines the SCR and particle filter into one component (FPT Industrial, 2016).

A key finding of the original technology assessment is that, at a given regulatory tier/stage, there can be significant variability in engine technology packages both across power classes as well as within a given power class. Variance across power classes is largely driven by the different levels at which emission limits are set. Smaller engines historically have been subject to less demanding emission performance requirements, and thus have not yet adopted the highly efficient pollution control technologies now found in larger engines.

At the same time, regulatory requirements for a given power class have not necessarily led to the adoption of similar emission control technologies across manufacturers. For example, two distinct engine design strategies emerged in the market for engines between 75 and 560 kW with the implementation of Tier 4i/Stage IIIB standards: tune engines for low engine-out PM emissions and control relatively high  $\text{NO}_x$  emissions with SCR or use PM aftertreatment devices such as DPF and/or DOC along with cooled EGR for  $\text{NO}_x$  control. These two strategies use different emission control technology packages and thus have different costs.



Power class	System component	Tier 1/Stage I	Tier 2/Stage II	Tier 3/Stage IIIA	Tier 4i/Stage IIIB	Tier 4f/Stage IV	Stage V <sup>a</sup>
< 19 kW <sup>b</sup>	FIE	IDI or MDI; injection timing delay; upgrades to mechanical fuel injection systems					
	AH	NA					
	EGR	None					
	ATD	None					
19-37 kW <sup>c</sup>	FIE	IDI or MDI; injection timing delay; upgrades to mechanical fuel injection systems				IDI or CR	EDI: CR
	AH	NA				NA or TC	
	EGR	None				iEGR, cEGR	cEGR
	ATD	None				DOC+(DPF)	DOC+DPF
37-56 kW	FIE	IDI or MDI; injection timing delay; upgrades to mechanical fuel injection systems		IDI or MDI; fuel injection system upgrades with limited application of ECU		EDI, CR	
	AH	NA, limited use of TC (FG)		TC (FG or WG), limited NA		TC (FG or WG)	
	EGR	None		Increased EGR application		iEGR, cEGR	cEGR
	ATD	None				DOC+(DPF)	DOC+DPF
56-75 kW	FIE	MDI; injection timing delay; upgrades to mechanical fuel injection systems		MDI; increasing use of EDI	EDI: CR		
	AH	Increasing application of TC (FG, WG)		TC (FG, WG)			
	EGR	None		Moderate iEGR, cEGR application			
	ATD	None			DOC+(DPF)	(DOC)+SCR / DOC+DPF+SCR	DOC+DPF+SCR
75-130 kW	FIE	MDI; injection timing delay, upgrade to mechanical fuel injection systems	MDI, increasing use of EDI: electronic EUI or CR (P <sub>inj</sub> = 1200 bar)	EDI: EUI or CR (P <sub>inj</sub> = 1600 bar); limited MDI		EDI: CR (P <sub>inj</sub> = 2000 bar)	
	AH	TC (FG, WG)			TC (WG, VGT)		
	EGR	None			cEGR used in ~50% of engine families		
	ATD	None			DOC+(DPF) / SCR	(DOC)+SCR / DOC+DPF+SCR	DOC+DPF+SCR
130-560 kW	FIE	MDI, limited EDI; injection timing delay,	Increasing use of EDI: EUI or CR (P <sub>inj</sub> = 1200 bar)	EDI: EUI or CR (P <sub>inj</sub> = 1600 bar);		EDI: CR or EUI (P <sub>inj</sub> = 2000 bar)	EDI: CR (P <sub>inj</sub> = 2000 bar)
	AH	TC (FG, WG)			TC (FG, WG, VGT)		TC (WG, VGT, 2stT)
	EGR	None			cEGR in ~50% engine families		
	ATD	None			DOC + DPF / SCR	(DOC)+SCR / DOC+DPF+SCR	DOC+DPF+SCR

(Dallman & Menon, 2016)

<sup>a</sup>Projected technology packages for Stage V engine designs.

<sup>b</sup>Emissions from non-road diesel engines with power ratings < 19 kW are regulated for the first time in Stage V standards.

<sup>c</sup>No Stage IIIB or IV emission standards adopted for 19-37 kW engines in Europe.

Fuel injection equipment (FIE): IDI=indirect injection; MDI = mechanical direct injection; EDI = electronic direct injection; CR = high-pressure common rail; ECU = electronic control unit; EUI = electronic unit injector; Air handling (AH): NA = naturally aspirated; TC = turbocharged; WG = wastegated; VGT = variable geometry; 2stT = 2-stage; FG = fixed geometry; Exhaust gas recirculation (EGR): cEGR = cooled external EGR; iEGR = internal EGR; Aftertreatment devices (ATD): DOC = diesel oxidation catalyst; DPF = diesel particle filter; SCR = selective catalytic reduction

**Figure 6.** Summary of non-road engine technology packages by emission control level and engine power category.

A second example of variability in engine design within a given power class is evident in current strategies being employed to meet Tier 4f/Stage IV standards. For engines between 56 and 560 kW, SCR systems are almost universally applied to meet the 0.40 g/kWh NO<sub>x</sub> limit. However, the Tier 4f/Stage IV PM limit is not stringent enough to compel the use of a diesel particulate filter. While some manufacturers have included DPFs in Tier 4f/Stage IV engine designs, others have relied solely on

in-cylinder approaches and DOCs for PM control. Reasons manufacturers have offered DPF-equipped engines include intended application, optimization of emission control system and engine performance, consideration of total fluid (fuel plus DEF) consumption, and decisions regarding technology development made at previous regulatory stages. As shown in Table 3, less than 50% of Tier 4f certified engine families with rated power between 56 and 560 kW are equipped with DPFs (EPA, 2018). A

similar dynamic also is observed for smaller engines (19-56 kW), where DPFs are used in less than half of Tier 4f certified engine families.

For cost modeling, we have addressed the variability in non-road engine designs across power classes by defining separate technology pathways for each engine power class. Within a given power class, we have selected to define a single representative technology package at each regulatory tier/stage in those instances

where there was not significant variability in the engine design strategies used by manufacturers. In cases where several engine design strategies using different emission control technology packages emerged in the market, we have defined and modeled costs for multiple engine designs. This includes Tier 4i/Stage IIIB engines between 75 and 560 kW, where both EGR and SCR pathways are assessed, as well as Tier 4f/Stage IV engines between 19 and 560 kW, where cost modeling is conducted for both DPF and non-DPF engine designs. In the former case, we make the assumption that emission control technology packages used in DPF-equipped Tier 4f/Stage IV engines will be similar to those employed in Stage V engine designs. We believe this is reasonable due to the fact that many DPF-equipped Tier 4f engine families already are meeting Stage V PM and NO<sub>x</sub> limits (see Table 3). Although Stage V standards do introduce a particle number emission limit, we do not anticipate that this will necessitate significant engine or aftertreatment design changes for those DPF-equipped engines already meeting the Stage V PM limit.

Additional details on technology pathways used for cost modeling are included in the following section.

**TECHNOLOGY PATHWAYS FOR COST MODELING**

In this section, we present non-road engine technology packages used for cost modeling. Emission control technologies are defined by power class and regulatory tier/stage. Although U.S. and EU regulations for non-road engines are largely harmonized, there are some differences in the relative stringency of emission limits for certain engine categories within a given regulatory tier or stage. Thus,

**Table 3.** Assessment of the use of diesel particulate filters in Tier 4f certified engine families

Power class	Tier 4f certified engine families	Engine families equipped with DPF	DPF-equipped engines meeting Stage V PM and NO <sub>x</sub> limits
19–37 kW	162	48%	95%
37–56 kW	315	41%	82%
56–75 kW	13	0%	NA
75–130 kW	117	32%	78%
130–560 kW	339	41%	94%

**Table 4.** Modeled technology pathway for 0–19 kW engines

	Baseline (Tier 2)	Tier 4i	Tier 4f/Stage V
<b>PM emission limit (% reduction from previous stage)</b>	0.8 g/kWh	No Tier 4i standards set for engines with rated power less than 19 kW.	0.4 g/kWh (-50%)
<b>NO<sub>x</sub> + nonmethane hydrocarbons (NMHC) emission limit (% reduction from previous stage)</b>	7.5 g/kWh		7.5 g/kWh (0%)
<b>Engine-out emissions and air/fuel controls</b>	<ul style="list-style-type: none"> <li>Natural aspiration</li> <li>Indirect or mechanical direct fuel injection</li> </ul>		No new engine technologies required to meet reduced PM emission limit
<b>Aftertreatment systems</b>	None		None

we have presented technology pathways in a way to provide a comprehensive overview of technologies that have been used to meet U.S. and EU regulations. For cost modeling, we focus on engines with rated power less than 560 kW.

The technology pathway for engines with rated power less than 19 kW is presented in Table 4. Engines in this power class are, from a technological perspective, relatively simple. Advanced engine technologies or aftertreatment systems are not required to meet emission standards set for this category, and the expense of such technologies is generally prohibitive given the low cost of these engines. In the U.S., the only change in emission regulations from the Tier 2 baseline for engines in this category was a 50% reduction of the PM emission limit to 0.4 g/kWh with the introduction of Tier 4f

standards. In rulemaking documents supporting the Tier 4 rule, the EPA noted that many engines certified to Tier 1 emission standards in the early 2000s already had PM emission levels below 0.4 g/kWh (EPA, 2004). Thus, for cost modeling, we assume any changes to Tier 4f engine designs came as a result of natural improvements and not specifically to meet the more stringent PM standard. In Europe, engines of this power class will be regulated for the first time with the implementation of Stage V standards. Stage V emission limits are set at the same level as U.S. Tier 4f limits, and we assume similar technology packages will be used.

The technological development of non-road engines between 19 and 37 kW is shown in Table 5. In the United States, engine designs evolved considerably with the introduction of Tier 4f standards, which lowered PM

and NO<sub>x</sub> + NMHC emission limits to 0.03 g/kWh and 4.7 g/kWh, respectively. Technologies adopted in Tier 4f engines include common rail fuel injection systems, cooled EGR, and DOCs. As previously noted, some manufacturers also have included DPFs in Tier 4f engine designs, however this technology is not required to meet the 0.03 g/kWh limit. We make the assumption that Tier 4f/Stage IV engines designs that include a DPF employ a similar set of technologies as those anticipated for Stage V engines. NO<sub>x</sub> aftertreatment systems are not needed to meet the Tier 4f NO<sub>x</sub> + NMHC limit.

Emission limits for engines between 19 and 37 kW sold in the EU remain at Stage IIIA levels and can be met without advanced engine or aftertreatment technologies. This will change with the introduction of Stage V standards, which will necessitate the use of DPFs to meet stringent PM and PN emission limits. The Stage V NO<sub>x</sub> + NMHC limit for this power class is set at the same level as the Tier 4f limit, 4.7 g/kWh, and thus no NO<sub>x</sub> aftertreatment devices are expected in Stage V engine designs.

Emission limits for engines in the 37–56 kW power class have progressed in a similar fashion as those for the 19–37 kW class, and engine technology developments, shown in Table 6, have generally proceeded in parallel. Key differences between the two power classes include more widespread use of turbochargers and an earlier adoption of EGR systems in 37–56 kW engines. There is no difference in the level at which Tier 4f and Stage V PM and NO<sub>x</sub> emission limits are set for the two engine categories. As such, with the exception of air-handling systems, engine and aftertreatment technologies are similar.

**Table 5.** Modeled technology pathway for 19–37 kW engines

	<b>Baseline (Tier 2/Stage IIIA)</b>	<b>Tier 4i</b>	<b>Tier 4f</b>	<b>Stage V (Tier 4f w/DPF)</b>
<b>PM emission limit (% reduction from previous stage)</b>	0.6 g/kWh	0.3 g/kWh (-50%)	0.03 g/kWh (-90%)	0.015 g/kWh (-98% relative to Stage IIIA limit) <sup>a</sup>
<b>NO<sub>x</sub> + NMHC emission limit (% reduction from previous stage)</b>	7.5 g/kWh	7.5 g/kWh (0%)	4.7 g/kWh (-37%)	4.7 g/kWh (-37% relative to Stage IIIA limit)
<b>Engine-out emissions and air/fuel controls</b>	<ul style="list-style-type: none"> <li>Naturally aspirated</li> <li>Mechanical direct fuel injection</li> </ul>	<ul style="list-style-type: none"> <li>No new engine technologies needed to meet reduced PM emission limit</li> </ul>	<ul style="list-style-type: none"> <li>Naturally aspirated</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Naturally aspirated</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic engine control</li> </ul>
<b>Aftertreatment systems</b>	None	None	PM control through DOC	PM control through DOC and DPF

<sup>a</sup>Emission limit for Stage V engines is shown. Tier 4f engines equipped with a DPF are subject to the Tier 4f PM limit of 0.03 g/kWh. Stage V engines also must meet a particle number emission limit of 1x10<sup>12</sup> #/kWh.

**Table 6.** Modeled technology pathway for 37–56 kW engines

	<b>Baseline (Tier 2/Stage II)</b>	<b>Tier 4i/Stage IIIA<sup>a</sup></b>	<b>Tier 4f/Stage IIIB<sup>a</sup></b>	<b>Stage V (Tier 4f/Stage IIIB w/DPF)</b>
<b>PM emission limit (% reduction from previous stage)</b>	0.4 g/kWh	0.3 g/kWh (-50%)	0.03 g/kWh (-90%)	0.015 g/kWh (-40% relative to Stage IIIB limit) <sup>b</sup>
<b>NO<sub>x</sub> + NMHC emission limit (% reduction from previous stage)</b>	7.5 g/kWh	4.7 g/kWh (-37%)	4.7 g/kWh (0%)	4.7 g/kWh (0%)
<b>Engine-out emissions and air/fuel controls</b>	<ul style="list-style-type: none"> <li>Fixed geometry turbocharger</li> <li>Mechanical direct fuel injection</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Mechanical direct fuel injection</li> <li>Cooled EGR</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>
<b>Aftertreatment systems</b>	None	None	PM control through DOC	PM control through DOC and DPF

<sup>a</sup>Tier 4i and 4f PM limits are shown. PM emission limits were set at 0.4 g/kWh and 0.025 g/kWh for Stage IIIA and IIIB engines in the EU, respectively. <sup>b</sup>Emission limit for Stage V engines is shown. Tier 4f/Stage IIIB engines equipped with a DPF are subject to Tier 4f/Stage IIIB PM limits. Stage V engines also must meet a particle number emission limit of 1x10<sup>12</sup> #/kWh.

Technology pathways for engines between 56 and 75 kW are shown in Table 7. Relative to smaller engine categories, engines in the 56–75 kW class have been subject to more stringent NO<sub>x</sub> and PM emission limits. Consequently, engine designs in this power class tend to be more sophisticated, and aftertreatment technologies were introduced at an earlier stage. Tier 4i/Stage IIIB standards reduced the PM limit by 95% and drove the incorporation of DOCs into engine designs.

As reflected in our model technology package, SCR systems generally are required to meet the Tier 4f/Stage IV 0.40 g/kWh NO<sub>x</sub> emission limit. We note, however, that there are few examples of Tier 4f/Stage IV engines in the 56–75 kW class being produced today (see Table 3). In response to Tier 4f standards, manufacturers have increasingly followed an engine downsizing strategy, producing engines rated at 55 kW, the highest rated engine power which can be certified to the less stringent 4.7 g/kWh NO<sub>x</sub> + NMHC limit (SAE, 2017). Because of the small number of actual examples, our representative Tier 4f/Stage IV and Stage V engine technology packages are based primarily on larger engine designs.

The development of emission regulations for engines in the 75–130 kW and 130–560 kW power classes has generally been similar. As such, modeled technology pathways for these two classes, shown in Tables 8 and 9, are

**Table 7.** Modeled technology pathway for 56–75 kW engines

	<b>Baseline (Tier 3/ Stage IIIA)</b>	<b>Tier 4i/Stage IIIB</b>	<b>Tier 4f/Stage IV</b>	<b>Stage V</b>
<b>PM emission limit (% reduction from previous stage)</b>	0.4 g/kWh	0.02 g/kWh (-95%)	0.02 g/kWh (0%)	0.015 g/kWh (-40%) <sup>b</sup>
<b>NO<sub>x</sub> emission limit (% reduction from previous stage)</b>	4.7 g/kWh <sup>a</sup>	3.4 g/kWh (-28%)	0.40 g/kWh (-88%)	0.40 g/kWh (0%)
<b>Engine-out emissions and air/fuel controls</b>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Electronic direct fuel injection</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>
<b>Aftertreatment systems</b>	None	PM control through DOC	<ul style="list-style-type: none"> <li>PM control through DOC</li> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC and DPF</li> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>

<sup>a</sup>NO<sub>x</sub> + NMHC limit. <sup>b</sup>Stage V engines also must meet a particle number emission limit of 1x10<sup>12</sup> #/kWh.

largely the same. Relative to smaller engine categories, these engines faced more stringent Tier 3/Stage IIIA PM and NO<sub>x</sub> standards, leading to an earlier adoption of EGR systems. As previously noted, we have modeled two separate Tier 4i/Stage IIIB engine designs to reflect the range of technology options available to manufacturers to meet these standards.

Selective catalytic reduction systems are almost universally applied in Tier 4f/Stage IV engine designs to meet the 0.40 g/kWh NO<sub>x</sub> limit, however

several different strategies are used for PM control. Here, we estimate costs for both DPF-equipped and non-DPF engines. Technology packages for Tier 4f/Stage IV engines equipped with DPFs are assumed to be similar to those expected for Stage V engines. As was the case for other power classes subject to stringent Stage V PM and PN emission limits, we project aftertreatment architectures for Stage V engines in these categories will include DOC, DPF, and SCR systems.

**Table 8.** Modeled technology pathway for 75–130 kW engines

	Baseline (Tier 3/Stage IIIA)	Tier 4i/Stage IIIB		Tier 4f/Stage IV	Stage V (Tier 4f/Stage IV w/DPF)
		SCR	EGR		
<b>PM emission limit (% reduction from previous stage)</b>	0.3 g/kWh	0.02 g/kWh (-93%)		0.02 g/kWh (0%)	0.015 g/kWh (-40%) <sup>b</sup>
<b>NO<sub>x</sub> emission limit (% reduction from previous stage)</b>	4.0 g/kWh <sup>a</sup>	3.4 g/kWh (-15%)		0.40 g/kWh (-88%)	0.40 g/kWh (0%)
<b>Engine-out emissions and air/ fuel controls</b>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Electronic direct fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic engine control</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>
<b>Aftertreatment systems</b>	None	<ul style="list-style-type: none"> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC and DPF</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC</li> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC and DPF</li> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>

<sup>a</sup>NO<sub>x</sub> + NMHC limit. <sup>b</sup>Emission limit for Stage V engines is shown. Tier 4f/Stage IV engines equipped with a DPF are subject to Tier 4f/Stage IV PM limits. Stage V engines also must meet a particle number emission limit of 1x10<sup>12</sup> #/kWh.

**Table 9.** Modeled technology pathway for 130–560 kW engines

	Baseline (Tier 3/Stage IIIA)	Tier 4i/Stage IIIB		Tier 4f/Stage IV	Stage V (Tier 4f/Stage IV w/DPF)
		SCR	EGR		
<b>PM emission limit (% reduction from previous stage)</b>	0.2 g/kWh	0.02 g/kWh (-90%)		0.02 g/kWh (0%)	0.015 g/kWh (-40%) <sup>b</sup>
<b>NO<sub>x</sub> emission limit (% reduction from previous stage)</b>	4.0 g/kWh <sup>a</sup>	2.0 g/kWh (-50%)		0.40 g/kWh (-80%)	0.40 g/kWh (0%)
<b>Engine-out emissions and air/ fuel controls</b>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Electronic direct fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Wastegated turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Variable geometry turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>	<ul style="list-style-type: none"> <li>Variable geometry turbocharger</li> <li>Common rail fuel injection</li> <li>Cooled EGR</li> <li>Electronic control unit</li> </ul>
<b>Aftertreatment systems</b>	None	<ul style="list-style-type: none"> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC and DPF</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC</li> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>	<ul style="list-style-type: none"> <li>PM control through DOC and DPF</li> <li>NO<sub>x</sub> control through SCR system</li> <li>ASC</li> </ul>

<sup>a</sup>NO<sub>x</sub> + NMHC limit. <sup>b</sup>Emission limit for Stage V engines is shown. Tier 4f/Stage IV engines equipped with a DPF are subject to Tier 4f/Stage IV PM limits. Stage V engines also must meet a particle number emission limit of 1x10<sup>12</sup> #/kWh.

## 5. 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 non-road engine 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. (2016) for heavy-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 understandably 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, emission reduction costs were found in the EPA RIAs for the Tier 4

non-road emission standards (EPA, 2004) and also from the on-road regulatory work for 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. RIA estimates of technology requirements may differ from the technology that is actually developed and commercialized. As an example, EPA's Tier 4 rule forecast that NO<sub>x</sub> adsorbents would be applied as the primary NO<sub>x</sub> control technology. In practice, this technology was never applied in commercial products. Manufacturers also commonly develop technology improvements that reduce compliance costs and were unknown at the time the regulatory analyses were conducted. 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 manufacturers' presentations. Additional adjustments followed from direct expert consultations. The expert review was conducted by the ICCT for the heavy-duty vehicle (HDV) emission control report published in 2016 (Posada et al., 2016). 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 found in RIAs to better reflect the current status of emission control technologies.

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 parts and supplier websites and then corrected by dividing the number by a fixed factor that scales the commercial price to manufacturer cost.<sup>6</sup> 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 estimated costs were assumed to go to emission control and the other half to improving performance and fuel economy (Posada et al., 2016).

This assessment also includes discounts for some technologies that have undergone cost reductions due to process learning and volume sales. It is widely accepted that as new technologies enter the market, manufacturing costs tend to drop because of increased sales volume

<sup>6</sup> As an example, FleetServe lists aftermarket cordierite-based DPFs for a Detroit Diesel DD13 at \$1,889 (FleetServe, 2017). That cost does not include the pressure sensor and brackets. Dividing that commercial price by 2.5 results in a value closer to manufacturer production cost, or \$756. That value and values from other DPFs were used to better define the DPF costs for this analysis.

and improved production processes. In its cost analysis, the EPA estimates 10% reduction per doubling of production volume and 1%–3% reduction per year from process improvements (EPA, 2004). These learning factors are also used in this report.

## **INCREMENTAL COSTS OF EMISSION CONTROL TECHNOLOGIES**

Assumptions are described below for incremental per-engine costs to the manufacturer for development and use of systems that contribute to emission control, including in-cylinder controls, 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 previously discussed, 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<sub>x</sub> control using high-pressure cooled EGR.

### ***Fuel injection systems***

The main fuel injection systems currently used in non-road applications are the unit injector, unit pump, and common rail systems. These replaced the in-line pump used widely in older non-regulated 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 and the number of fuel injectors is the same as the number of cylinders.

The cost to upgrade a fuel system from rotary to common rail fuel injection is estimated as \$750 for a 6-cylinder, 11.0 L engine. This estimate comes from extrapolating the cost of non-road engines as described in the RIA prepared by ICF International for EPA's Tier IV non-road diesel engines standards (EPA, 2004) and by correcting for inflation. In that report, the engines have two and three cylinders. Thus, a linear extrapolation was developed for each cost item—specifically, injector, pump, electronic control system, sensors and wiring—based on cylinder count. The cost for different engine sizes was proportionally corrected based on engine size/power. In addition, the cost assigned to emission control technologies is 50% of that, which is to say \$375, because the fuel injection system has other functions besides emission control. The other 50% is allocated to engine operation and performance.

The fuel injection system costs for different regulatory stages/tiers were estimated by proportional correction based on injection pressure, which is assumed to have increased from 1,300 bar for Tier 3 to 2,200 bar for Tier 4f. The incremental cost to common rail systems, \$10 per each 10% of fuel injection pressure increase, comes from a report by FEV on the incremental cost for light-duty diesel technology, including common rail fuel injection systems, by 2020 (FEV, 2012). The report summarizes a teardown analysis carried out to estimate the incremental cost of moving from a 2000 bar CR to a 2500 bar CR on a 6-cylinder, 3.0 L diesel engine. Tier 4f and Stage V engines were assumed to be equivalent in terms of fuel injection technology requirements. This cost increase

estimate is conservative, as in many cases technology tends to provide better performance at the same cost over time.

### ***Conventional turbochargers and variable geometry turbochargers***

For diesel engines, turbochargers are key elements for achieving high performance and low emission levels. The most basic form of turbochargers commercially offered were wastegate turbochargers, limited to operating properly at mid-loads. These turbos dominated diesel markets until the advent of the latest emission standards. Variable geometry turbochargers (VGTs), which include a mechanism for varying the turbine geometry, increased their market share because this technology allows for better PM and NO<sub>x</sub> control and increased fuel economy due to proper air delivery during most of the operating engine envelope, or speed-load map.

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.

The cost of a turbo wastegate and cooler is estimated at \$875, based on U.S. RIA estimates (EPA, 2011). An electrically actuated VGT is estimated to add \$370 to the cost, which also covers a wastegate turbocharger and inter-cooler. As with fuel injection system costs, only 50% of the cost of turbochargers is counted toward emission standard compliance, as these systems also provide performance benefits.

### ***Exhaust gas recirculation valve and cooling***

A high-pressure EGR system consists of piping, flanges, gaskets, one or

more EGR control valves, and one or more EGR coolers. It also may include a heater plate for use at low ambient temperatures. The high pressure EGR system is estimated to cost \$439, with an additional \$108 (ranging from \$85 to \$130) for a cooling system. In recent years, several non-road equipment 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.

Table 10 summarizes in-cylinder control costs.

**Table 10.** In-cylinder control costs.

Technology	Cost (2017 US\$)
<b>Fuel system, common rail or extra with respect to unit injector systems</b>	\$750 + \$10 for each 10% of injection pressure increase
<b>Turbo wastegate + cooler</b>	\$876
<b>VGT (extra cost with respect to turbocharger)</b>	\$370
<b>EGR system - high pressure</b>	\$439
<b>EGR intercooler</b>	\$108 (\$85-130)

**Engine control unit and sensor costs**

The cost of the engine control unit (ECU) was extracted from the Tier 4 RIA. The ECU cost ranges from \$250 to \$300 for 4-cylinder engines. A cost of \$275 was used as the starting point for this assessment. The cost was further reduced by 50% considering that the ECU and all components also take part on most engine operations. An incremental factor of 10% was added to the ECU cost for wiring and sensors for 6-cylinder and larger engines.

**Aftertreatment systems**

The cost structure of the three after-treatment 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.<sup>7</sup>

The major cost for both the DOC and the DPF is the PGM loading on the catalyst. Details on data sources for PGM loading are presented in Table 11. The DOC includes the precious metals platinum and palladium in a ratio that can vary from 1:1 to 5:1 Pt:Pd, with a typical ratio of 2:1 and total precious metal loading of 1.4 g per liter (Posada et al., 2016). The DPF has higher costs due to higher loadings in general and a higher Pt:Pd ratio. It should be noted that the Pt:Pd ratio used for automotive catalysts fluctuates over time, as manufacturers find ways to optimize the design and PGM loading to the price swings of the PGM market. PGM prices have remained close to \$30 per gram as of November 2017. In this report, DPF’s Pt:Pd ratios can vary from 5:1 to 1:1, with a typical ratio of 2:1 (Posada et al., 2016). 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. In this report a loading of 1.0 g per liter was assumed. The size of the catalyst depends on the engine displacement, and the metric that defines that relationship is the SVR, or the ratio between engine displacement volume and catalyst volume.

The other components of 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,

<sup>7</sup> Details on the cost elements for SCR storage and dosing system can be found in the emission control technology cost assessment report for light-duty vehicles, by Posada-Sanchez et al. (2012).

additional electronic control unit processing capabilities, and in some cases an oxygen sensor; a fuel injector also is used in most heavy-duty diesel applications.

The greatest cost for the SCR catalyst is for the substrate, washcoat, and canning; SCR systems do not require precious group metals. In on-road applications that are subject to ammonia slip emission standards, the SCR system typically includes an ammonia slip catalyst. The European non-road program includes a NH<sub>3</sub> emission limit, and although U.S. non-road applications do not have an NH<sub>3</sub> emission standard, the non-road engine certification database that EPA maintains shows that this type of technology is present in a large number of engines. Therefore, the cost of an ASC is included in our analysis. The urea system includes a tank and tank accessories, which include brackets, bolts, and spacer, urea pump and injector, urea dosing control unit, tubing, heating system, urea level sensor, two temperature sensors, and NO<sub>x</sub> sensors, the quantity of which depends on the emission standard. Cost details for these components are sourced from the HDV emission control cost report (Posada et al., 2016)

The aftertreatment design parameters used to estimate the cost for aftertreatment systems were based on systems deployed in on-road heavy-duty applications. The main reason for this decision is that there is not enough detail on non-road equipment that can be used to properly estimate the characteristics that define the cost of non-road emission control technologies. Some of these cost components scale directly with catalyst volume, which is 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, 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 11.

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 12), DPFs (Table 13), and SCR systems (Tables 14, 15). Cost details for substrate, washcoat, and canning listed in Tables 12 to 15 are sourced from the HDV emission control cost report (Posada et al., 2016). The main difference in the data presented here is that DPF substrate cost dropped and now it can be found at \$23 per liter, which is down from \$30 when the HDV report was produced. For the DPF, the cost of a regeneration system is added; this includes a differential pressure sensor, plus wiring and connectors. The costs were updated from the original cost assessment done by Posada et al. in 2012. The cost of the ASC was sourced from the HDV emission control cost report and assumes an SVR of 0.25 and Pt loading of 0.15 g/L (Posada et al., 2016).

The direct manufacturing costs for aftertreatment technology were then converted to long-term costs after applying a 5% discount to the short-term costs. The rationale behind this cost reduction is to account for the fact that cost reductions due to process learning occur for

**Table 11.** Literature values referenced for aftertreatment costs

Technology	Parameter	Value	Source
DOC	Catalyst loading	PGM 1.8 g/L	Shakya, Sukumar, López-De Jesús, & Markatou, 2015.
		PGM 1.4 g/L PGM 1.2 g/L Pt: 0.5–0.4 g/L	Desai et al., 2010; Glover et al., 2011. Nazarpour, Golden, & Liu, 2017. Chatterjee, Naseri, & Li, 2017.
Catalyzed DPF	SVR	0.5–0.8	Johnson, 2011.
		0.83	Folic, Lemus, Gekas, & Vressner, 2010.
Catalyzed DPF	Catalyst loading	0.18 g/L	Voss, 2011.
		0.7g/L	Xu, Dearth, Ruona, & McCabe, 2009.
	SVR	1.4	Folic et al., 2010.
		1.6 2.0 2.4	Nazarpour et al., 2017. Voss, 2011. Kotrba, Gardner, Bai, & Yetkin, 2013.
Euro IV SCR	SVR	1.7–2.5	Arrowsmith, Bott, & Bush, 2006; Cho, Won, Kim, Kang, & Lee, 2008.
		1.5–2.0	Tang, Chen, Hallstrom, & Wille, 2016.
Euro V SCR	SVR	1.4–2.8	Blakeman, Arnby, Marsh, Newman, & Smedler, 2009; Johnson, 2002.
		1.5–2.0	Tang et al., 2016
Euro VI SCR	SVR	1.8–2.8	Folic et al., 2010
		2.0–2.5	Yang et al., 2017

Note. PGM is the total loading of platinum (Pt) and palladium (Pd); SVR is the ratio of catalyst volume to engine volume (displacement).

**Table 12.** Diesel oxidation catalyst costs

Engine displacement	1.7 L	2.6 L	4.9 L	10.8 L
<b>Catalyst volume (SVR = 0.7)</b>	<b>1.2</b>	<b>1.8</b>	<b>3.4</b>	<b>7.6</b>
Platinum 0.94 g/L × CV × \$30/g	\$34	\$51	\$97	\$213
Palladium 0.47 g/L × CV × \$30/g	\$17	\$26	\$48	\$107
<b>Total PGMs</b>	<b>\$50</b>	<b>\$77</b>	<b>\$145</b>	<b>\$320</b>
Substrate (\$6*CV)	\$8	\$12	\$23	\$51
Washcoat (\$13*CV)	\$15	\$24	\$45	\$98
<b>Total PGMs + substrate + washcoat</b>	<b>\$74</b>	<b>\$113</b>	<b>\$213</b>	<b>\$469</b>
Canning (\$5*CV)	\$6	\$9	\$17	\$38
Accessories—brackets	\$10	\$10	\$12	\$15
<b>Total manufacturing – short term</b>	<b>\$90</b>	<b>\$132</b>	<b>\$242</b>	<b>\$522</b>
<b>Total manufacturing – long term</b>	<b>\$81</b>	<b>\$119</b>	<b>\$218</b>	<b>\$470</b>

Note. CV = catalyst volume.

any technology and the impact of that learning has been studied and applied by EPA in previous studies (EPA, 2011). According to EPA, the third year of production of a new commercial technology generates a

20% reduction in direct manufacturing costs. After that there is a series of cost reductions—3% per year for 5 years, followed by 2% per year for 5 years, and 1% per year for 5 years—resulting in a 35% cost reduction 10 years after the introduction of the technology. In this assessment we are applying a 10% long-term cost reduction, taking into consideration that the technologies have been in the HDV sector since 2005 for SCR systems and since 2007 for DPFs. That is more than 10 years of development and potential cost reduction measures, and therefore the initial 20% cost reduction does not apply.

**Table 13.** Catalyzed diesel particulate filter costs

Engine displacement	1.7 L	2.6 L	4.9 L	10.8 L
<b>Catalyst volume (SVR = 2.0)</b>	<b>3.4</b>	<b>5.2</b>	<b>9.8</b>	<b>21.6</b>
Platinum $2/3 * 0.2 \text{ g/L} \times \text{CV} \times \$31/\text{g}$	\$12	\$18	\$34	\$76
Palladium $1/3 * 0.2 \text{ g/L} \times \text{CV} \times \$27/\text{g}$	\$6	\$9	\$17	\$38
<b>Total PGMs</b>	<b>\$18</b>	<b>\$27</b>	<b>\$52</b>	<b>\$114</b>
Substrate ( $\$23 \times \text{CV}$ )	\$78	\$120	\$225	\$497
Washcoat ( $\$10 \times \text{CV}$ )	\$34	\$52	\$98	\$216
<b>Total PGMs + substrate + washcoat</b>	<b>\$130</b>	<b>\$199</b>	<b>\$375</b>	<b>\$826</b>
Canning ( $\$5 \times \text{CV}$ )	\$17	\$26	\$49	\$108
Accessories—brackets	\$10	\$11	\$12	\$13
Regeneration system ( $\Delta\text{P}$ sensor, piping, electronic hardware)	\$81	\$81	\$81	\$81
<b>Total manufacturing - short term</b>	<b>\$238</b>	<b>\$317</b>	<b>\$517</b>	<b>\$1,029</b>
<b>Total manufacturing - long term</b>	<b>\$214</b>	<b>\$285</b>	<b>\$465</b>	<b>\$926</b>

Note. CV = catalyst volume.

**Table 14.** Costs of vanadium-based SCR system used for Tier 4f/Stage IV - Non-DPF systems

Average engine displacement	1.7 L	2.6 L	4.9 L	10.8 L
<b>Catalyst volume (SVR = 2.0)</b>	<b>3.4</b>	<b>5.2</b>	<b>9.8</b>	<b>21.6</b>
Precious metals not required; base metals costs negligible	\$0	\$0	\$0	\$0
Ammonia slip catalyst (25 ppm emission standards)	\$2	\$3	\$6	\$12
<b>Total PGMs</b>	<b>\$2</b>	<b>\$3</b>	<b>\$6</b>	<b>\$12</b>
Substrate and washcoat (vanadium: $\$12 \times \text{CV}$ )	\$41	\$62	\$118	\$259
Canning ( $\$25 \times \text{CV}$ ) - includes ASC costs	\$85	\$130	\$245	\$540
<b>Total SCR catalyst: PGMs + substrate + washcoat</b>	<b>\$128</b>	<b>\$195</b>	<b>\$368</b>	<b>\$811</b>
Urea tank volume ( $6 \times \text{Vd}$ )	<b>10</b>	<b>16</b>	<b>29</b>	<b>65</b>
Urea tank cost	\$85	\$112	\$172	\$290
Urea level sensor	\$48	\$48	\$48	\$48
Urea tank accessories (brackets, bolts, spacers)	\$30	\$33	\$36	\$40
Urea pump	\$49	\$57	\$70	\$91
Urea injector	\$33	\$38	\$46	\$60
Tubing, stainless steel	\$14	\$21	\$40	\$89
Urea injection pipe section	\$14	\$21	\$40	\$89
Urea injection mounting parts (brackets, bolts, gaskets, spacers, tubing connectors)	\$15	\$19	\$25	\$38
Urea heating system, 200 W, 12 V DC	\$38	\$44	\$54	\$70
Temperature sensor (4 per system)	\$84	\$84	\$84	\$84
Urea Mixer	\$20	\$25	\$34	\$50
Dosing control unit	\$200	\$200	\$200	\$200
NO <sub>x</sub> sensor not required—open loop NO <sub>x</sub> control	\$0	\$0	\$0	\$0
<b>Total urea system</b>	<b>\$629</b>	<b>\$701</b>	<b>\$850</b>	<b>\$1,149</b>
<b>Total manufacturing - short term</b>	<b>\$757</b>	<b>\$897</b>	<b>\$1,218</b>	<b>\$1,960</b>
<b>Total manufacturing - long term</b>	<b>\$681</b>	<b>\$807</b>	<b>\$1,096</b>	<b>\$1,764</b>

Note. Vd = engine displacement; CV = catalyst volume.

**Table 15.** Costs of zeolite-based SCR system used for Stage V – incorporating DPF systems.

Average engine displacement	1.7 L	2.6 L	4.9 L	10.8 L
<b>Catalyst volume (SVR = 2.5)</b>	<b>4.3</b>	<b>6.5</b>	<b>12.3</b>	<b>27.0</b>
Precious metals not required; base metals costs negligible	\$0	\$0	\$0	\$0
Ammonia slip catalyst (25 ppm emission standards)	\$2	\$3	\$6	\$12
<b>Total PGMs</b>	<b>\$2</b>	<b>\$3</b>	<b>\$6</b>	<b>\$12</b>
Substrate and washcoat (zeolites: \$18*CV)	\$77	\$117	\$221	\$486
Canning (\$25*CV) – includes ASC costs	\$106	\$163	\$306	\$675
<b>Total SCR catalyst: PGMs + substrate + washcoat</b>	<b>\$185</b>	<b>\$282</b>	<b>\$532</b>	<b>\$1,173</b>
Urea tank volume (6*Vd)	10	16	29	65
Urea tank cost	\$85	\$112	\$172	\$290
Urea level sensor	\$48	\$48	\$48	\$48
Urea tank accessories (brackets, bolts, spacers)	\$30	\$33	\$36	\$40
Urea pump	\$49	\$57	\$70	\$91
Urea injector	\$33	\$38	\$46	\$60
Tubing, stainless steel	\$14	\$21	\$40	\$89
Urea injection pipe section D2.5" × 38 cm	\$14	\$21	\$40	\$89
Urea injection mounting parts (brackets, bolts, gaskets, spacers, tubing connectors)	\$15	\$19	\$25	\$38
Urea heating system, 200 W, 12 V DC	\$38	\$44	\$54	\$70
Temperature sensor (4 per system)	\$84	\$84	\$84	\$84
Mixer	\$20	\$25	\$34	\$50
Dosing control unit	\$200	\$200	\$200	\$200
NO <sub>x</sub> sensor (\$170 × 1 per system)	\$170	\$170	\$170	\$170
<b>Total urea system</b>	<b>\$799</b>	<b>\$871</b>	<b>\$1,020</b>	<b>\$1,319</b>
<b>Total manufacturing – short term</b>	<b>\$984</b>	<b>\$1,154</b>	<b>\$1,552</b>	<b>\$2,492</b>
<b>Total manufacturing – long term</b>	<b>\$886</b>	<b>\$1,038</b>	<b>\$1,397</b>	<b>\$2,243</b>

Note. Vd = engine displacement; CV = catalyst volume.

## Fixed costs

Fixed costs in this report cover R&D, manufacturing tooling, and certification, following the methodology from the EPA for this kind of cost assessment (EPA, 2004). The method estimates a cost amount per engine power class and spreads that value among all the units sold during a production period. R&D cost primarily covers an estimated number of engineering staff and development vehicles. R&D costs are accrued by manufacturers for improving engine-out emissions while integrating the aftertreatment systems with the engine and power train 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 EPA non-road Tier 4 emission standards (EPA, 2004).

Tooling costs cover the cost associated with changes to production lines due to engine-out control (EGR, VGT, and others), as well as aftertreatment systems, DOC, DPF, and SCR. These costs were estimated by EPA for the Tier 4 rule from the information provided by HDV engine manufacturers for EPA 2007–2010 standards. Tooling costs are estimated as equal for NO<sub>x</sub> and PM control, meaning that standards that require a step change in only one or the other pollutant incur only half the estimated costs.

Costs of certification will be accrued as non-road engine manufacturers develop engines meeting progressively more stringent standards. These costs cover the staff time and engineer time and laboratory costs associated with engine dynamometer certification tests. These costs are split by emissions target, PM and HC control, and NO<sub>x</sub> control.

EPA-estimated fixed costs (R&D, tooling, and certification) are presented in Table 16, with corrections due to inflation. The reader should note that the values for non-road engines are higher than those for heavy-duty on-road engines due to the larger market size of the HDV on-road sector,

which makes it possible to spread R&D costs over a larger number of units. Long-term fixed costs account for the cost reduction due to learning and because the technologies are going to be fully developed for application in countries where this assessment is expected to be used as a cost and benefit tool. The value for the short-term to long-term cost reduction was sourced from EPA’s RIA on non-road emission control technology costs (EPA, 2004).

These values are added to each regulatory step where DPF and SCR are introduced for emission control, which in reality only applies to some power ranges in Stage V. This implies that R&D integration costs for PM/HC control are applied here only to Tier 4i, Tier 4f, and Stage V; NO<sub>x</sub> control costs are applied at Stage IV/Tier 4f for engines > 56 kW. This translates into our cost estimates as full fixed costs (Table 16) applied to Stage V, where all aftertreatment systems are required; a reduction of the fixed cost values corresponding to half the R&D for combinations of stages and power ratings where only one technology is required; and only certification costs required for stages and power ratings where no aftertreatment technologies are needed.

## 6. Incremental Costs of Non-Road Emission Standards

The final step in this analysis focuses on the most globally relevant regulations for non-road equipment: Stage II/III through Stage V in the EU and Tier 2/3 through Tier 4f in the United States. For each regulatory stage, the total incremental costs are estimated by matching the technologies required for that stage

**Table 16.** Estimated fixed costs for integrating emission control technology, from Tier IV EPA impact assessment (EPA, 2004)

Fixed costs item	19–37 kW 1.7 L	37–56 kW 2.6 L	75–130 kW 4.9 L	224–447 kW 10.8 L
R&D costs, per engine	\$51	\$54	\$51	\$414
Tooling, per engine	\$7	\$6	\$16	\$76
Certification, per engine	\$16	\$16	\$12	\$37
<b>Total TIER IV (2002 dollars)</b>	\$74	\$76	\$79	\$527
<b>Total (2017 dollars)<sup>a</sup></b>	<b>\$101</b>	<b>\$103</b>	<b>\$107</b>	<b>\$716</b>
<b>Long-term fixed costs</b>	<b>\$68</b>	<b>\$69</b>	<b>\$74</b>	<b>\$431</b>

<sup>a</sup>Inflation correction between 2002 and 2017 = 1.35892, from U.S. Bureau of Labor Statistics (2017).

(Tables 4 through 9) with their costs (Tables 10 and 12 through 16).

The costs presented here represent updated estimates of manufacturer compliance costs. These include costs for hardware, and fixed costs from R&D, tooling, and certification. These do not include the operational costs incurred by vehicle owners, including the cost of diesel exhaust fluid and low- or ultralow-sulfur fuel as well as any change in maintenance costs. Nor do these estimates include costs incurred by equipment manufacturers for equipment redesign, new hardware, and increased equipment assembly time, as equipment manufacturers purchase a complete engine and emission control package from engine manufacturers. 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 regulatory assessments that projected the technology needs to meet upcoming regulatory stages. The analysis is informed by publicly available data

on already adopted in-cylinder and aftertreatment technologies that are in widespread commercial use. Nonetheless, these values are only approximations, as information on the exact cost 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. As the technology continues to improve, further process learning takes place, and manufacturers continue to scale production, we expect that these costs will continue to decline.

Tables 17 through 20 list the incremental cost of each component, compared with its cost under the previous standard for select engine power classes. 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

**Table 17.** Technology costs to meet U.S. and European standards at different tiers/stages for a 19–37 kW, 1.7 L engine

	U.S.				EU	
	Tier 2	Tier 4i	Tier 4f		Stage IIIA	Stage V
			No DPF	DPF		
<b>Hardware</b>						
<b>Air/fuel control and engine-out emissions</b>						
Fuel system – 50% of total cost	\$237	\$237	\$604	\$604	\$237	\$604
Naturally aspirated (NA)	\$-	\$-	\$-	\$-	\$-	\$-
Turbocharger – 50% of total cost	\$-	\$-	\$-	\$-	\$-	\$-
VGT (extra cost) – 50% of total cost	\$-	\$-	\$-	\$-	\$-	\$-
EGR system	\$-	\$-	\$190	\$190	\$-	\$190
EGR cooling	\$-	\$-	\$58	\$58	\$-	\$58
Total for air/fuel control and engine-out emissions	\$237	\$237	\$852	\$852	\$237	\$852
<b>Aftertreatment systems</b>						
DOC	\$-	\$-	\$81	\$81	\$-	\$81
DPF	\$-	\$-	\$-	\$214	\$-	\$214
SCR	\$-	\$-	\$-	\$-	\$-	\$-
<i>Total for aftertreatment systems</i>	\$-	\$-	\$81	\$295	\$-	\$295
<i>Total for hardware</i>	\$237	\$237	\$933	\$1,147	\$237	\$1,147
<b>ECU, wiring, and sensors</b>	\$-	\$-	\$34	\$34	\$-	\$34
<b>Fixed costs (R&amp;D, tooling, certification)</b>	\$14	\$28	\$68	\$68	\$14	\$68
<b>Total cost</b>	\$251	\$265	\$1,035	\$1,249	\$251	\$1,249
<b>Incremental cost (compared to previous standard)</b>	-	\$14	\$770	\$984	-	\$998

in this analysis. Cost estimates for all power classes are included in the final section of the paper.

According to the EPA's Tier 4f impact assessment report, the incremental cost incurred in upgrading a 19–37 kW engine from a Tier 3 to a Tier 4f was estimated at \$1,000 (2017 dollars) after inflation correction (BLS, 2017); this is very close to ICCT's estimate based on our updated cost figures for the DPF equipped option (\$984), and about 23% higher than ICCT's estimates for the non-DPF option (\$770). For the 37–56 kW engines, the EPA estimated a total cost of compliance of \$1,340 (2017 dollars),

after corrections, which is about 31% more than our estimate of \$927; the difference is mainly driven by EPA's assumptions on DPF adoption and cost reductions due to learning. The EPA's cost estimate for the 75–130 kW range was about \$2,770 (2017 dollars), whereas ICCT estimates \$1,441; the difference is again due to the industry ability to comply with the standards without DPFs, which was assumed by EPA's staff back in 2004, and cost reductions due to learning. For the larger engines to meet the Tier 4f standards compared to the Tier 3 standards, ICCT estimates a cost of \$2,845, compared to EPA's assessment of \$6,055; the inflated

EPA value is once again driven by the assumption of DPF adoption for Tier 4f compliance, which has been avoided in production engines.

Figure 7 shows total cost per regulatory step. As expected compliance costs are proportional to the regulatory level stringency and engine rated power range. Note that costs for non-road equipment are lower than the cost of emission control technology required to meet the HDV EPA 2010 emission standard: around \$7,000 for a 12-liter HDV engine with SCR, DPF, DOC, advanced air and fuel management systems and ECU (Posada et al., 2016).

**Table 18.** Technology costs to meet U.S. and European standards at different stages for a 37–56 kW, 2.6 L engine

	Tier 2/Stage II	Tier 4i/ Stage IIIA	Tier 4f/Stage IIIB	Stage V (Tier 4f/ Stage IIIB w/DPF)
<b>Hardware</b>				
<b>Air/fuel control and engine-out emissions</b>				
Fuel system — 50% of total cost	\$257	\$257	\$628	\$628
Naturally aspirated (NA)	\$-	\$-	\$-	\$-
Turbocharger — 50% of total cost	\$204	\$272	\$272	\$272
VGT (extra cost) — 50% of total cost	\$-	\$-	\$-	\$-
EGR system	\$-	\$218	\$218	\$218
EGR cooling	\$-	\$67	\$67	\$67
<i>Total for air/fuel control and engine-out emissions</i>	<b>\$461</b>	<b>\$815</b>	<b>\$1,185</b>	<b>\$1,185</b>
<b>Aftertreatment systems</b>				
DOC	\$-	\$-	\$119	\$119
DPF	\$-	\$-	\$-	\$285
SCR	\$-	\$-	\$-	\$-
<i>Total for aftertreatment systems</i>	<b>\$-</b>	<b>\$-</b>	<b>\$119</b>	<b>\$404</b>
<i>Total for hardware</i>	<b>\$461</b>	<b>\$815</b>	<b>\$1,304</b>	<b>\$1,589</b>
<b>ECU, wiring, and sensors</b>	\$-	\$-	\$38	\$38
<b>Fixed costs (R&amp;D, tooling, certification)</b>	\$23	\$47	\$69	\$69
<b>Total cost</b>	<b>\$484</b>	<b>\$862</b>	<b>\$1,411</b>	<b>\$1,696</b>
<b>Incremental cost (compared to previous standard)</b>	-	<b>\$378</b>	<b>\$549</b>	<b>\$285<sup>a</sup></b>

<sup>a</sup>Incremental cost of Stage V engine relative to non-DPF Stage IIIB engine

**Table 19.** Technology costs to meet U.S. and European standards at different stages for a 75–130 kW, 4.9 L engine

	Tier 3/ Stage IIIA	Tier 4i/Stage IIIB		Tier 4f/ Stage IV	Stage V (Tier 4f/ Stage IV w/DPF)
		SCR	EGR		
<b>Hardware</b>					
<b>Air/fuel control and engine-out emissions</b>					
Fuel system — 50% of total cost	\$604	\$710	\$710	\$710	\$710
Naturally aspirated (NA)	\$-	\$-	\$-	\$-	\$-
Turbocharger — 50% of total cost	\$336	\$336	\$336	\$336	\$336
VGT (extra cost) — 50% of total cost	\$-	\$-	\$-	\$-	\$-
EGR system	\$270	\$-	\$270	\$270	\$270
EGR cooling	\$83	\$-	\$83	\$83	\$83
<i>Total for air/fuel control and engine-out emissions</i>	<b>\$1,293</b>	<b>\$1,046</b>	<b>\$1,399</b>	<b>\$1,399</b>	<b>\$1,399</b>
<b>Aftertreatment systems</b>					
DOC	\$-	\$-	\$218	\$218	\$218
DPF	\$-	\$-	\$465	\$-	\$465
SCR	\$-	\$1,075	\$-	\$1,075	\$1,376
<i>Total for aftertreatment systems</i>	<b>\$-</b>	<b>\$1,075</b>	<b>\$683</b>	<b>\$1,293</b>	<b>\$2,059</b>
<i>Total for hardware</i>	<b>\$1,293</b>	<b>\$2,121</b>	<b>\$2,082</b>	<b>\$2,692</b>	<b>\$3,458</b>
<b>ECU, wiring, and sensors</b>	\$42	\$42	\$42	\$42	\$42
<b>Fixed costs (R&amp;D, tooling, certification)</b>	\$32	\$64	\$64	\$74	\$74
<b>Total cost</b>	<b>\$1,367</b>	<b>\$2,227</b>	<b>\$2,188</b>	<b>\$2,808</b>	<b>\$3,574</b>
<b>Incremental cost (compared to previous standard)</b>	-	<b>\$860</b>	<b>\$821</b>	<b>\$581–\$620</b>	<b>\$766<sup>a</sup></b>

<sup>a</sup>Incremental cost of Stage V engine relative to non-DPF Stage IV engine

**Table 20.** Technology costs to meet U.S. and European standards at different stages for a 224–447 kW, 10.8 L engine

	Tier 3/ Stage IIIA	Tier 4i/Stage IIIB		Tier 4f/ Stage IV	Stage V (Tier 4f/ Stage IV w/DPF)
		SCR	EGR		
<b>Hardware</b>					
<b>Air/fuel control and engine-out emissions</b>					
Fuel system – 50% of total cost	\$813	\$990	\$990	\$990	\$990
Naturally aspirated (NA)	\$-	\$-	\$-	\$-	\$-
Turbocharger – 50% of total cost	\$438	\$438	\$438	\$438	\$438
VGT (extra cost) – 50% of total cost	\$-	\$-	\$-	\$185	\$185
EGR system	\$351	\$-	\$351	\$351	\$351
EGR cooling	\$108	\$-	\$108	\$108	\$108
<i>Total for air/fuel control and engine-out emissions</i>	<b>\$1,710</b>	<b>\$1,428</b>	<b>\$1,887</b>	<b>\$2,072</b>	<b>\$2,072</b>
<b>Aftertreatment systems</b>					
DOC	\$-	\$-	\$470	\$470	\$470
DPF	\$-	\$-	\$926	\$-	\$926
SCR	\$-	\$1,772	\$-	\$1,772	\$2,251
<i>Total for aftertreatment systems</i>	<b>\$-</b>	<b>\$1,772</b>	<b>\$1,396</b>	<b>\$2,242</b>	<b>\$3,647</b>
<i>Total for hardware</i>	<b>\$1,710</b>	<b>\$3,200</b>	<b>\$3,283</b>	<b>\$4,314</b>	<b>\$5,719</b>
<b>ECU, wiring, and sensors</b>	\$42	\$42	\$42	\$42	\$42
<b>Fixed costs (R&amp;D, tooling, certification)</b>	\$190	\$380	\$380	\$431	\$431
<b>Total cost</b>	<b>\$1,942</b>	<b>\$3,622</b>	<b>\$3,705</b>	<b>\$4,787</b>	<b>\$6,192</b>
<b>Incremental cost (compared to baseline)</b>	-	<b>\$1,680</b>	<b>\$1,763</b>	<b>\$1,082– \$1,165</b>	<b>\$1,405<sup>a</sup></b>

<sup>a</sup>Incremental cost of Stage V engine relative to non-DPF Stage IV engine

## 7. Summary and Conclusions

Tables 21 and 22 summarize the result of the non-road emission control technology cost assessment. Values presented in these tables represent the technology progression with lowest total compliance costs at each regulatory step. Total cost of emission control technologies is proportional to engine rated power. For some engine rating categories, the incremental cost is insignificant, as can be observed for engines rated below 19 kW. The most popular agricultural tractors in India are fitted with engines rated between 19 and 37 kW; for this particular segment, the incremental cost to reach Tier 4f from Tier 3 is estimated to be less than \$785 and reaching Stage V would require around \$1,000. Non-road equipment rated at the higher end of the power range shows cost numbers similar to those observed in the HDV vehicle sector. For this equipment segment, the largest incremental cost is driven by the adoption of DPF and SCR systems in the Tier 4f and Stage V steps.

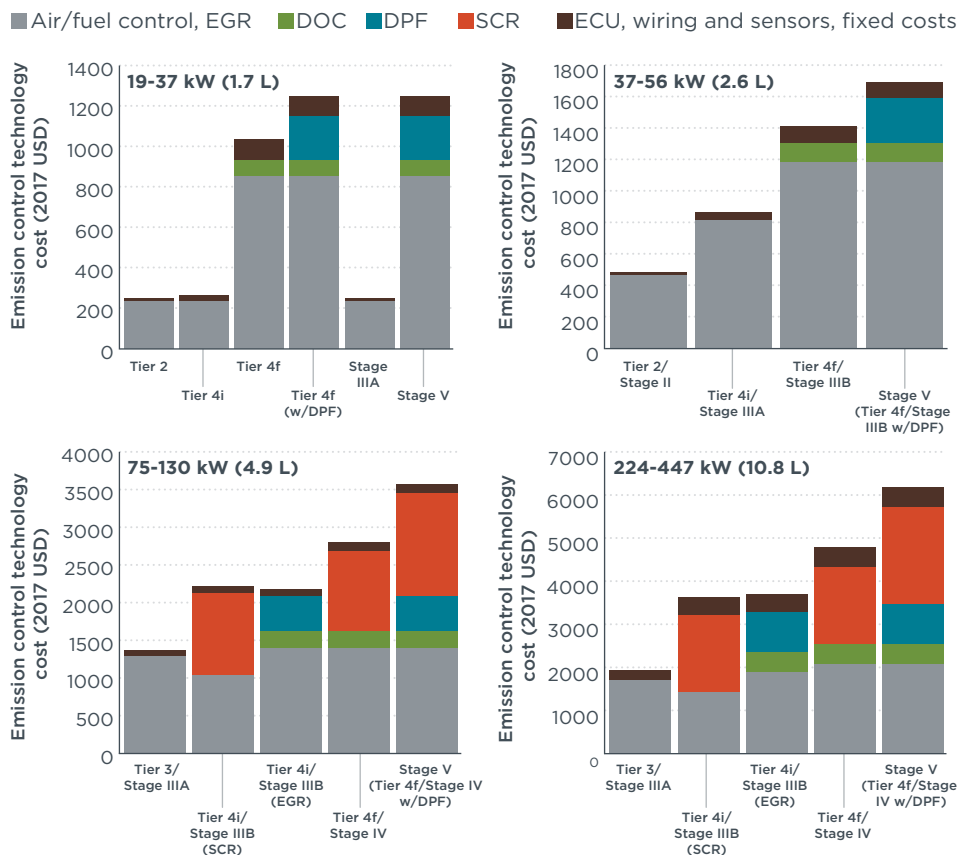


Figure 7. Estimated cost of emission control technology, in 2017 dollars.

Table 21. Summary of non-road emission control technology costs for U.S. regulatory progression

	Standard	<19 kW	19-37 kW	37-56 kW	56-75 kW	75-130 kW	130-224 kW	224-447 kW	447-560 kW
<b>Total costs</b>	Baseline	\$223	\$251	\$485	\$850	\$1,366	\$1,627	\$1,941	\$2,731
	Tier 4i	—	\$265	\$862	\$1,569	\$2,227	\$2,859	\$3,621	\$5,933
	Tier 4f	\$229	\$1,035	\$1,412	\$2,544	\$2,808	\$3,797	\$4,787	\$7,759
<b>Incremental costs with respect to baseline</b>	Tier 4i	—	\$14	\$377	\$719	\$861	\$1,232	\$1,680	\$3,202
	Tier 4f	\$6	\$785	\$927	\$1,694	\$1,442	\$2,171	\$2,845	\$5,028
<b>Incremental costs with respect to previous standard</b>	Tier 4i	—	\$14	\$377	\$719	\$861	\$1,232	\$1,680	\$3,202
	Tier 4f	\$6	\$770	\$550	\$975	\$581	\$939	\$1,165	\$1,826



**Table 22.** Summary of non-road emission control technology costs for European regulatory progression

	Standard	<19 kW	19–37 kW	37–56 kW	56–75 kW	75–130 kW	130–224 kW	224–447 kW	447–560 kW
<b>Total costs</b>	Baseline	\$223	\$251	\$485	\$850	\$1,366	\$1,627	\$1,941	\$2,731
	Stage IIIB	—	\$265	\$862	\$1,569	\$2,227	\$2,859	\$3,621	\$5,933
	Stage IV	\$229	\$1,035	\$1,412	\$2,544	\$2,808	\$3,797	\$4,787	\$7,759
	Stage V	\$229	\$1,250	\$1,697	\$3,201	\$3,574	\$4,877	\$6,191	\$10,366
<b>Incremental cost with respect to baseline</b>	Stage IIIB	—	\$14	\$377	\$719	\$861	\$1,232	\$1,680	\$3,202
	Stage IV	\$6	\$785	\$927	\$1,694	\$1,442	\$2,171	\$2,845	\$5,028
	Stage V	\$6	\$999	\$1,212	\$2,351	\$2,208	\$3,520	\$4,250	\$7,635
<b>Incremental costs with respect to previous standard</b>	Stage IIIB	—	\$14	\$377	\$719	\$861	\$1,232	\$1,680	\$3,202
	Stage IV	\$6	\$770	\$550	\$975	\$581	\$939	\$1,165	\$1,826
	Stage V	\$6	\$215	\$285	\$657	\$766	\$1,080	\$1,405	\$2,607

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