WHITE PAPER

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TECHNOLOGY PATHWAYS FOR DIESEL ENGINES USED IN NON-ROAD VEHICLES AND EQUIPMENT

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INTRODUCTION

BACKGROUND

Internal combustion engines are ubiquitous in today's society. Applications for these engines cover a broad spectrum, ranging from vehicles that transport passengers and move goods to specialized vehicles and equipment used in the construction and agriculture industries. Internal combustion engines are integral to today's economy, however, they have also long been recognized as a significant source of pollutant emissions that contribute to poor air quality, negative human health impacts, and climate change. Efforts to mitigate the emissions impact of these sources, such as regulatory control programs, have played a key role in air quality management strategies around the world, and have helped to spur the development of advanced engine and emission control technologies.

Regulatory control programs have typically been developed first for engines used for on-road applications. Complementary programs for other mobile source types, including non-road vehicles and equipment, locomotives, marine vessels, and aircraft, have generally lagged behind those for on-road vehicles. As a result, the relative importance of non-road sources of air pollution increases as emissions from on-road vehicles are reduced. Many countries around the world have progressed in controlling emissions from on-road vehicles and are in the process of targeting other source categories through enhanced emission control programs.

As non-road engine emissions control programs are developed in a growing number of countries around the world, it is instructive to look at the development of programs in two of the regions that have progressed furthest in controlling emissions from non-road engines, the United States and European Union. By understanding the progression of engine emission standards and parallel developments in engine emission control technologies in these countries, pathways for the continued control of emissions from this important source category can be projected for other regions.

SCOPE

This report aims to investigate several aspects of the evolution of diesel engines used in non-road vehicles and equipment in the United States and European Union. First, the historical progression of regulatory programs controlling emissions from non-road diesel engines in the two regions is examined, beginning with the initial promulgation of emission standards for these engines in the mid-1990s and continuing through proposed European Stage V regulations, which are expected to be implemented in 2018. Second, the development and application of engine emission control strategies and technologies in response to these increasingly stringent regulatory programs is considered. This paper outlines the steps taken by engine manufacturers to go from low-technology diesel engines to modern technology engine systems that incorporate advanced emission control technologies and emit 95% less pollution than their predecessors.

The focus of this analysis is placed on regulatory programs and engine markets in the United States and European Union. These regions were amongst the first to regulate emissions from non-road diesel engines, and U.S. and EU regulations have generally served as models for non-road diesel emission control programs in other areas of the world.[1] By tracing the development of non-road diesel engines in these regions, this analysis will inform the potential for advancement towards cleaner engines in countries and regions with no or less stringent emission standards in place, such as India and China.[2] The progression of non-road diesel engine technologies in the United States and European Union presented here will provide insight into potential pathways and timelines for the introduction of lower-emitting engines in these emerging markets.

In the following sections, we show the relative importance of non-road diesel engines as sources of pollutant emissions in the two regions, trace the regulatory history of these engine types, and outline engine and emission control technology pathways followed in response to increasingly stringent regulatory standards.

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[1] Other global regulatory frameworks for the control of emissions from non-road sources include UNECE Regulation 96 and Global Technical Regulation No. 11.

[2] These emerging markets are growing quickly and are expected to surpass the US and EU in terms of demand for non-road diesel engines in upcoming years. Non-road diesel engine emission standards in these countries lag behind those in the US and EU. Given the growing market for non-road diesel engines in India and China, the adoption of more stringent standards will be an important component in strategies to address existing air pollution problems.

NON-ROAD SECTOR CHARACTERIZATION

Mobile sources of air pollution can generally be divided into two categories: on-road sources and non-road sources. On-road sources include vehicles used in on-highway applications, and primarily consist of light- and heavy-duty vehicles used for passenger and goods transport. Specialty on-road vehicles, such as refuse trucks and emergency response vehicles, are also included in this sector. All other mobile sources can be categorized as non-road sources. As is shown in Table 1, the non-road sector encompasses a very diverse and broad range of vehicle and equipment types. Major non-road engine applications include locomotives, aircraft, marine vessels, and equipment used in construction and agriculture industries.

Table 1. Mobile sources of air pollution

Types	Examples
On-Road	
Light-duty vehicles	Passenger cars, light trucks, motorcycles
Heavy-duty vehicles	Heavy trucks, buses
Non-Road	
Non-road diesel engines	Agricultural, construction, mining equipment
Small spark-ignition engines	Lawn and garden equipment, personal water craft
Large spark-ignition engines	Forklifts, generators, compressors
Land based recreational vehicles	Snowmobiles, all terrain vehicles
Commercial marine	Container ships, bulk carriers
Locomotive and railcar	Passenger rail, line-haul
Aircraft	Passenger aircraft, cargo aircraft

For the purposes of this paper, the term non-road engine will henceforth refer solely to engines used in non-road vehicles and equipment, and will exclude other non-road sources such as locomotives, aircraft, and marine vessels.

NON-ROAD ENGINE APPLICATIONS

Non-road engine applications include a wide variety of vehicle and equipment types used in a broad range of end-use sectors. The U.S. Environmental Protection Agency (EPA) has identified a number of characteristics that differentiate non-road engines from on-highway engines (EPA, 1998a). These characteristics include:

1. The engine is used in a piece of motive equipment that propels itself in addition to performing an auxiliary function (e.g., bulldozer, agricultural tractor)
2. The engine is used in a piece of equipment that is intended to be propelled as it performs its function (e.g., lawnmower)
3. The engine is used in a piece of equipment that is stationary but portable (e.g., generator, compressor)
4. The engine is used in a piece of motive equipment that propels itself, but is primarily used for off-road functions (e.g., off-highway truck)

EU regulations classify non-road vehicles and equipment within the broader category of non-road mobile machinery (NRMM), which also includes other non-road sources such as locomotives. For regulatory purposes, NRMM is defined as “any mobile machine, transportable industrial equipment or vehicle with or without body work, not intended for the use of passenger- or goods-transport on the road, in which an internal combustion engine is installed” (European Commission, 1997).

Major end-use sectors for non-road engines are similar in the United States and European Union and include agriculture, forestry, construction, mining, and commercial industries. Table 2 provides examples of non-road vehicle and equipment types for each of these end-use sectors. Other major non-road sectors include lawn and garden applications, port equipment, recreational vehicles and boats, and military equipment.

Table 2. Examples of non-road vehicle and equipment types by sector

Sector	Vehicle and equipment types		
Agriculture and forestry	Agricultural tractors Combines Two-wheel tractors	Irrigation sets Balers Sprayers	Feller/bunch/skidder Chain saws
Construction and industry	Wheel loaders Crawler tractors/ dozers Excavators Off-highway trucks	Tractors/loaders/ backhoes Skid steer loaders Scrapers/graders Paving equipment	Cranes Rollers Forklifts Refrigeration units
Commercial	Generator sets Air/gas compressors	Welders Pumps	Gas compressors
Lawn and garden	Lawn and garden tractors Turf equipment	Trimmers/edgers/ brush cutters Lawnmowers	Leaf blowers/vacuums
Other	Military equipment Railway maintenance	Recreational boats Snowmobiles	All terrain vehicles

Engine types used in non-road vehicles and equipment vary by engine size and application. Compression-ignition (CI), or diesel, engines are widely used in large equipment applications typical of the construction and agriculture sectors and other industrial applications. Spark-ignition (SI) engines, mainly fueled with gasoline, are commonly used in lawn and garden equipment, land-based recreational vehicles, and marine pleasure craft. Regulatory pathways in the United States and European Union have differed for non-road CI and SI engines, with standards for CI engines implemented prior to those for SI engines in both regions. This analysis focuses on non-road diesel engines and will touch only briefly on aspects of non-road spark ignition engines.

A key distinguishing characteristic of the non-road engine market is the wide variation in the power rating of engines used in non-road vehicles and equipment. As shown in Figure 1, engine sizes used in common non-road applications can span several orders of magnitude, from small (< 19 kW) engines used in lawn and garden equipment to very large (> 560 kW) engines used in generator sets and off-highway trucks. Some applications, such as skid steer loaders or refrigeration units, utilize a relatively narrow range of engine sizes. In contrast, engine sizes can span several hundreds of kilowatts for equipment such as agricultural tractors or excavators. In both U.S. and EU regulatory programs, emission standards are set according to engine power, with the stringency and timing of emission standards varying across engine power classes. Generally, those engines sizes with on-road analogues (~75-560 kW) were subjected to more stringent emission standards at an earlier date than engine sizes with no direct on-road counterpart. The following sections further discuss the role of engine size in regulatory trajectories and engine technology design pathways.

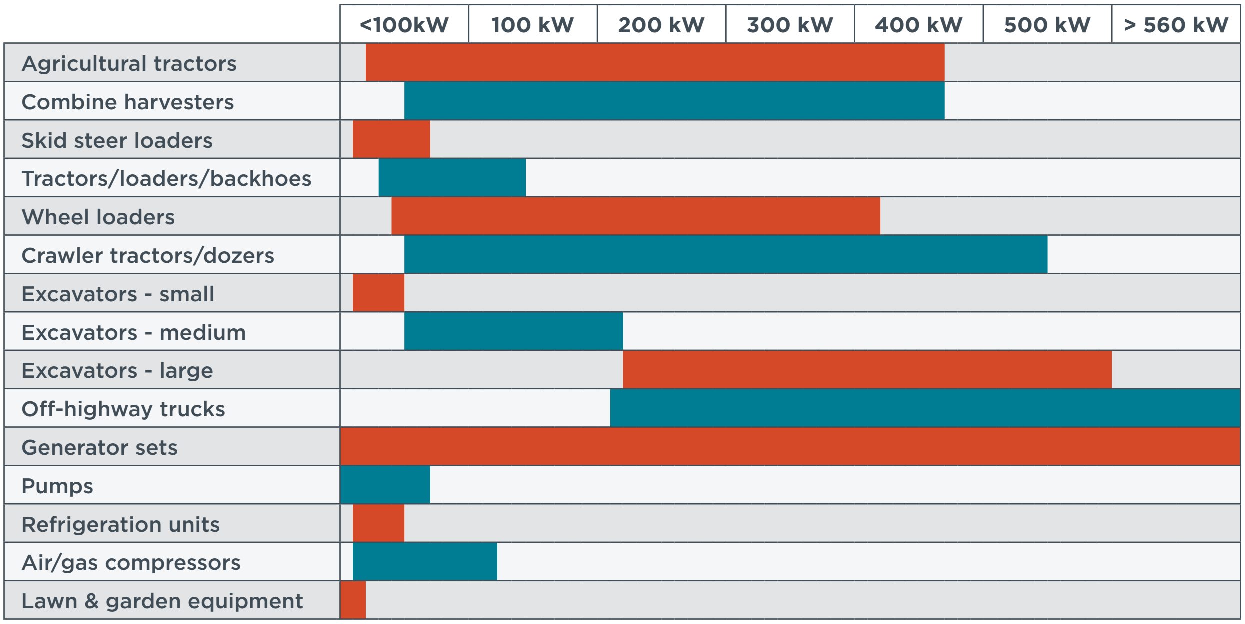


Figure 1. Range of engine sizes used in common non-road vehicles and equipment types (EPA, 2010; EEA, 2013)

NON-ROAD ENGINE EMISSIONS AND POPULATIONS

Despite ongoing emission control efforts, non-road engines remain a significant source of air pollutant emissions in the United States and European Union. Figure 2 shows the relative contributions of individual mobile source categories to emissions of two important pollutants of concern, nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$). Data presented here is taken from official emission inventories compiled by the European Environment Agency (EEA) and EPA (EPA, 2015a; EEA, 2015). In both regions, on-road vehicles are the dominant source of mobile source NO_x and $PM_{2.5}$ emissions; however, non-road engines are also an important source of both pollutants. In these regions, non-road vehicles and equipment are responsible for approximately 15–20% and 25–40% of total NO_x and $PM_{2.5}$ emissions, respectively. Also in both regions, non-road vehicles and equipment emit approximately 10% of total anthropogenic NO_x emissions and 4% of anthropogenic $PM_{2.5}$ emissions. While not shown here, non-road engines are also an important source of carbon monoxide (CO) and hydrocarbon (HC) emissions. These data make clear the considerable emissions impact of non-road sources and highlight the need for the continued control of emissions from these engines.

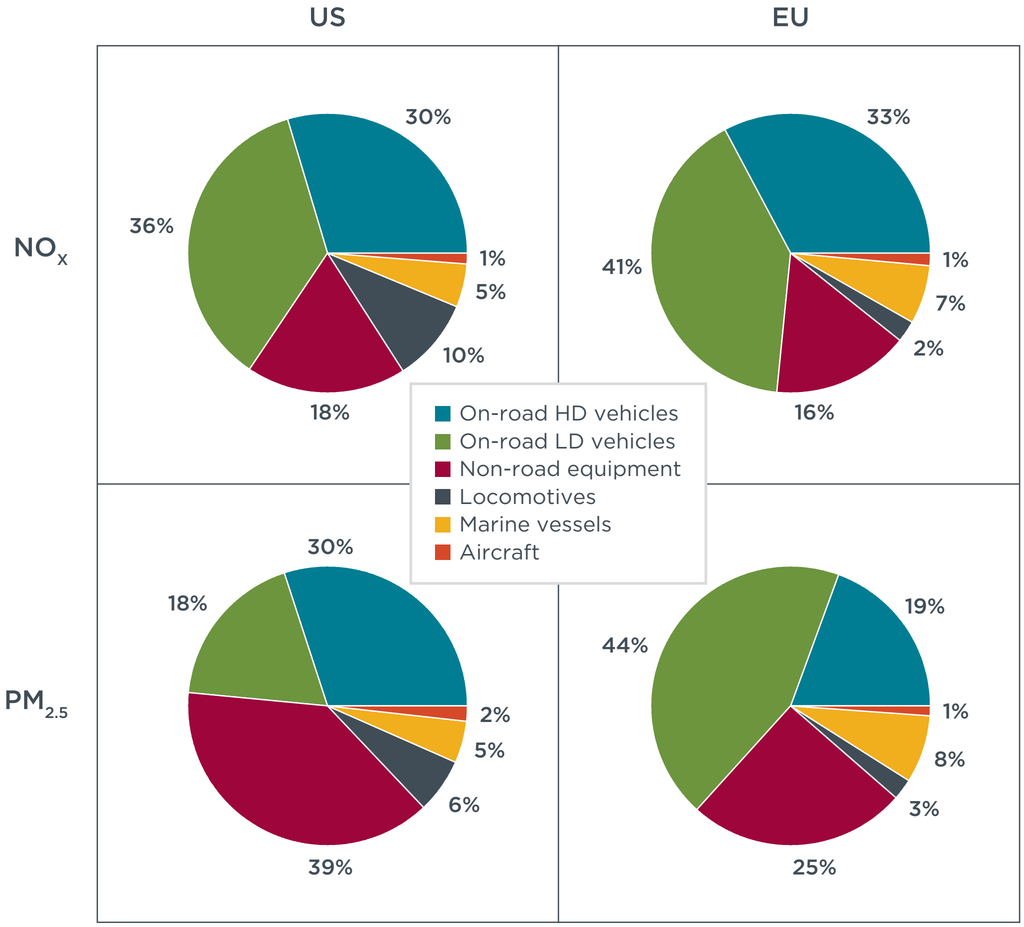


Figure 2. Relative contributions of individual source categories to mobile-source NO_x and $PM_{2.5}$ emissions in the United States and European Union for 2011 (EPA, 2015a; EEA, 2015)

A more detailed analysis of emission inventory data enables comparisons between emissions contributions from specific end-use categories in the non-road sector. Figure 3 presents relative NO_x and $PM_{2.5}$ emissions from engines used in major non-road end-use categories, including construction and industry, agriculture and forestry, commercial, and lawn and garden applications. In both regions, non-road NO_x and $PM_{2.5}$ emissions are dominated by equipment used in the agriculture and construction industries. Engines in these source categories respectively account for 77% and 62% of total non-road NO_x and $PM_{2.5}$ emissions in the United States, with emissions from construction equipment exceeding those from agriculture equipment. In the European Union, agricultural engines have the largest non-road emission inventory contribution for NO_x and $PM_{2.5}$, accounting for 63% and 70% of total emissions, respectively. Construction engines account for the majority of the remaining non-road $PM_{2.5}$ and NO_x emissions in the European Union.

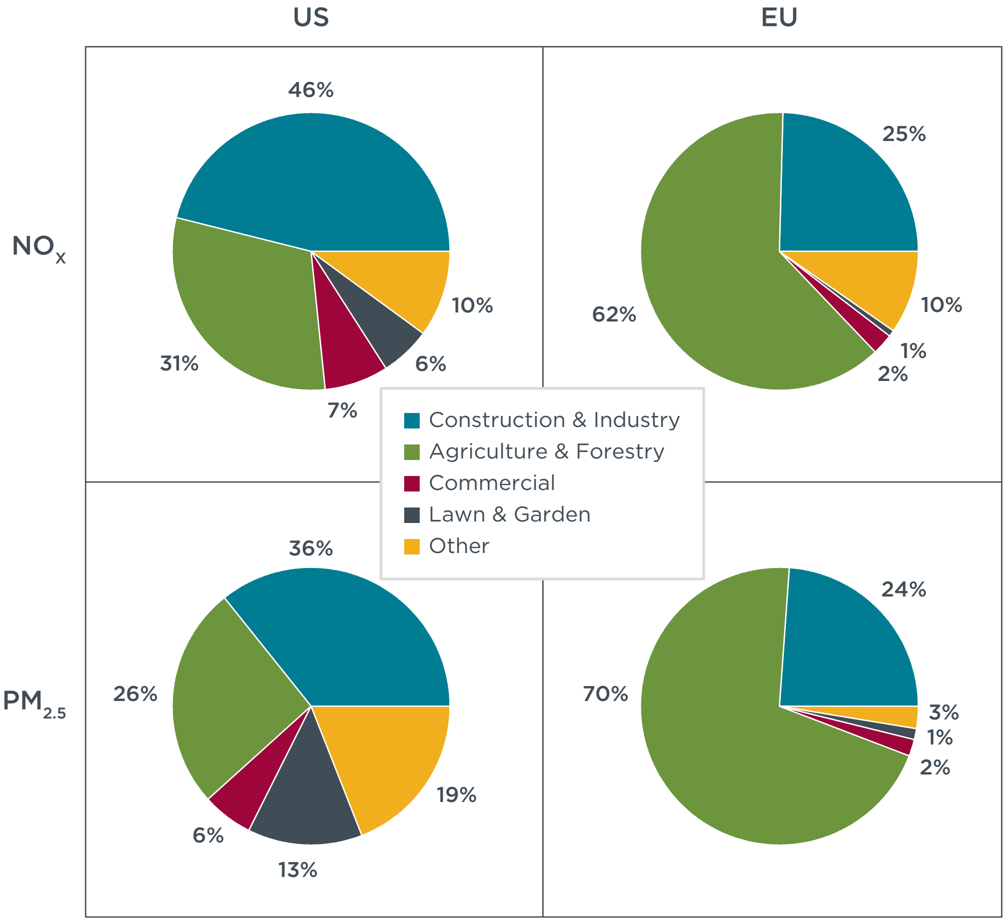


Figure 3. Relative contributions to non-road vehicle and equipment NO_x and $PM_{2.5}$ emissions in the United States and European Union by end-use sector for 2011 (EPA, 2015a; EEA, 2015)

In both the agriculture and construction industries, vehicles and equipment are primarily powered by diesel engines. For example, in the United States, diesel engines are responsible for greater than 98% of total carbon dioxide (CO_2) emissions from these sectors. Emissions of CO_2 are directly proportional to fuel consumption, and thus can be considered a proxy for engine activity. Diesel engines are more commonly used in these sectors relative to other types of internal combustion engines because of their superior low-speed torque performance, greater durability, fuel efficiency advantages, and suitability for large applications (DTF, 2003). Given the widespread use of diesel engines in agriculture and construction equipment, and the significance of these sectors to total non-road emissions of NO_x and $PM_{2.5}$, this analysis will primarily focus on the technological development of diesel engines used in these industries. This focus is not meant to diminish the importance of other non-road engine types as sources of air pollution. Non-road gasoline engines are significant sources of CO and HC emissions, and two-stroke gasoline engines in particular are of concern due to their high emission rates of $PM_{2.5}$ relative to other engine types.

Specific applications for diesel engines in the construction and agriculture industries are diverse and representative of the wide variety of specialized tasks required of non-road equipment in each sector. Figure 4 shows relative CO_2 emissions for specific agriculture and construction equipment types. Again, because CO_2 emissions are a proxy for activity, the relative contributions shown in Figure 4 are indicative of the most commonly used equipment types in each sector. Data presented here are for the United States only, as similar equipment-level inventory results are not reported in the EEA European emission inventory.

In general, the diversity of equipment types used in the agriculture sector is much lower than that for the construction sector. Non-road diesel engine activity in agricultural applications is dominated by agricultural tractors, which account for 84% of total CO_2 emissions from this sector. Other agriculture equipment types include combines, balers, and irrigation sets. In the construction industry, non-road diesel engines are used in a much broader range of equipment types, as befits the diversity of tasks required of equipment used in this sector. Major construction applications include loaders, excavators, off-highway trucks, and backhoes. In total, 26 distinct construction equipment types are included in the EPA National Emission Inventory.

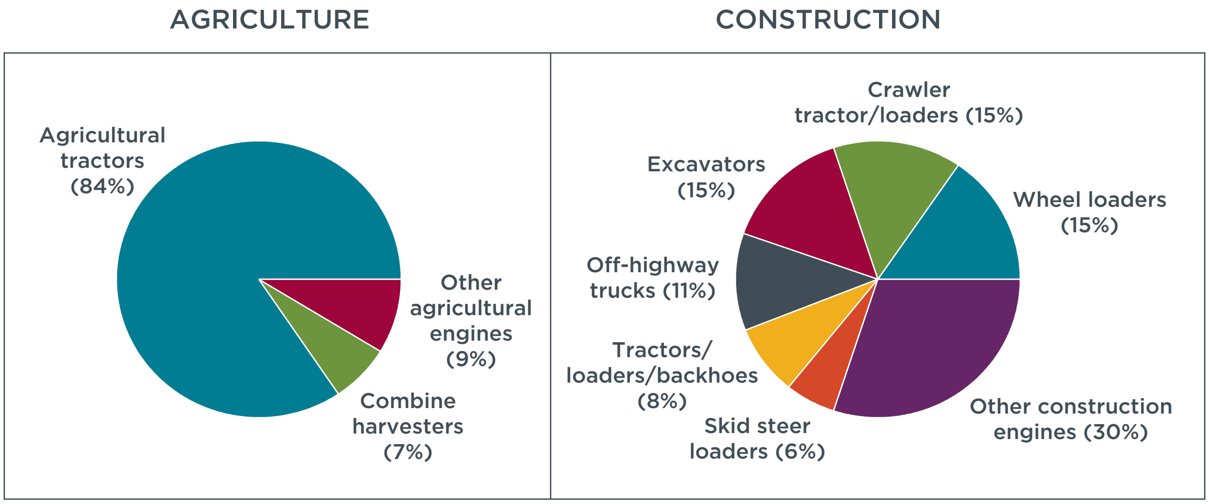


Figure 4. Relative emissions of CO_2 from non-road vehicles and equipment in the United States by equipment type for the agriculture (left panel) and construction (right panel) end use segments (EPA, 2015a).

The diversity of equipment types used in non-road applications is relevant to the development and application of engine emission control technologies, as duty cycles and operating conditions can vary considerably for different types of non-road equipment. For example, a common duty cycle for agricultural tractors is characterized by relatively constant, high-speed high-load operating modes. In contrast, backhoe duty cycles tend to be more transient with a wider variety in speed and power demands across equipment activities and more time spent at idle (EPA, 2004a). These differences in engine operating conditions create pronounced differences in exhaust gas temperature, which is a key parameter in determining the suitability of NO_x and PM aftertreatment control technologies for non-road diesel engine applications (Ohrnberger, 2012). The broad range of non-road diesel engine applications has contributed to the greater degree of diversity in emissions control strategies applied to non-road engines relative to those for on-road diesel engines.

A second factor that has increased the diversity of emission control strategies applied to non-road diesel engines is the wide variation in installed power that is characteristic of this source category. As mentioned above and shown in Figure 1, power ratings of diesel engines used in non-road applications span from less than 8 kW to upwards of 1000 kW. Given this wide range, engine power rating has been and remains a key parameter in regulatory control programs and engine technology development. Emission control strategies and technologies for non-road diesel engines are not universal and vary significantly by engine power class. As such, it is useful to understand the distribution of engine power installed in construction and agricultural equipment. Figure 5 shows relative equipment populations for seven engine power classes disaggregated by region and end-use sector. In general, diesel engines of higher power ratings are more common in agricultural equipment relative to construction equipment, though in both cases, equipment is distributed across a range of power classes. Small engines less than 19 kW are more common in Europe than the United States while larger construction equipment, with engine sizes greater than 75 kW, is more prevalent in the United States. In both regions, the most common power class for construction equipment is the 56-75 kW class. Engine sizes greater than 560 kW are for the most part not used in agricultural applications, and make up a very small percentage of the construction equipment population.

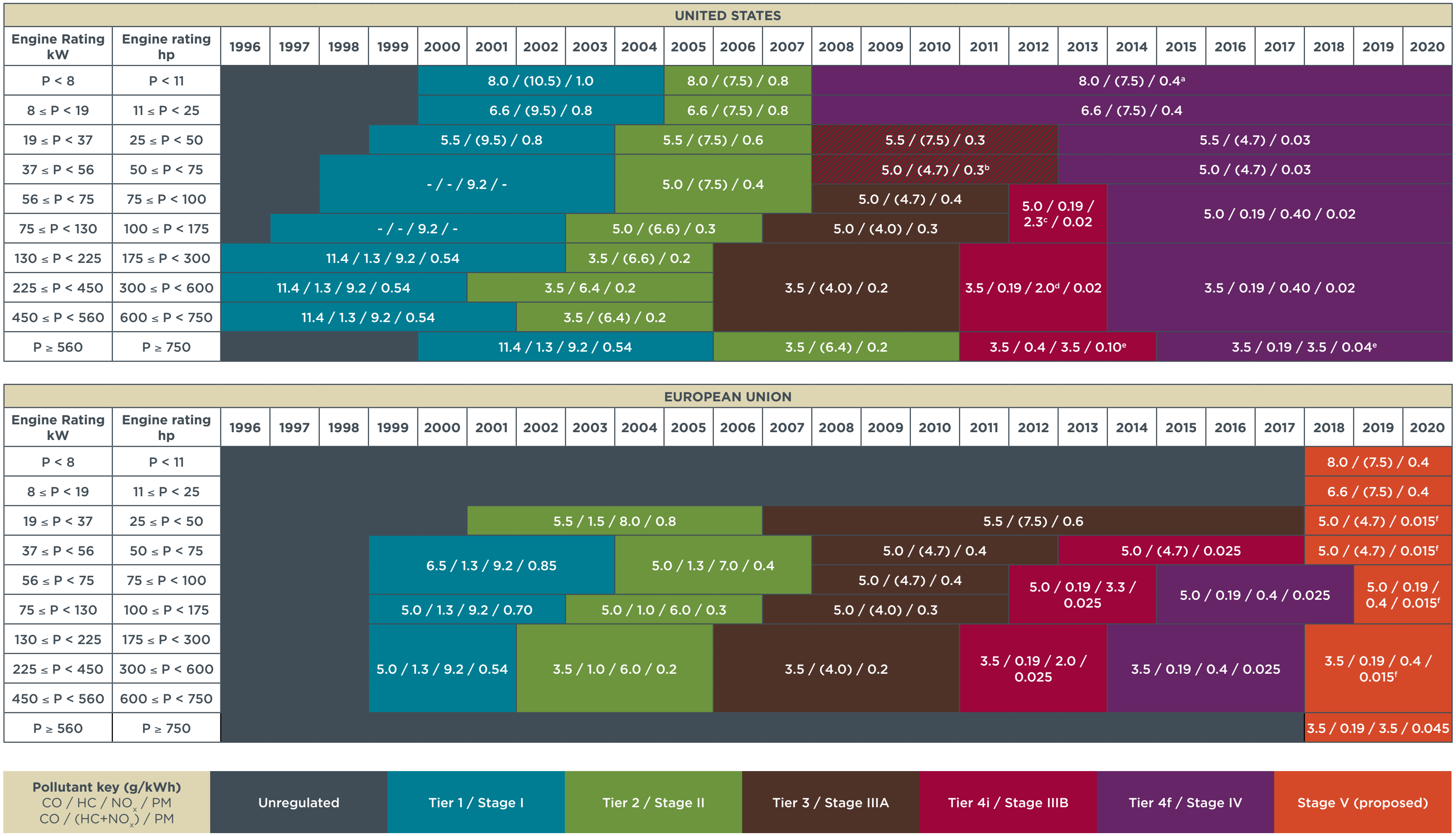
Figure 5. Power class distributions for non-road vehicles and equipment used in construction and agriculture sectors in the United States and European Union (EPA, 2010; EC, 2014a)

GLOBAL REGULATORY PROGRAMS

Analysis of non-road diesel engine technology pathways requires, as a first step, an understanding of the regulatory programs that spurred engine development through increasingly stringent regulations on allowable air pollutant emissions. The following sections detail the development of U.S. and EU programs to control emissions from non-road diesel engines.

EMISSION STANDARDS

The U.S. EPA promulgated emission standards for non-road diesel engines for the first time 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 EPA emission standards are divided into tiers, while 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_x, PM, HC, and CO. The EPA also regulates smoke emissions from non-road diesel engines, while 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 EU. Timelines and details for the implementation of non-road engine emission standards in both regions are illustrated in Figure 6 and described briefly in the following paragraphs.



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) / 0.8			8.0 / (7.5) / 0.4[a]												
8 ≤ P < 19	11 ≤ P < 25					6.6 / (9.5) / 0.8					6.6 / (7.5) / 0.8			6.6 / (7.5) / 0.4												
19 ≤ P < 37	25 ≤ P < 50				5.5 / (9.5) / 0.8					5.5 / (7.5) / 0.6				5.5 / (7.5) / 0.3					5.5 / (4.7) / 0.03							
37 ≤ P < 56	50 ≤ P < 75			- / - / 9.2 / -						5.0 / (7.5) / 0.4				5.0 / (4.7) / 0.3[b]					5.0 / (4.7) / 0.03							
56 ≤ P < 75	75 ≤ P < 100													5.0 / (4.7) / 0.4				5.0 / 0.19 / 2.3[c] / 0.02		5.0 / 0.19 / 0.40 / 0.02						
75 ≤ P < 130	100 ≤ P < 175		- / - / 9.2 / -						5.0 / (6.6) / 0.3				5.0 / (4.0) / 0.3													
130 ≤ P < 225	175 ≤ P < 300	11.4 / 1.3 / 9.2 / 0.54							3.5 / (6.6) / 0.2			3.5 / (4.0) / 0.2					3.5 / 0.19 / 2.0[d] / 0.02			3.5 / 0.19 / 0.40 / 0.02						
225 ≤ P < 450	300 ≤ P < 600	11.4 / 1.3 / 9.2 / 0.54					3.5 / 6.4 / 0.2																			
450 ≤ P < 560	600 ≤ P < 750	11.4 / 1.3 / 9.2 / 0.54						3.5 / (6.4) / 0.2																		
P ≥ 560	P ≥ 750					11.4 / 1.3 / 9.2 / 0.54						3.5 / (6.4) / 0.2					3.5 / 0.4 / 3.5 / 0.10[e]				3.5 / 0.19 / 3.5 / 0.04[e]					

EUROPEAN UNION

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						5.5 / 1.5 / 8.0 / 0.8						5.5 / (7.5) / 0.6											5.0 / (4.7) / 0.015[f]		
37 ≤ P < 56	50 ≤ P < 75				6.5 / 1.3 / 9.2 / 0.85					5.0 / 1.3 / 7.0 / 0.4				5.0 / (4.7) / 0.4					5.0 / (4.7) / 0.025					5.0 / (4.7) / 0.015[f]		
56 ≤ P < 75	75 ≤ P < 100													5.0 / (4.7) / 0.4				5.0 / 0.19 / 3.3 / 0.025			5.0 / 0.19 / 0.4 / 0.025				5.0 / 0.19 / 0.4 / 0.015[f]	
75 ≤ P < 130	100 ≤ P < 175				5.0 / 1.3 / 9.2 / 0.70				5.0 / 1.0 / 6.0 / 0.3				5.0 / (4.0) / 0.3													
130 ≤ P < 225	175 ≤ P < 300				5.0 / 1.3 / 9.2 / 0.54			3.5 / 1.0 / 6.0 / 0.2				3.5 / (4.0) / 0.2					3.5 / 0.19 / 2.0 / 0.025			3.5 / 0.19 / 0.4 / 0.025				3.5 / 0.19 / 0.4 / 0.015[f]		
225 ≤ P < 450	300 ≤ P < 600																									
450 ≤ P < 560	600 ≤ P < 750																									
P ≥ 560	P ≥ 750																							3.5 / 0.19 / 3.5 / 0.045		

Pollutant key (g/kWh) CO / HC / NO_x / PM CO / (HC+NO_x) / PM	Unregulated	Tier 1 / Stage I	Tier 2 / Stage II	Tier 3 / Stage IIIA	Tier 4i / Stage IIIB	Tier 4f / Stage IV	Stage V (proposed)

Figure 6. Emission standards for non-road diesel engines in the United States and European Union

[a] *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.*

[b] *Manufacturer can alternatively certify to Tier 2 PM limit and demonstrate compliance with Tier 4f limit in 2012.*

[c] *For NO_x compliance manufacturers may a) If banked Tier 2 credits are used for compliance, certify at an alternate NO_x standard of 2.3 g/kW or 50% of engines must demonstrate compliance with Tier 4f standard from 2012-13, or b) If no banked Tier 2 credits are used for compliance, certify to an alternate NO_x standard of 3.4 g/kWh or 25% engines must demonstrate compliance with Tier 4f standard from 2012-14.*

[d] *Manufacturer may certify to an alternate NO_x standard of 2.0 g/kW or 50% of the engines must demonstrate compliance with Tier 4f standard through 2011-13.*

[e] *Tier 4i NO_x emission limit for generator sets rated at > 900 kW is set at 0.67 g/kWh. Tier 4f NO_x and PM emission limits for generator sets rated at ≥ 560 kW are 0.67 and 0.03 g/kWh, respectively.*

[f] *A particle number emission limit of $1x10^{12}$ #/kWh is introduced in proposed Stage V standards for for engines between 19 and 560 kW.*

UNITED STATES

Tier 1

Tier 1 emission standards for non-road diesel engines with rated power at or above 37 kW were promulgated in 1994 (EPA, 1994a). The standards were phased in between 1996 and 2000 depending on engine power class. Tier 1 standards for engines below 37 kW were subsequently introduced in 1998 (EPA, 1998b). Tier 1 standards were first implemented for engines between 130 and 560 kW due to their similarity to on-road engines and the relative straightforward transference of on-road emission control technologies. For non-road engines of sizes without on-road engine analogues, emission control strategies and technologies are not as easily transferred. Standards for these engines were implemented later in order to give manufacturers sufficient time to adapt on-road emission control strategies.

Tier 1 emission standards aimed primarily to reduce NO_x and smoke emissions from non-road engines. In the rulemaking process, EPA expressed doubt as to the representativeness of steady state test cycles to characterize in-use emissions of HC, CO, and PM. Because emissions of these species tend to increase during transient operation, EPA did not expect that regulations would result in real-world emissions reductions. However, HC, CO, and PM standards were included for engines at or above 130 kW in order to provide regulatory harmonization with California and the European Union.

Tier 1 standards also included flexibility provisions for engine manufacturers through an averaging, banking, and trading (ABT) program, and for equipment manufacturers, who were allowed to use unregulated engines in equipment produced during a transition period following the implementation of the Tier 1 program.

Tier 2

Tier 2 and 3 emission standards for non-road diesel engines were promulgated in 1998 (EPA, 1998b). Tier 2 standards were implemented between 2001 and 2006 based on engine power class and generally parallel EPA 1998 on-road heavy-duty vehicle standards. Emission limits for PM were reduced by 63% for 130–560 kW engines and were included for the first time for 37–130 kW engines. The Tier 2 program introduced a combined limit for non-methane hydrocarbons (NMHC) and NO_x, which replaced independent limits for the two pollutant types. Crankcase emissions from naturally aspirated engines were regulated for the first time in Tier 2 standards. The stringency of Tier 2 standards was also increased through the inclusion of durability requirements, whereby engine manufacturers were required to demonstrate that emissions performance was maintained throughout the useful life of an engine. In addition to ABT programs for engine manufacturers, flexibility provisions for equipment manufacturers were extended in Tier 2 rulemaking through transition programs for original equipment manufacturers (OEMs). A transition period was fixed for seven years following the implementation date of the standard for a particular power class, during which OEMs were allowed to produce certain percentages of equipment for the U.S. market with engines certified to the Tier 1 emission standards.

Tier 3

Tier 3 standards were phased in between 2006 and 2008 for engines between 37 and 560 kW. The standards parallel EPA 2004 on-road heavy-duty vehicle standards. The $NMHC+NO_x$ limit was reduced by 37–39% relative to Tier 2 levels for engines between 37 and 560 kW. CO limits were not changed from Tier 2 levels. At the time of Tier 3 rulemaking, a non-road transient test cycle had yet to be developed and stringent fuel sulfur regulations for non-road diesel were not in place. For these reasons, new PM standards were not included in the Tier 3 rulemaking.

Tier 4

Tier 4 emission standards were adopted by the EPA in 2004 and implemented between 2008 and 2014 (EPA, 2004b). EPA estimated these standards would result in greater than 90% reductions in NO_x and PM emissions, and a virtual elimination of emissions of sulfur oxides from Tier 4 certified engines. Tier 4 standards treat engines and fuel as a system in the sense that diesel fuel sulfur content was reduced by 99% in conjunction with the tightening of PM emission standards. This tightening of the non-road diesel sulfur content limit promoted emission reductions through the direct control of sulfur-derived emissions (e.g. sulfur dioxide and PM) and the removal of a major barrier for the implementation of advanced emission control technologies. A new non-road transient cycle (NRTC) was introduced, along with not-to-exceed (NTE) requirements. NRTC and NTE tests were required for engine certification from 2011 for 130–560 kW engines, from 2012 for 56–130 kW engines, and from 2013 for engines smaller than 56 kW. Engines above 560 kW and constant speed, variable-load engines were exempted from testing on the NRTC.

Tier 4 interim (4i) standards were set for 19–56 kW engines in 2008 and for engines above 560 kW in 2011. For 56–130 kW and 130–560 kW power classes, manufacturers could either opt for alternate standards or a percentage phase-in of Tier 4 engines for NO_x compliance. The Tier 4 final (4f) standards for 56–560 kW engines were expected to compel the widespread use of aftertreatment technologies for PM and NO_x control. For engines below 19 kW, Tier 4f standards were implemented in 2008. The standards for these engines were less stringent than those above 19 kW due to the high cost of aftertreatment technologies relative to the cost of engines of this size and a prerequisite need for electronic fuel injection for diesel particulate filter regeneration.

Separate standards were set for generator sets above 560 kW as well as for engines above 900 kW. Owing to the long product design cycles for these engines, stringent PM standards were not implemented for these engines until 2015. Smoke standards were exempted for engines certified with PM emissions less than 0.07 g/kWh.

Relative to EPA 2010 standards for on-road heavy-duty diesel engines, notable omissions from the Tier 4 rulemaking in the United States include on-board diagnostic (OBD) requirements and mandatory in-use compliance testing provisions.

EUROPEAN UNION

Stage I

Stage I emission standards for NRMM were laid out in Directive 97/68/EC promulgated by the European Commission and phased in from 1999 to 2002 (EC, 1997). The Commission regulated agricultural tractors in a separate directive adopted in 2000 (EC, 2000). This directive mandated Stage I and II standards for agricultural and forestry tractors, to be implemented in 2001 and 2002, respectively. Stage I limits generally parallel EPA Tier 1 limits and applied to engines with power ratings between 37 and 560 kW. HC, CO, and PM limits were included for all regulated power classes, in contrast to U.S. Tier 1 standards, where limits for these pollutants were included only for 130-560 kW engines. CO limits were set at 5 g/kWh, as opposed to 11.4 g/kWh in corresponding U.S. standards. Smoke standards were never adopted in the European Union.

Stage II

Stage II standards were promulgated along with Stage I in Directive 97/68/EC. The standards were set for 18-560 kW range engines. Stage II standards were phased in from 2002 to 2003. Emission standards for PM and NO_x were reduced by 50–60% and ~30%, respectively, relative to Stage I levels. In contrast to EPA Tier 1 and 2 programs, regulated engines under Stage I and II programs did not include constant-speed engines, which are primarily used in generator sets.

Stage IIIA

Stage IIIA standards were promulgated in 2004 through Directive 2004/26/EC and phased in between 2006 and 2007 (EC, 2004). Stage IIIA standards are equivalent to U.S. Tier 3 standards for 19-560 kW engines. Constant-speed engines were included for the first time in EU NRMM regulations. Stage IIIA standards introduced a flexibility program for engine manufacturers, which allows for the market placement of a limited number of engines certified to the previous stage of emission limits during the period between two successive regulatory stages. The number of engines that manufacturers are allowed to place in the market using this provision is either a fixed number specified in the regulation or a percentage of the manufacturer's five-year average annual sales. The flexibility program is applicable for all transitions from Stage II through Stage IV.

Stage IIIB

Stage IIIB standards were promulgated through the same directive (Directive 2004/26/EC) as Stage IIIA standards. The standards were phased in between 2011 and 2013. Stage IIIB standards regulate engines between 37 and 560 kW and largely mirror U.S. Tier 4i standards, with the exception of PM emission limits for certain power classes. Stage IIIB PM standards for 37–56 kW are 92% lower than the corresponding Tier 4i limits. For the 56–560 kW power class, the PM emission limit is 0.025 g/kWh in Stage IIIB standards, compared with 0.02 g/kWh in Tier 4i standards. Because U.S. procedures for reporting engine certification PM emission rates call for rounding to two decimal places, the two PM standards are functionally equivalent. Constant speed engines were exempted from the regulations, as were engines below 37 kW. Stage IIIB enforced a limit on emissions of ammonia, which were not to exceed 25 ppm over the certification test cycle. Transient testing on the NRTC was required for all regulated engine sizes beginning with Stage IIIB.

Stage IV

Stage IV standards for non-road engines and for agricultural and forestry tractors were adopted in 2005 through Directive 2004/26/EC. Stage IV standards were implemented in 2014 and largely mirror EPA Tier 4f standards for commonly regulated power classes, with the exception of engines between 19 and 37 kW, which continue to be regulated at the Stage IIIA level. Stage IV standards tighten the ammonia emission limit to 10 ppm. Ammonia emissions are not regulated in U.S. non-road engine standards.

Stage V

Stage V standards were proposed in 2014, with adoption expected in 2016. The standards will most likely be implemented beginning in 2018. Stage V standards will introduce particle number (PN) limits for non-road engines for the first time. Emission standards for engines below 19 kW and above 560 kW will also be included for the first time. Stage V PM limits for engines between 19 to 560 kW will see a 40% reduction from Stage IV levels. Stage V standards also include manufacturer-run in-use compliance programs. Unlike on-road engine in-use compliance programs, the proposed requirements for non-road engines do not define emission limits or conformity factors and would entail only monitoring and reporting requirements for manufacturers. No OBD requirements are included in the Stage V proposal.

Global Regulatory Programs

Many countries around the world have adopted regulations for non-road engines equivalent to U.S. or EU programs. Canada, Japan, and South Korea have already implemented Tier 4f equivalent standards. China non-road standards are currently equivalent to EU Stage IIIA. China has adopted standards equivalent to EU Stage IIIB and IV, though implementation dates have yet to be announced. India has adopted U.S. Tier 3 standards. Table 3 illustrates current non-road emission standards adopted for select countries.

Table 3. Global non-road vehicle and equipment regulatory programs.

Country	Emission standard	Size regulated	Implementation	Reference standard
Brazil	PROCONVE MAR-I	19-560 kW	2015-19	US Tier 3/EU Stage IIIA
Canada	Tier 2 and 3	0-P>560 kW	2006-2007	US Tier 2 and 3
	Tier 4i	56-560 kW	2012-2014	US Tier 4i
	Tier 4	0-P>560 kW	2015	US Tier 4f
China	China Stage I	0-560 kW	2007	EU Stage I
	China Stage II	0-560 kW	2009	EU Stage II
	China Stage III	0-P>560 kW	2014	EU Stage IIIA
India	BS-I (Trem)[1]	0-560 kW	1999	—
	BS-II (Trem)	0-560 kW	2003	—
	BS-III (Trem)	0-560 kW	2005	US Tier 1
	BS-II (CEV)[2]	0-560 kW	2007	EU Stage I
	BS-III (CEV)	0-560 kW	2011	US Tier 2/3
	BS-IIIA (Trem)	0-560 kW	2011	US Tier 2/3
Japan	2006-08	19-560 kW	2006-2008	US Tier 3
	2011-13	19-560 kW	2011-13	US Tier 4i
	2015-16	19-560 kW	2015-16	US Tier 4f
South Korea	Tier 1	19-560 kW	2004	US Tier 1
	Tier 2	19-560 kW	2005	US Tier 2
	Tier 3	19-560 kW	2009	US Tier 3
	Tier 4	0-560 kW	2015	US Tier 4f

[1] *TREM: Agricultural tractors*
[2] *CEV: Construction equipment*

Additional programs to control emissions from in-use non-road vehicles and equipment have been introduced in a number of jurisdictions. In general, these programs aim to accelerate the introduction of low-emitting engines and advanced emission control technologies. Examples of these programs are included in Table 4.

Table 4. Examples of additional non-road emission regulations implemented at the national, state, and city level

Location	Regulation	Description
Switzerland	Ordinance on Air Pollution Control	Construction machinery above 18 kW is required to comply with a specified maximum level of particle emissions or be equipped with a verified particle filter system.
California, United States	In-Use Off-Road Diesel Vehicle Regulation	Requires fleets to reduce their emissions by retiring, replacing, or repowering older engines, or retrofitting engines with approved aftertreatment control devices.
New York City, United States	Local Law 77	Requires use of ultra-low sulfur diesel fuel and best available technology (BAT) for reducing emissions from non-road equipment above 37 kW used on city construction projects. Engines meeting Tier 4 emission standards are deemed to be meeting BAT requirements.
London, United Kingdom	Low Emission Zone for NRMM	Beginning in 2015, requires non-road mobile machinery between 37 and 560 kW operating in Greater London and Central London to meet Stage IIIA and IIIB emission standards, respectively. Beginning in 2020 these requirements are tightened to Stage IIIB and Stage IV.

TEST CYCLES

Beginning with the implementation of Tier 4i and Stage IIIB emission standards, on-road emissions are measured over both steady-state and transient test cycles performed on an engine dynamometer for the purpose of engine certification/type approval. The U.S. EPA has also established a not-to-exceed (NTE) requirement for non-road engines. Similarly, the European Union has established a control area for type-approval testing based on the U.S. EPA NTE zone.

The steady-state test cycle (NRSC) is equivalent to the ISO 8178 C1 (8-mode) test cycle and is used for measuring emissions from most engines. Exceptions include engines that are limited by design to operate with a constant speed (ISO 8178 D2 cycle) and variable speed engines rated below 19 kW (ISO 8178 G2 test cycle). Steady-state test cycles consist of operation at a number of distinct operating modes characterized by engine speed and load. Emissions at each operating mode are weighted to derive a cycle average emission rate. Engine speed and load settings, along with weighting factors for C1, D2, and G2 cycles are described in Table 5. These data are also shown for the NRSC (C1) cycle in Figure 7.

Table 5. Non-road steady-state cycle parameters

Mode Number	1	2	3	4	5	6	7	8	9	10	11
Torque	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated Speed[1]					Intermediate Speed[2]					Low Idle
Type C1	0.15	0.15	0.15	—	0.10	0.10	0.10	0.15	—	—	0.15
Type D2	0.05	0.25	0.30	0.30	0.10	—	—	—	—	—	—
Type G2	0.09	0.20	0.29	0.30	0.07	—	—	—	—	—	0.05

[1] Rated speed is defined as the maximum full load speed for governed engines and the speed at maximum horsepower for ungoverned engines.

[2] Intermediate speed is defined as the peak torque speed if peak torque speed occurs from 60–75% of rated speed. If peak torque speed is less than 60% of rated speed, intermediate speed is 60% of rated speed, and if the peak torque speed is greater than 75% of rated speed, intermediate speed is 75% of the rated speed.

Emissions testing on the non-road transient cycle (NRTC) is required for certification/type approval of Tier 4 and Stage IIIB/IV engines. NRTC is a composite test cycle consisting of representative duty cycles for seven common types of non-road equipment. NRTC characterizes the transient nature of non-road equipment with improved accuracy. The test cycle is run twice, once with a cold start and once with a hot start. Emissions measured during the cold start cycle are weighted at 5% in the United States and 10% in the European Union. Engine speed and load traces for the NRTC are shown in Figure 7.

In addition to NRTC test requirements, the U.S. Tier 4 program also established NTE requirements, which generally mirror those in place for on-road heavy-duty vehicles. These requirements apply to Tier 4 certified engines. They establish an NTE zone or NTE control area under the engine's torque curve. The NTE zone is defined by the torque curve (maximum torque at a given engine speed), 100% engine's rated speed, 15% engine speed, 30% power line and 30% torque line. This zone or control area is considered a subset of the engine's possible load and speed. The peak emissions within the NTE zone should not exceed the emission standard limits times a multiplier. The multiplier is 1.5 if the NO_x and PM limits are less than 2.5 g/kWh and 0.07 g/kWh, respectively, and 1.25 if NO_x and PM limits are higher than 2.5 g/kWh and 0.07 g/kWh, respectively. The NTE test procedure does not include a specific test cycle run for a specific length, but rather includes non-road equipment operation of any type (steady-state or transient) expected to occur during the equipment's normal operation, under varying ambient conditions. Emissions are averaged over a minimum time period of 30 seconds of continuous operation within the NTE zone and compared with the applicable emission standard. For highly transient operation, obtaining a valid window over which to assess NTE performance can be challenging.

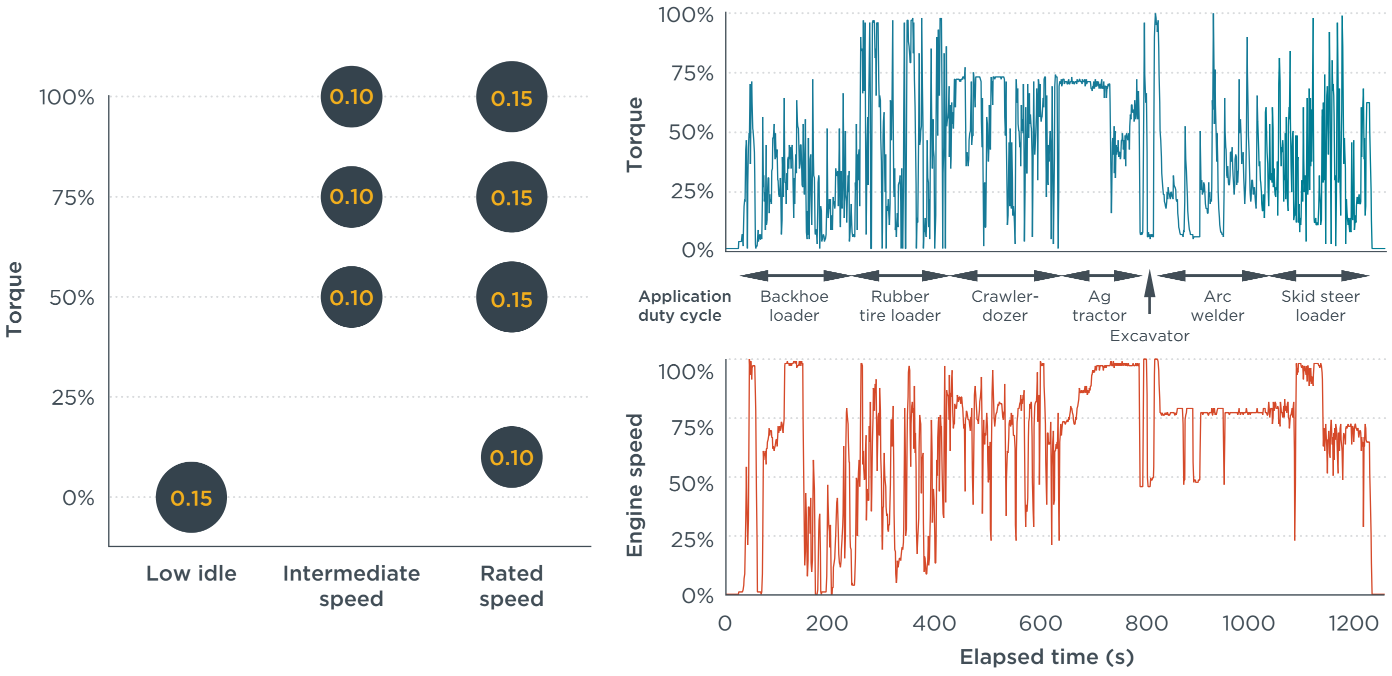


Figure 7. Operating modes for NRSC (left panel) and NRTC (right panel) engine test cycles[3]

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[3] Numbers included in the NRSC plot show weighting factors used to quantify cycle-average emission rates.

Under EU Stage IV standards, a type approval test requirement establishes a control area much like the U.S. NTE zone. The control area is defined between a speed point declared by the manufacturer,[4] a high speed, 30% power line, and 30% torque line. The high speed is the highest engine speed where 70% of rated power is delivered. Under the testing requirement, three load and speed points within the control area are randomly selected and tests are run according to NRSC test requirements. Emissions measured at these points are not to exceed the applicable Stage IV limit multiplied by a factor of two.

Fuel Quality and Durability Requirements

The sulfur content of certification test fuel is specified for different tiers/stages and is stipulated in non-road standards. Fuel sulfur requirements across different U.S. and EU non-road regulatory programs are listed in Table 6. High-sulfur fuel impedes introduction of advanced emission control technologies and also contributes to PM emissions. In order to encourage use of low and ultra-low sulfur diesel fuel in real-world applications, EPA allowed use of 300–500 ppm sulfur fuel for 2006-07 MY engines above 75 kW and 7–15 ppm sulfur fuel for 2007–11 MY engines below 56 kW for engine certification. Engine manufacturers were mandated to inform end users that the use of low or ultra-low sulfur diesel fuel is recommended for engine operation. Also, equipment manufacturers using such engines were recommended to use labels and the fuel inlet to remind the end users about this recommendation. Non-road diesel fuel of 500 ppm sulfur content was introduced in the U.S. market in June 2007, and 15 ppm sulfur fuel was introduced in June 2010. Diesel fuel of 10 ppm for NRMM was introduced in January 2011 in the European Union (EC, 2009).

Table 6. Fuel sulfur requirements for US and EU non-road engine certification testing.

US		EU	
Tier 1	300–5,000 ppm	**Stage I**	1,000–2,000 ppm
Tier 2 and 3	300–4,000 ppm[1]	**Stage II**	1,000–2,000 ppm
Tier 4	300–500 ppm (for MY 2008–10)[2]	**Stage IIIA**	≤300 ppm
	7–15 ppm (for MY 2011 onwards)[3]	**Stages IIIB & IV**	≤10 ppm

1 Diesel fuel with sulfur content ≤2,000 ppm used for Tier 1–3 engines through MY 2007
2 Diesel fuel with sulfur content between 300 and 500 used for MY 2006–2007 Tier 2 or 3 engines at or above 75 kW that do not use sulfur-sensitive technologies.
3 Diesel fuel with sulfur content between 7 and 15 ppm used for MY 2007–2010 engines that use sulfur-sensitive technology, for MY 2008–2010 engines under 56 kW.

Durability provisions in EPA's non-road regulations include specification of useful life, warranty, and recall testing periods. Useful life is the time period during which an engine manufacturer is liable for engine emissions. The recall testing period is the period during which EPA can test for in-use compliance of non-road engines. Finally, the warranty period applies to emission related components of non-road engines. EPA also requires service accumulation on engines and generation of deterioration factors.

EU stages III and IV require manufacturers to generate deterioration factors and also specify emission durability periods, equivalent to EPA's useful life. Durability requirements for non-road diesel engines in the United States and European Union are listed in Tables 7 and 8, respectively.

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[4] The speed point is calculated using the formula: speed A=low speed+15%(high speed-low speed), where low speed is the lowest speed where 50% of rated power is delivered. If the manufacturer declared value is not within +/-3% of the calculated value, the calculated value is taken as the speed point.

Table 7. U.S. durability requirements for non-road diesel engines

Engine size	Rated engine speed	Useful life		Warranty		Recall testing	
		Tier 1	Tiers 2-4	Tier 1	Tier 2-4	Tier 1	Tier 2-4
<19kW	All	8,000 hours or ten years[1]	3,000 hours or five years	3,000 hours or five years	1,500 hours or two years	6,000 hours or seven years	2,250 hours or four years
19-37kW	Constant speed ≥3,000 rpm		3,000 hours or five years		1,500 hours or two years		2,250 hours or four years
	All		5,000 hours or five years		3,000 hours or fiveyears		3,750 hours or five years
>37kW	All		8,000 hours or ten years		3,000 hours or five years		6,000 hours or seven years

Table 8. EU durability requirements for non-road diesel engines in the EU

Engine size	Rated engine speed	Emission durability period (hours)
≤37kW	Constant-speed engines	3,000
	All	5,000
>37kW	All	8,000

TECHNOLOGY PATHWAYS

APPROACH

The increasingly stringent regulatory programs for non-road diesel engines in the United States and European Union have spurred developments in engine design and aftertreatment technologies to control air pollutant emissions. The primary goal of the remaining sections of this paper is to describe this evolution in non-road engine design, identifying key technology changes made at each tier/stage of the U.S. and EU regulatory programs. Technology pathways are assessed as a function of engine power class, as different power classes faced different emission requirements at each regulatory tier/stage and engine designs can vary significantly across power classes. This assessment begins with a brief description of emission control technologies, including both in-cylinder strategies used to control engine-out emissions and aftertreatment systems which remove pollutants from the exhaust gas stream. As many of these technologies were first developed for on-road diesel engines, an overview of on-road diesel engine emissions control technology development in the United States and European Union is also presented.

EMISSION CONTROL STRATEGIES AND TECHNOLOGIES

A variety of technologies and strategies have been developed to control air pollutant emissions from diesel engines. Broadly, these emission control strategies can be subdivided into two groups: in-cylinder approaches and exhaust aftertreatment devices. In-cylinder approaches encompass engine design changes that aim to limit pollutant formation during the fuel combustion process. Emission control is achieved primarily through developments and modifications of the fuel injection and air handling systems, though in-cylinder approaches also include changes to engine geometries aimed at promoting better mixing of air and fuel. Engine-out NO_x emissions can also be reduced through the use of exhaust gas recirculation (EGR). In-cylinder emission control strategies have advanced through the widespread deployment of electronic engine controls, which enable advanced control over the combustion process.

For in-cylinder emission control approaches, there is oftentimes a trade-off between control of particulate matter and nitrogen oxides emissions. Because of fundamentally different formation mechanisms, PM control strategies oftentimes are not effective in reducing NO_x emissions, and in some cases can lead to increased emissions of NO_x. The same is generally true for the effect of NO_x emission control strategies on PM emissions.

The adoption of increasingly stringent regulatory programs has lowered emission standards to a point where in-cylinder strategies are not sufficient to control both NO_x and PM emissions. The need for additional emissions reductions beyond what is achievable through control of the combustion process alone has led to the increased use of aftertreatment technologies capable of removing pollutants from the exhaust gas stream. The key aftertreatment technologies applied in the non-road sector include diesel particulate filters (DPF) for the control of PM and selective catalytic reduction (SCR) systems for the control of NO_x. These technologies offer significant emission reduction potentials when incorporated into non-road diesel engine designs.

When these aftertreatment technologies are used in engine designs, fuel quality becomes an increasingly important design parameter. In particular, the diesel fuel sulfur content can affect both the performance and durability of aftertreatment systems. Sulfur tolerance varies among aftertreatment devices, though modern aftertreatment technologies are most effective when used with ultra-low-sulfur diesel fuels of 15 ppm or less.

Diesel engine emission control technologies have been reviewed in a number of previous publications (EPA, 2000; MECA, 2003; Posada et al., 2016), to which the reader is referred for a more in-depth treatment of the various methods used to control emissions from diesel engines. Table 9 is a brief overview of important technologies and strategies that have been used for the control of emissions from non-road diesel engines.

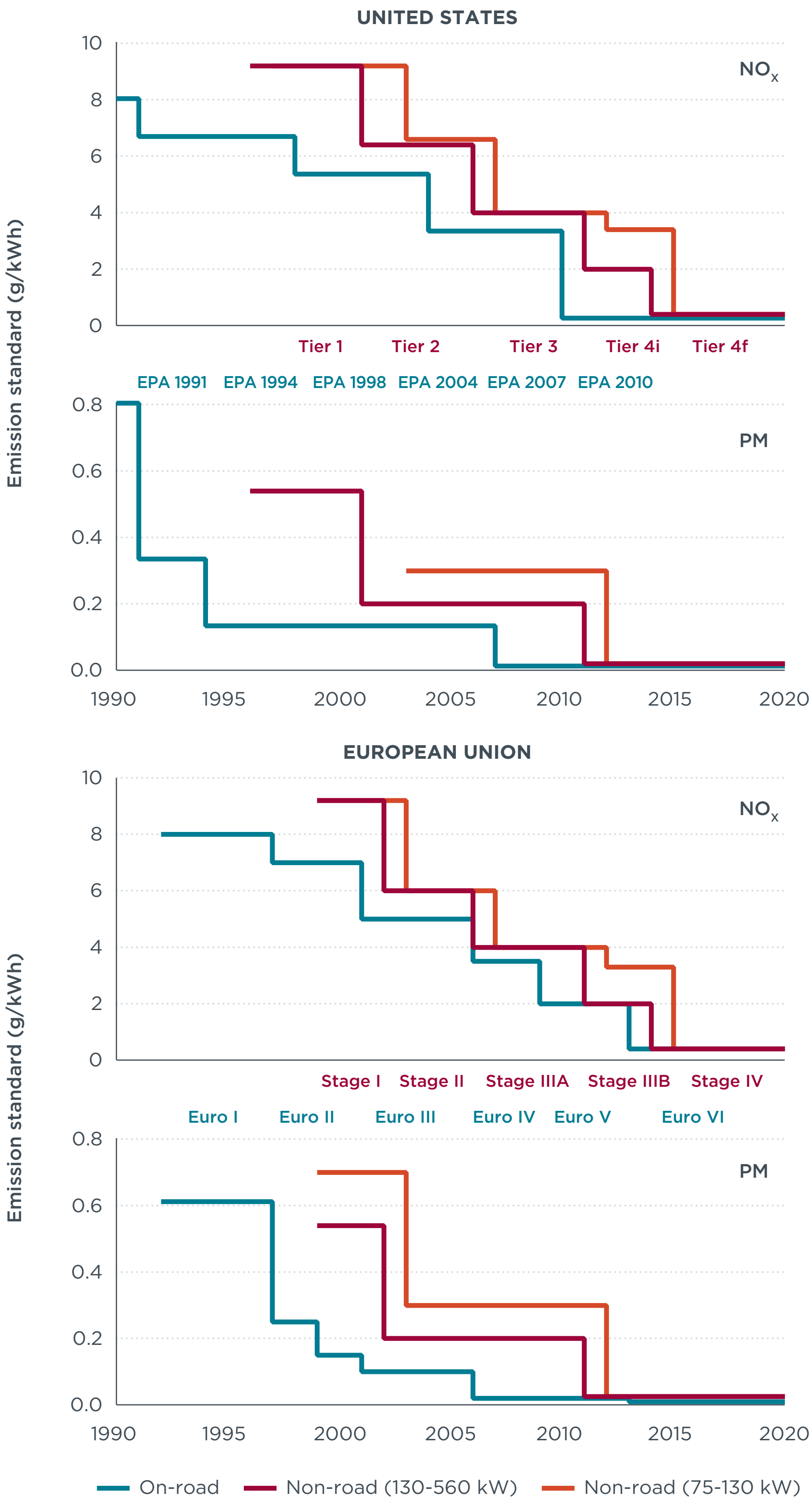
Table 9. Engine design strategies and aftertreatment technologies used for the control of air pollutant emissions from non-road diesel engines

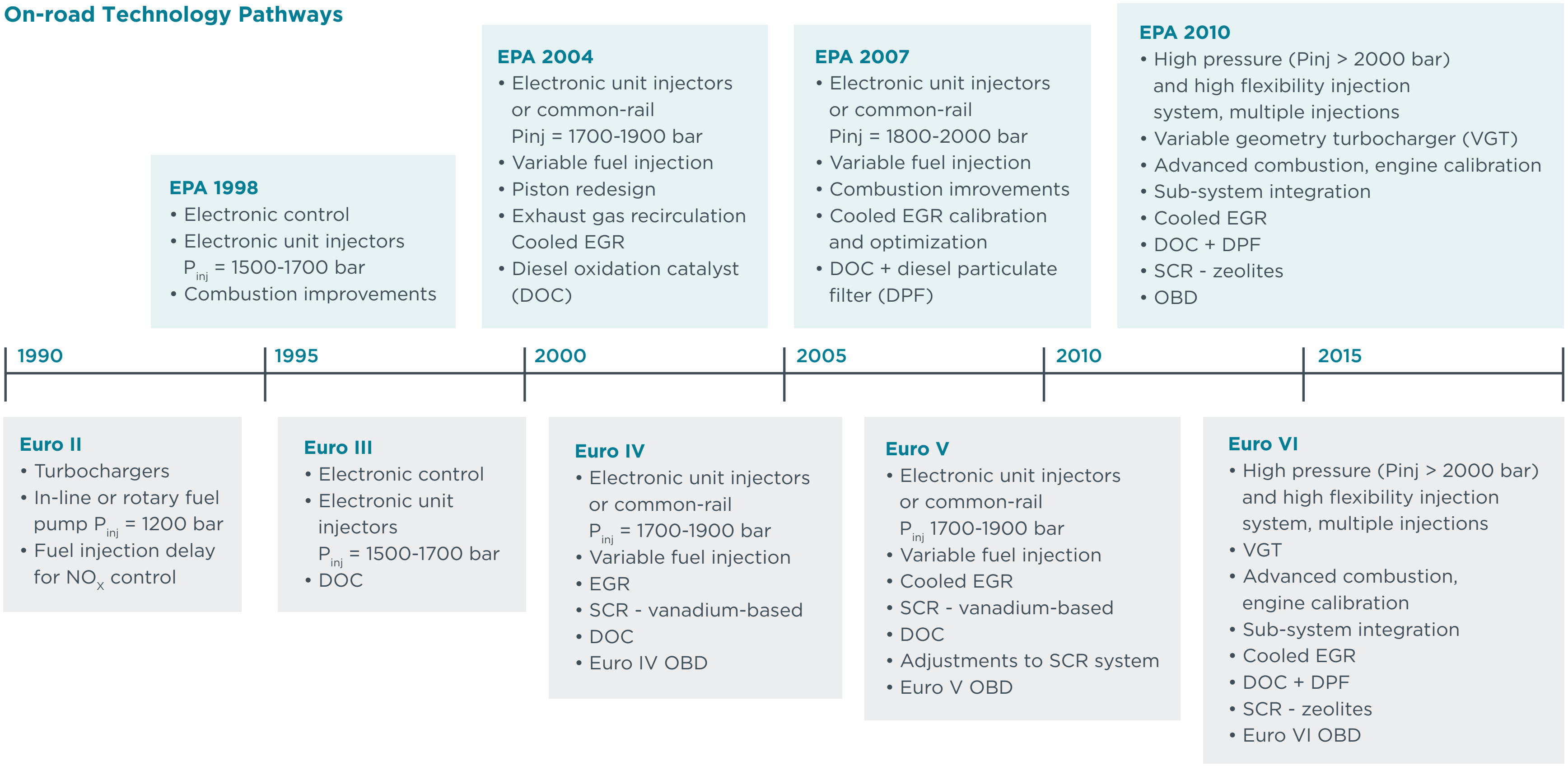
Design strategy/ technology	Pollutants targeted	Description
In-cylinder—fuel injection system		
Fuel injection pressure	PM, NO_x, HC, CO	Increased injection pressure promotes fuel atomization and better air and fuel mixing, resulting in improved combustion efficiency.
Rate of fuel injection, multiple injections	NO_x	Fine tuning of fuel injection during single combustion event by varying rate of injection or using multiple injections. Multiple injection strategies require electronically controlled high-pressure unit injectors or common rail injection systems.
Fuel injection timing	Advanced: PM, CO, HC Delayed: NO_x	Advanced or delayed fuel injection to tune combustion process. Advanced timing increases combustion pressures and temperatures resulting in improved fuel efficiency, reduced PM emissions, and increased NO_x formation. Delayed fuel injection timing reduces NO_x emissions at the expense of fuel economy and PM emission penalties.
In-cylinder—air handling technology		
Turbocharger	PM, CO, HC	Compressor used to boost intake air pressure. Wastegated, multiple-stage, and variable geometry turbochargers developed to improve turbocharger performance over a broad range of engine operating conditions.
Charge air cooling	NO_x	Heat exchanger used to lower temperature of gases entering combustion chamber to reduce peak combustion temperatures. Air-to-air systems can achieve lower temperatures and thereby better NO_x control than air-to-water systems.
Exhaust gas circulation (EGR)	NO_x	Portion of exhaust gas mixed with intake air to serve as diluent and reduce peak combustion temperatures. EGR systems used in non-road engines include internal EGR in which residual exhaust is retained within the combustion chamber, and external high pressure loop systems where exhaust gas is routed from upstream of the turbocharger exhaust turbine to the intake manifold. Cooled EGR systems incorporate a cooler to increase system NO_x reduction efficiencies.
Aftertreatment devices		
Diesel oxidation catalyst (DOC)	PM[1], HC, CO	Flow-through catalytic converter composed of a monolith honeycomb substrate coated with a platinum group metal catalyst.
Diesel particulate filter (DPF)	PM	Wall-flow filtration device. Filters are regenerated using active and/or passive regeneration methods to oxidize and remove collected particles.
Selective catalytic reduction (SCR)	NO_x	Catalytic reduction of NO and NO_2 to N_2 and H_2O using ammonia as reducing agent. Catalysts types include vanadium, iron-exchanged zeolite, and copper-exchanged zeolite. Catalysts vary in effective temperature ranges, exhaust NO_2/NO_x sensitivity, and sulfur tolerance. Ammonia is generated from the decomposition of a urea solution, which is referred to as diesel exhaust fluid in the United States and by the brand name AdBlue in Europe.
Ammonia slip catalyst (ASC)	NH_3	Oxidation catalyst used for the control of ammonia passing through the SCR system.

[1] DOC treats the soluble organic fraction of exhaust PM only.

ON-ROAD HEAVY-DUTY DIESEL ENGINE EMISSION CONTROL PATHWAYS

On-road heavy-duty (HD) diesel engines were subject to regulation prior to non-road engines in the United States and European Union. Regulatory programs developed for on-road diesel engines thus provided a model for subsequent programs implemented to control emissions from non-road diesel engines. The progression of NO_x and PM mass emission standards for on-road HD diesel engines in the two regions is shown in Figure 8, which also includes standards for the two non-road diesel engine classes most similar in size to on-road engines, 75–130 kW and 130–560 kW. In general, emission standards for non-road diesel engines have lagged behind similar on-road engine standards by about two to six years, depending on both the regulated pollutant and engine power class. This gap has been reduced with more recent non-road regulatory tiers/stages. Mass emission standards for non-road engines are generally set at a higher level than for on-road engines at similar control stages. While different test cycles and durability requirements make it difficult to compare mass emission standards for the two engine types directly, this gap reflects challenges engine manufacturers faced in applying emission control strategies developed for on-road engines to non-road engines.


UNITED STATES
Emission standard (g/kWh)
10
8
6
4
2
0
NO_x
Tier 1
Tier 2
Tier 3
Tier 4i
Tier 4f
EPA 1991
EPA 1994
EPA 1998
EPA 2004
EPA 2007
EPA 2010
0.8
0.6
0.4
0.2
0.0
PM
1990
1995
2000
2005
2010
2015
2020
EUROPEAN UNION
Emission standard (g/kWh)
10
8
6
4
2
0
NO_x
Stage I
Stage II
Stage IIIA
Stage IIIB
Stage IV
Euro I
Euro II
Euro III
Euro IV
Euro V
Euro VI
0.8
0.6
0.4
0.2
0.0
PM
1990
1995
2000
2005
2010
2015
2020
On-road
Non-road (130-560 kW)
Non-road (75-130 kW)



On-road Technology Pathways

EPA 1998
- Electronic control
- Electronic unit injectors P_{inj} = 1500-1700 bar
- Combustion improvements

EPA 2004
- Electronic unit injectors or common-rail Pinj = 1700-1900 bar
- Variable fuel injection
- Piston redesign
- Exhaust gas recirculation Cooled EGR
- Diesel oxidation catalyst (DOC)

EPA 2007
- Electronic unit injectors or common-rail Pinj = 1800-2000 bar
- Variable fuel injection
- Combustion imrovements
- Cooled EGR calibration and optimization
- DOC + diesel particulate filter (DPF)

EPA 2010
- High pressure (Pinj > 2000 bar) and high flexibility injection system, multiple injections
- Variable geometry turbocharger (VGT)
- Advanced combustion, engine calibration
- Sub-system integration
- Cooled EGR
- DOC + DPF
- SCR - zeolites
- OBD

Euro II
- Turbochargers
- In-line or rotary fuel pump P_{inj} = 1200 bar
- Fuel injection delay for NO_x control

Euro III
- Electronic control
- Electronic unit injectors P_{inj} = 1500-1700 bar
- DOC

Euro IV
- Electronic unit injectors or common-rail P_{inj} = 1700-1900 bar
- Variable fuel injection
- EGR
- SCR - vanadium-based
- DOC
- Euro IV OBD

Euro V
- Electronic unit injectors or common-rail P_{inj} 1700-1900 bar
- Variable fuel injection
- Cooled EGR
- SCR - vanadium-based
- DOC
- Adjustments to SCR system
- Euro V OBD

Euro VI
- High pressure (Pinj > 2000 bar) and high flexibility injection system, multiple injections
- VGT
- Advanced combustion, engine calibration
- Sub-system integration
- Cooled EGR
- DOC + DPF
- SCR - zeolites
- Euro VI OBD

Figure 8. Comparison of on-road HD and non-road engine regulatory pathways in the United States and European Union (top panel); EPA and EU on-road technology pathways for HD diesel vehicles[5]

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[5] Bottom panel of Figure 8 is adapted from Posada et al. (2015).

On account of this earlier regulatory attention, advanced diesel engine emission control strategies and technologies were first developed for on-road engines. Many of these technologies were later adopted in non-road engine designs. As such, on-road technology pathways provide a general framework for understanding the development of emission control technologies for non-road diesel engines, particularly for engine power classes most similar to on-road diesel engines. The bottom panel of Figure 8 shows key engine technologies utilized at each stage of U.S. and EU on-road HD vehicle emission control programs.

In general, in-cylinder control strategies were sufficient to meet emissions requirements through the EPA 1998 and Euro III stages of on-road HD engine regulatory programs. To meet these standards, similar technologies were utilized in the two regions, including turbochargers, electronic engine controls, electronic unit injectors, and variable fuel injection. Succeeding regulatory stages introduced more stringent requirements and led to the development and widespread use of aftertreatment control technologies. Today, engines designed to meet EPA 2010 and Euro VI level emission requirements incorporate similar design elements: high-pressure variable fuel injection, cooled EGR, and an aftertreatment system of DOC, DPF, SCR, and ASC in series (Posada et al., 2016).

Generally, the development of non-road diesel engines has followed a similar trajectory: initial emissions reductions from in-cylinder controls followed by the incorporation of aftertreatment control devices to meet increasingly stringent regulatory standards. However, the complexity of the non-road engine market, which is characterized by a much wider range of engine sizes and applications than the on-road sector, has led to a greater degree of variability in emission control strategies employed by engine manufacturers. Although many technologies developed for on-road engines are applicable to non-road engines, the diversity in engine sizes and applications in the non-road sector can make the use of these technologies technically challenging, particularly for engine sizes with no direct on-road analogue. In addition, non-road engine manufacturers face a number of additional design challenges unique to their equipment market, some of which are shown in Table 10.

Table 10. Barriers to the implementation of on-road emission control strategies to non-road engines

Barrier	Description
Cost	Especially for smaller-sized engines, the cost of advanced emission control technologies relative to the cost of the engine can be prohibitive. For large engine sizes, costs associated with engine development must be recovered on a relatively low sales volume.
Packaging constraints	Non-road engines must fit in a variety of equipment envelopes. Engine size and shape changes resulting from the adoption of emission control technologies can affect sales and suitability of engines for specific equipment types.
Operating environment	Non-road equipment is oftentimes used in more challenging environments than those encountered by on-road vehicles, leading to higher vibration and mechanical stress and increased exposure to dust. The velocity of non-road equipment cannot be relied upon to cool the engine, resulting in thermal management challenges.
Duty cycles	Engine operating modes tend to be different from on-road duty cycles and therefore key parameters for effective emission control design, such as exhaust temperature, may differ. Non-road equipment work cycles over which control equipment must be effective vary considerably.

NON-ROAD TECHNOLOGY PATHWAYS BY REGULATORY TIER

The following sections consider key technologies and engine modifications incorporated into non-road engine designs in response to increasingly stringent regulatory programs in the United States and European Union. On-road diesel engine technology developments provide a starting point for this 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 (EPA, 2015b). 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 2015 model year engine families. Figure 9 shows the number of engine families included in the database by engine model year and power class.

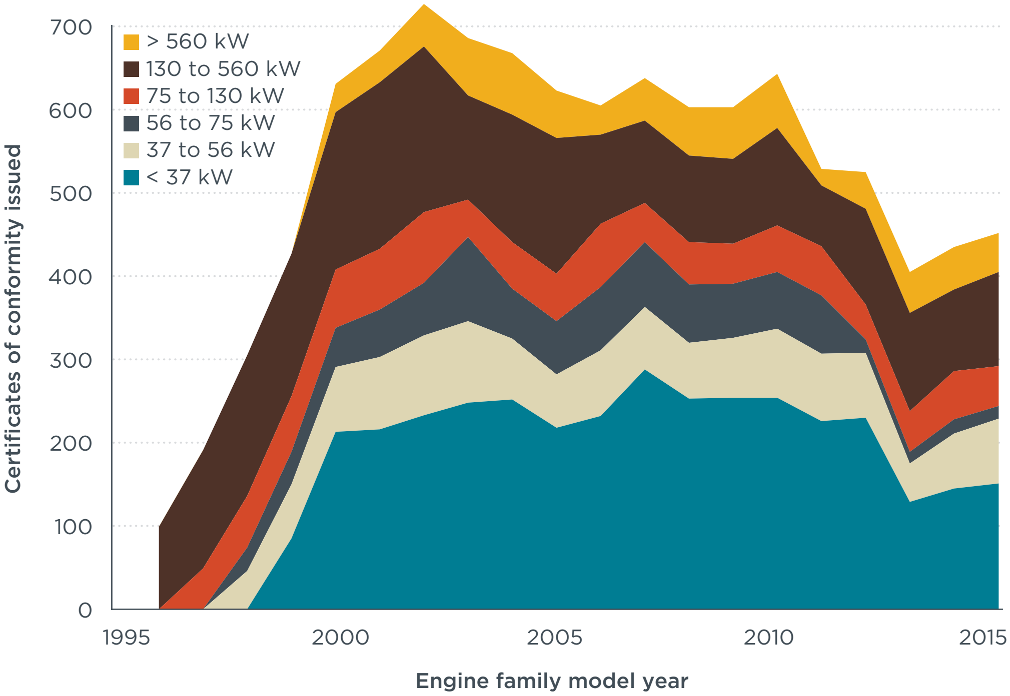

Figure 9. Historical trends in the number of certificates of conformity issued by the US EPA for non-road diesel engine families by power class[6]

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. The results of our analysis are summarized in Figure 10, and show, for each model year, the percentage of certified engine families of a given power class that have adopted a specific technology. Vertical white lines in each power class plot indicate implementation years for

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[6] Data shown in Figure 9 exclude engines designed for use in other non-road vehicle types, such as marine vessels, locomotives, and aircraft.

successive regulatory tiers.[7] 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 the following 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 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.

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[7] Due to regulatory flexibility provisions, it is possible to have engine families of multiple tier certifications in any given model year.

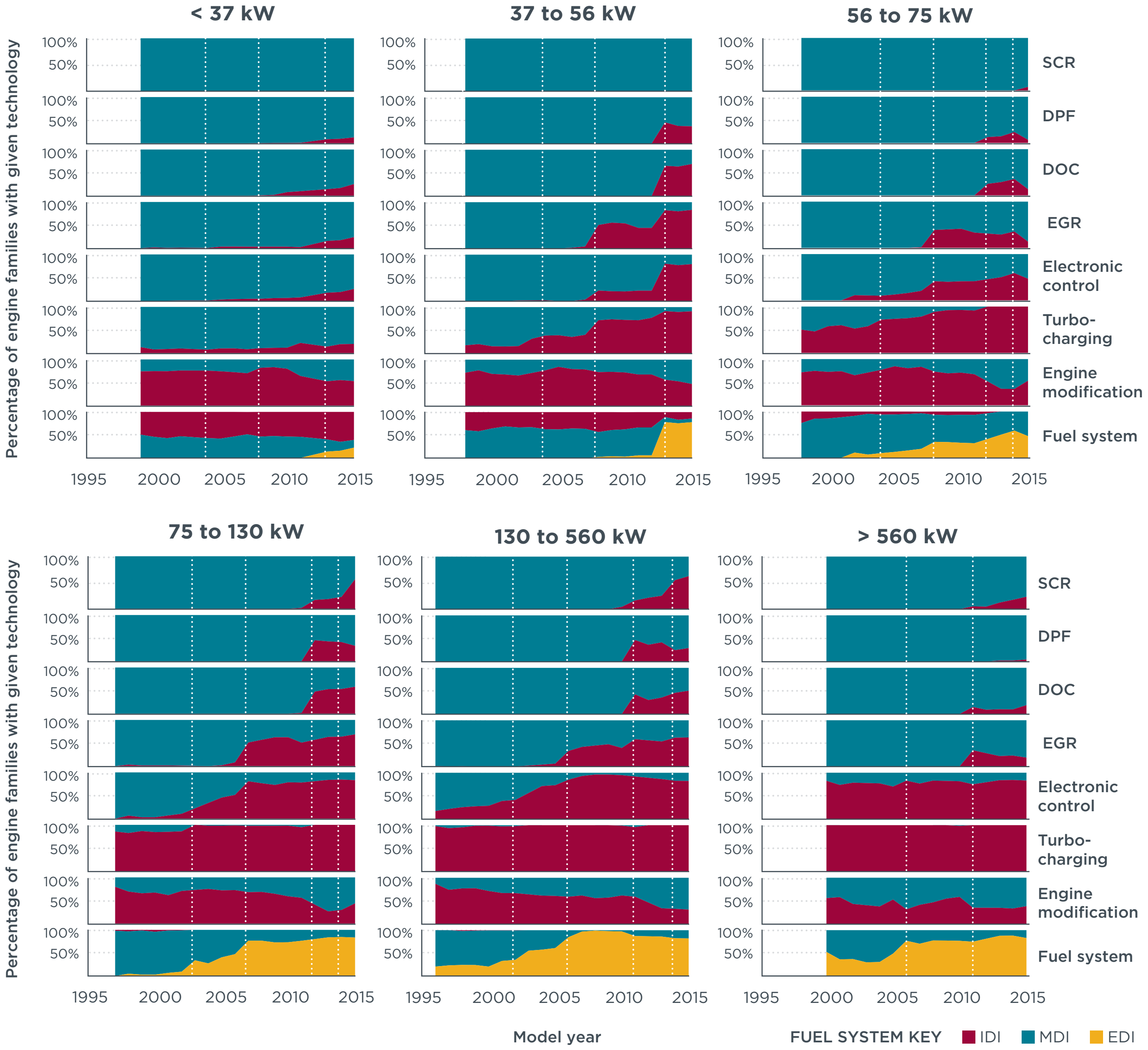

Figure 10. Progression of non-road engine emission control technology adoption in the United States[8]

Tier 1 / Stage I

Tier 1 and Stage 1 standards represent the first systematic regulatory efforts to control air pollutant emissions from non-road diesel engines in the United States and European Union. While largely harmonized, Tier 1 and Stage I programs vary somewhat in regulated engine sizes, implementation dates, and level of mass emission standards for certain pollutants. As shown in Figure 6, the Tier 1 program was phased in at an earlier date and encompasses a broader range of engine sizes than the Stage I program.

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[8] With the exception of fuel system panels, red shading indicates the percentage of engine families of a given power class utilizing the respective control technology. SCR = selective catalytic reduction; DPF = diesel particulate filter; DOC = diesel oxidation catalyst; EGR = exhaust gas circulation; IDI = indirect injection; MDI = mechanical direct injection; EDI = electronic direct injection.

In each regulation, a NO_x emission limit of 9.2 g/kWh was set for engines between 37 and 560 kW. The U.S. NO_x limit was extended to engines larger than 560 kW and combined NO_x+NMHC limits were also set for smaller engines (< 37 kW). Stage I PM emission standards were set for all regulated engine sizes in the European Union, with the most stringent level set at 0.54 g/kWh for engines between 130 to 560 kW. U.S. Tier 1 standards also adopted a 0.54 g/kWh PM limit for this power class, though this action was taken solely to provide regulatory harmonization with programs in Europe and California. Due to the lack of a transient test cycle, the U.S. EPA did not think Tier 1 PM standards would result in real-world emissions reductions and thus anticipated technology changes aimed primarily at controlling NO_x emissions (EPA, 1994b).

From an engine technology perspective, NO_x emission control was the primary focus of engine manufacturers for compliance with Tier 1/Stage I regulations. At this time, NO_x emission reductions were achievable through a number of in-cylinder control strategies and technologies, including delayed fuel injection timing and turbochargers incorporating charge air coolers. In their regulatory impact assessment for the Tier 1 rule, the U.S. EPA estimated that delayed fuel injection timing would be adopted for 98% of engines requiring NO_x emission reductions to meet the Tier 1 limit (EPA, 1994b). To offset the small PM emission and fuel economy penalties associated with delayed injection timing, the EPA also anticipated improvements in fuel injection systems, such as upgrades to fuel pumps and injector nozzles, to increase injection pressure. For engines with turbochargers, the addition or improvement of charge air coolers was seen as an alternative/additional NO_x control strategy. Smoke puff limiters or wastegates were also incorporated into Tier 1 engine designs to control smoke emissions from turbocharged engines.

Engine certification data presented in Figure 10 give an indication of technology packages employed during the Tier 1 regulatory phase for different engine power classes. Indirect injection, naturally aspirated engines were preferred for small engine applications (< 37 kW). Indirect injection engines tend to have lower NO_x and PM emissions than similarly sized direct injection engines. For the most part, engines in this size range were already compliant with Tier 1 emission standards prior to rule implementation. Engine design characteristics for Tier 1 engines between 75 and 560 kW are similar, and include mechanical direct injection fuel systems and turbocharging. Throughout the Tier 1 regulatory phase, there is an increase in the number of certified engine families using air-to-air charge air coolers in this engine size range. For all engine power classes, the primary Tier 1 emission control strategy self-reported by manufacturers in engine certification applications is “engine modification.” While this term is somewhat ambiguous, it is inclusive of in-cylinder emission control strategies such as changes to fuel injection timing. Typical Tier 1/Stage I technology packages are summarized in Figure 11.

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

Figure 11. Summary of non-road engine technology packages by emission control level and engine power category

[a] *Emissions from non-road diesel engines with power rating < 19 kW are currently unregulated in Europe. Proposed Stage V emission regulations include standards for this power class.*
[b] *No Stage IIIB or IV emission standards adopted for 19–37 kW engines in Europe.*
[c] *Emissions from non-road diesel engines with power rating > 560 kW are unregulated in Europe. Proposed Stage V emission regulations include standards for this power class.*
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*

Tier 2 / Stage II

Tier 2 and Stage II engines were phased in from 2001 to 2006 in the United States and from 2001 to 2004 in the European Union respectively. Regulated engine power classes were unchanged in the United States, while Stage 2 regulations extended the scope of the EU non-road regulatory program to include engines between 19 and 37 kW. Key aspects of the Tier 2 and Stage II programs include a tightening of NO_x and PM emission limits, the introduction of PM limits for 37–130 kW engines in the United States for the first time, and more stringent durability requirements in the U.S. Tier 2 and Stage II PM emission limits are equivalent, with the exception of the 19–37 kW power class for which the Stage II limit is 33% higher. In the U.S. Tier 2 program, NO_x emissions are regulated through a combined NO_x+NMHC standard, while NMHC and NO_x continued to be regulated independently in the EU Stage II program. Despite these differences, NO_x emission control requirements remained similar for the two regulatory programs.

Main technology responses to the implementation of Tier 2/Stage II include the continued improvement of fuel injection systems, widespread adoption of electronic engine controls in larger engine sizes, and increased use of air-to-air charge air cooling systems with turbocharged engines. Representative technology packages for Tier 2/Stage II are shown in Figure 11.

Advanced fuel injection technologies developed for on-road engines were transferred to non-road engine designs during this time period, enabling higher injection pressures and increasingly sophisticated fuel injection strategies. For engines greater than 75 kW, rotary fuel pumps and electronic unit injectors were increasingly used to provide higher injection pressures and improved control over the fuel injection process. Additionally, manufacturers incorporated common rail systems into non-road diesel engine designs for the first time (EPA, 2001; Karino et al., 2006). These developments in non-road engine fuel injection systems provided both emission reductions and performance improvements, such as improved fuel economy.

The advancement of fuel injection systems for Tier 2/Stage II was supported by the increasing use of electronic engine controls for engines greater than 75 kW. As shown in Figure 10, the percentage of engine families using electronic controls increased from 10% to 50% for 75–130 kW engines and from 40% to 73% for 130–560 kW during the years in which Tier 2 standards were in place. Electronic controls were also common in very large (> 560 kW) Tier 2 non-road engine families. Electronic engine controls provide for greater control over the combustion process and enable pollutant limiting fuel injection strategies such as rate shaping and multiple injections.

Emissions reductions in Tier 2/Stage II engines were also realized from the increased application of and improvements to turbochargers and charge air cooling systems. As shown in Figure 10, turbochargers were incorporated into a greater percentage of 37–75 kW engine families during the Tier 2 regulatory phase. For larger engines, where turbochargers were common in Tier 1 engines, air-to-air charge air coolers were increasingly preferred to the less efficient air-to-water systems. At the end of the Tier 2 phase of the U.S. non-road engine regulatory program, nearly all certified engine families in the 75–560 kW size range incorporated fixed geometry or wastegated turbochargers with air-to-air charge air coolers.

For small non-road diesel engines (< 37 kW), major engine design changes were not required to meet Tier 2 standards. In a review of certification emission test data, EPA found that most Tier 1 engine designs in this power class either already met, or were close to meeting Tier 2 emission standards (EPA, 2001).

Tier 3 / Stage IIIA

Tier 3 and Stage IIIA standards were largely harmonized in terms of both emission limits and implementation dates for engines between 37 and 560 kW. In both regions, NO_x emissions are regulated through combined NO_x+NMHC limits, which were set at 4.0 g/kWh and 4.7 g/kWh for 75–560 kW and 37–75 kW engine size ranges, respectively. These limits represent a reduction of ~40% from corresponding U.S. Tier 2 standards. PM emission limits remained unchanged from Tier 2/Stage II levels. As mentioned above, this was partially due to the lack of a standardized transient emissions test cycle at the time. Tier 3 standards were not set for engines below 19 kW and above 560 kW in the United States, and emissions from these engines sizes continued to be unregulated in the European Union.

For most engine sizes, Tier 3/Stage IIIA emission standards were the final level for which in-cylinder controls were sufficient to meet regulatory emission control requirements. The most important emission control technology incorporated into non-road diesel engine designs during this regulatory phase was EGR, which was introduced in response to the tightening of NO_x emission requirements. Other key technologies include advanced, full authority electronic engine controls, variable geometry turbochargers, and increasingly sophisticated high-pressure fuel injection systems. Figure 11 summarizes representative Tier 3/Stage IIIA technology packages by power class.

The incorporation of EGR systems into non-road engine designs is readily apparent in the EPA engine certification data shown in Figure 10. Nearly 50% of engine families between 37 and 560 kW certified in the first year of Tier 3 implementation included some type of EGR. For larger engines, external, cooled EGR systems were common, while smaller engine sizes incorporated either external, cooled, or internal EGR systems. The percentage of engine families in this size range using EGR remained relatively constant throughout the Tier 3 regulatory phase, indicating that, while important in many engine designs, EGR was not required to meet Tier 3 standards.

Non-road engine designs continued to vary both across engine power classes and, to a lesser extent, within power classes during the Tier 3/Stage IIIA regulatory phase. This variability was driven both by differences in emission requirements amongst power classes, and by developments in emission control technologies, which provided engine manufacturers with a certain degree of design flexibility in meeting emission limits for a given power class. Examples of representative Tier 3/Stage IIIA non-road engine designs of varying technological complexity are shown in Table 11.

Table 11. Tier 3/Stage IIIA technology packages[9]

Technology intensity	Engine design
Low	Mechanical fuel injection + fixed geometry turbocharger + (charge air cooling)
Medium	Common rail fuel injection + wastegated turbocharger + charge air cooling + full electronic control
High	Common rail fuel injection + variable geometry turbocharger + charge air cooling + cooled EGR + full electronic control

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9 Table 11 is adapted from Xingun et al. (2010).

Advanced technology packages are more common of larger engines (130–560 kW), which were required to meet more stringent Tier 3/Stage IIIA emission standards and for which technology transfer from on-road diesel engines was more straightforward. Variable geometry turbochargers were incorporated into non-road engine designs during this period, allowing for improved performance over a wider range of operating conditions relative to fixed geometry and wastegated turbochargers. Fuel injection systems also continued to improve, with high-pressure electronic unit injector and common rail systems increasingly used for engine sizes greater than 75 kW. Full-authority electronic engine controls were also common in this size range, which led to the continued refinement of fuel injection strategies to improve both emissions control and engine performance.

For smaller engine sizes (37–75 kW), where Tier 3/Stage IIIA PM and NO_x emission limits are less stringent, engine designs are more similar to the low or medium technology packages shown in Table 11. Many engines in this size range continued to utilize mechanical fuel injection systems, with improvements made to rotary pump or unit pump fuel systems to maximize performance and control emissions. Indirect injection engines remained common in the 37–56 kW power class. Examples of emission reduction strategies for these engines include optimization of combustion chamber shape and improvements to fuel injection systems (Tanaka et al., 2007). In the 56–75 kW power class, common rail and electronic unit pump fuel systems were used more frequently in engine designs as these technologies were transferred and adapted from initial applications in larger engines. Most engines in the 37–75 kW range were equipped with either fixed geometry or wastegated turbochargers, with some designs also incorporating charge air cooling systems.

Tier 3 standards were not set for very large (> 560 kW) engines in the United States, and therefore, engine designs remained at the Tier 2 level until the implementation of Tier 4i standards for this power class in 2011. Similarly, for very small engines (< 19 kW), Tier 2 standards were in force up until the implementation of Tier 4f standards in 2008.

Tier 4i / Stage IIIB

The increased stringency of Tier 4i/Stage IIIB regulations led to the widespread introduction of aftertreatment control technologies to the non-road engine market. PM emission standards for engines between 56 and 560 kW were set at 0.02 g/kWh in the United States and 0.025 g/kWh in the European Union, representing a reduction of approximately 90% from Tier 3/Stage IIIA levels. These more stringent PM standards were accompanied by new test requirements in which manufacturers were required to demonstrate emissions performance on the more challenging NRTC test cycle. Additionally, in the United States, NTE requirements were instituted to increase the representativeness of the engine certification test process.

In addition to reduced PM limits, NO_x emission standards were also reduced by 30-50% for engines between 56 and 560 kW. Flexibility provisions for NO_x standards were included in the U.S Tier 4 program, though most manufacturers opted to meet interim NO_x emission limits shown in Figure 6 (Ayala, 2015). Stage IIIB standards were set for 37 to 56 kW engines in the EU. Because emission limits and implementation dates are similar to U.S. Tier 4f standards for this power class, resulting technology changes will be discussed in the next section. No Stage IIIB standards were introduced for 19–37 kW engines in the European Union, and these engines continue to be regulated at the Stage IIIA level. In the United States, Tier 4i standards were set for engines larger than

560 kW, though NO_x and PM limits are a factor of 1.75 and 5 greater, respectively, than corresponding Tier 4i limits for 130–560 kW engines.

Technology decisions confronting manufacturers with the implementation of Tier 4i/Stage IIIB programs were influenced by many factors: performance requirements, engine power rating, application, duty cycle, durability and regulatory requirements, fuel economy concerns, and total operating costs (fuel costs, maintenance, DEF, etc.) (Wise and Combs, 2010; Ohrnberger et al., 2012). To a certain degree, the same advanced emission control technologies were available to engine manufacturers at this point, including EGR, DOC, DPF, and SCR. The widespread availability of ultra-low-sulfur fuels enabled the use of these technologies in engine designs; however, emission limits were not set at a level that forced one particular technology pathway. Because U.S. and EU regulatory programs are technology-neutral, manufacturers were able to adopt these technologies in a variety of ways in order to balance emission control requirements with engine performance and cost. The general approach of non-road engine manufacturers in response to Tier 4i/Stage IIIB regulatory programs is reflected in the design philosophy of one major manufacturer, Duetz AG: “As much technology as necessary and not as much as possible” (Deutz, 2015).

Generally, two engine design pathways emerged for 56–560 kW engines at this point: tune engines for low engine-out PM emissions and control relatively high NO_x emissions with SCR, or use PM aftertreatment devices such as DPF and/or DOC along with cooled EGR for NO_x control. The main advantage of the first pathway is that optimizing engine designs for low engine-out PM emissions also optimizes for efficiency and reduces fuel consumption. On the other hand, if SCR is used to treat resultant higher engine-out NO_x emissions, engine owners incur additional expenses for urea solution and engine designs have to accommodate space for a urea storage tank. In both cases, engine applications need to be considered, as duty cycles affect important operational parameters for aftertreatment technologies, such as exhaust gas temperature.

Examples of these two design approaches can be found in Tier 4i/Stage IIIB engines developed by Liebherr, a manufacturer of non-road engines and equipment. For earthmoving moving equipment, such as excavators, Liebherr developed engines incorporating cooled EGR, DOC, and DPF technologies. An additional diesel injection unit was also included for active filter regeneration to account for the fluctuating load profiles of these equipment types (Doppelbauer et al., 2012). In contrast, SCR only engines were developed for use in mobile and crawler cranes, which are characterized by intermittent, low-load duty cycles (Liebherr, 2016).

Engine certification data shown in Figure 10 provide further details on the general engine design pathways pursued by manufacturers in response to Tier 4i/Stage IIIB regulatory programs. For 130–560 kW engines, the two primary emission control packages were (1) cooled EGR+DOC+DPF and (2) SCR. Of these two pathways, SCR-only designs were less common. Approximately 20–25% of certified engine families in this power class included SCR systems. Reasons as to why the cooled EGR+DOC+DPF pathway was preferred at this point include relatively underdeveloped SCR technology and urea distribution infrastructure for the non-road market, as well as decisions made by engine manufacturers for Tier 3 engine designs, primarily regarding the incorporation of EGR (Xingun et al., 2010; Lombardo di Bello, 2015). A detailed listing of Tier 4i/Stage IIIB engine designs for major engine manufacturers can be found in the Appendix. Additional technologies included in Tier 4i/Stage IIIB engine designs in this power class include high-pressure common rail fuel injection systems, multi-stage turbochargers, full authority electronic controls, and advanced engine calibrations.

Non-road engines between 56 and 130 kW faced less stringent Tier 4i/Stage IIIB NO_x emission standards than the 130–560 kW power class, leading to more flexibility in engine designs. For larger engines in this engine range, emission control technology choices generally mirror those for 130–560 kW engines. Aftertreatment technology packages primarily consist of cEGR+DOC+DPF or SCR only. SCR was used in ~20% of Tier 4i certified engine families between 75 and 130 kW, but is not listed as being used for any engine families between 56 and 75 kW in the EPA's engine certification database. Owing largely to the relaxed NO_x standards for this power class, several manufacturers were able to design Tier 4i/Stage IIIB-compliant engines without DPF or SCR systems. For example, all Cummins Tier 4i/Stage IIIB engine models met regulatory limits with high-pressure common rail fuel systems, cooled EGR, and DOC (Cummins, 2013). Similarly, JCB designed Tier 4i/Stage IIIB engines in this size range that excluded aftertreatment devices altogether and achieved emissions performance through in-cylinder controls and cooled EGR (JCB, 2016).

Tier 4i emission standards for engines greater than 560 kW were mostly met without the need for aftertreatment control technologies. For engines of this size, PM regulations were largely met through in-cylinder controls, which are generally more effective for engines in this size range relative to smaller engines. A small number (~10%) of engine families did include DOCs in engine designs, however. Cooled EGR and SCR systems were adopted for some engines in this size range in response to tightened NO_x emission standards.

Tier 4f / Stage IV

Tier 4f/Stage IV emission standards were implemented between 2008 and 2015 in the United States and from 2014 to 2015 in the European Union. U.S. Tier 4f standards were adopted for all engine sizes. In contrast, EU Stage IV standards were set only for engines between 56 and 560 kW. Engines smaller than 19 kW and larger than 560 kW continue to be unregulated, and emission standards for engines between 19 and 37 kW remain at Stage IIIA levels. With the exception of these power classes, regulatory programs in both regions are largely harmonized. Figure 12 shows current NO_x and PM emission standards for non-road diesel engines in the United States and European Union.

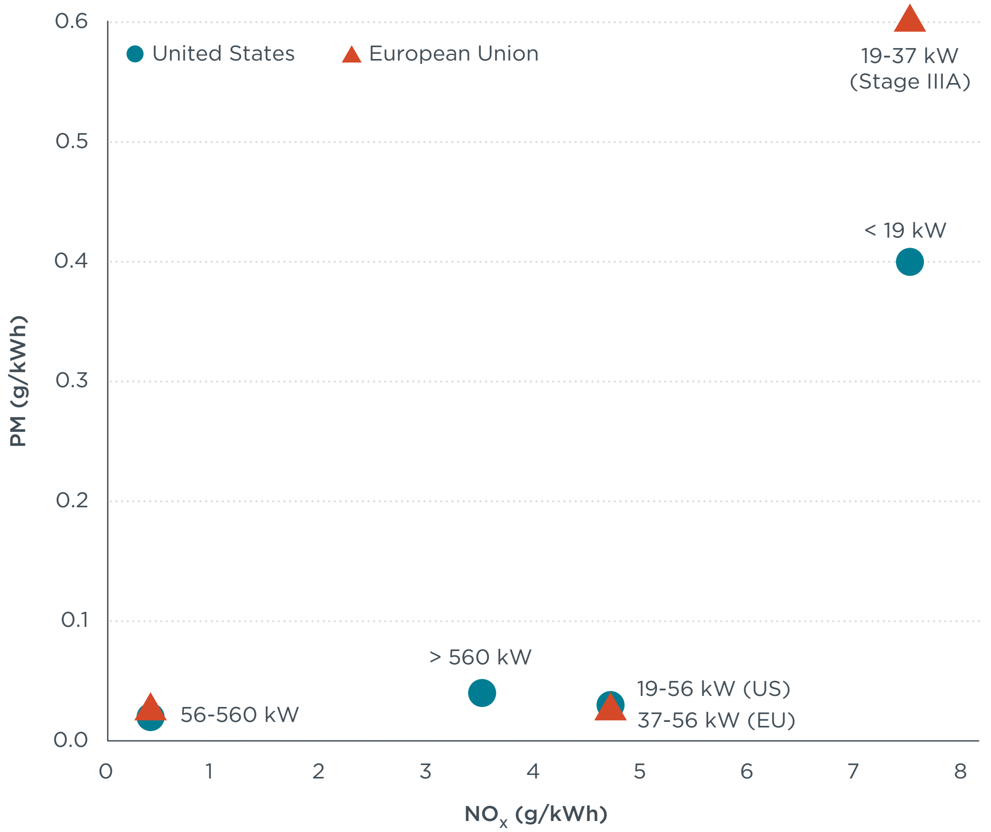

Figure 12. Current PM and NOx emission standards for non-road diesel engines in the United States and European Union[10]

A key component of the Tier 4f and Stage IV regulatory programs is the 0.4 g/kWh NO_x emission limit set for engines between 56 and 560 kW, which represents a reduction of 80–90% from Tier 4i/Stage IIIB standards. While no new PM standards were set for this power class, PM limits for engines between 19 and 56 kW, as well as greater than 560 kW in the United States and between 37 and 56 kW in the European Union, were tightened significantly.

As was the case with previous regulatory tiers/stages, non-road engine manufacturers have adopted a variety of technology packages to comply with Tier 4f/Stage IV emission standards. Advances in SCR systems have led to the widespread adoption of this technology for engines between 56 and 560 kW, which face the most stringent NO_x control requirements. Cooled EGR is used along with SCR in some engine designs in order to lower NO_x conversion efficiencies required of the SCR system (from ~95% to less than 90%) and reduce urea consumption. In-cylinder controls and DOC are generally sufficient to meet PM emission requirements for engines in this size range, though DPFs are also included in some engine designs, particularly larger engines or engines designed for applications where passive filter regeneration is possible, such as agricultural tractors. In general, non-road engine manufacturers have shifted away from emission control systems incorporating DPFs to SCR systems in response to Tier 4f/Stage IV regulations. As shown in Figure 10, the percentage of 56–560 kW certified engine families using DPFs fell following the implementation of Tier 4f standards.

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[10] For engines less than 56 kW, NO_x emission limit shown represents combined NO_x+NMHC standard.

From an emissions perspective, it is important to note that current non-road standards for 56–560 kW engines are not stringent enough to compel the use of both DPF and SCR systems, the best available technologies for PM and NO_x control for diesel engines. This is in contrast to on-road HD diesel engine designs for similarly sized engines, which have converged on a common emission control package consisting of cooled EGR, DOC, DPF, and SCR in response to the more stringent EPA 2010 and Euro VI regulatory programs (see Figure 8).

Consequences of omitting DPFs from non-road engine designs include higher PM emission rates relative to DPF-equipped engines and a greater risk for very high PM emission rates resulting from engine malfunctions as engines age. Figure 13 shows average PM emission rates for model year 2016 Tier 4f certified engines disaggregated by engine power class and emission control system design. While all engines are in compliance with current PM emission limits, engines between 56 and 560 kW without DPFs emit approximately four to five times as much PM as comparably sized DPF-equipped engines. Additionally, systems without DPFs lack a physical mechanism to prevent excess PM emissions resulting from engine component malfunctions. Thus, there is a greater chance that these engines will not sustain emissions performance over their in-use lifetimes (Ayala, 2015).

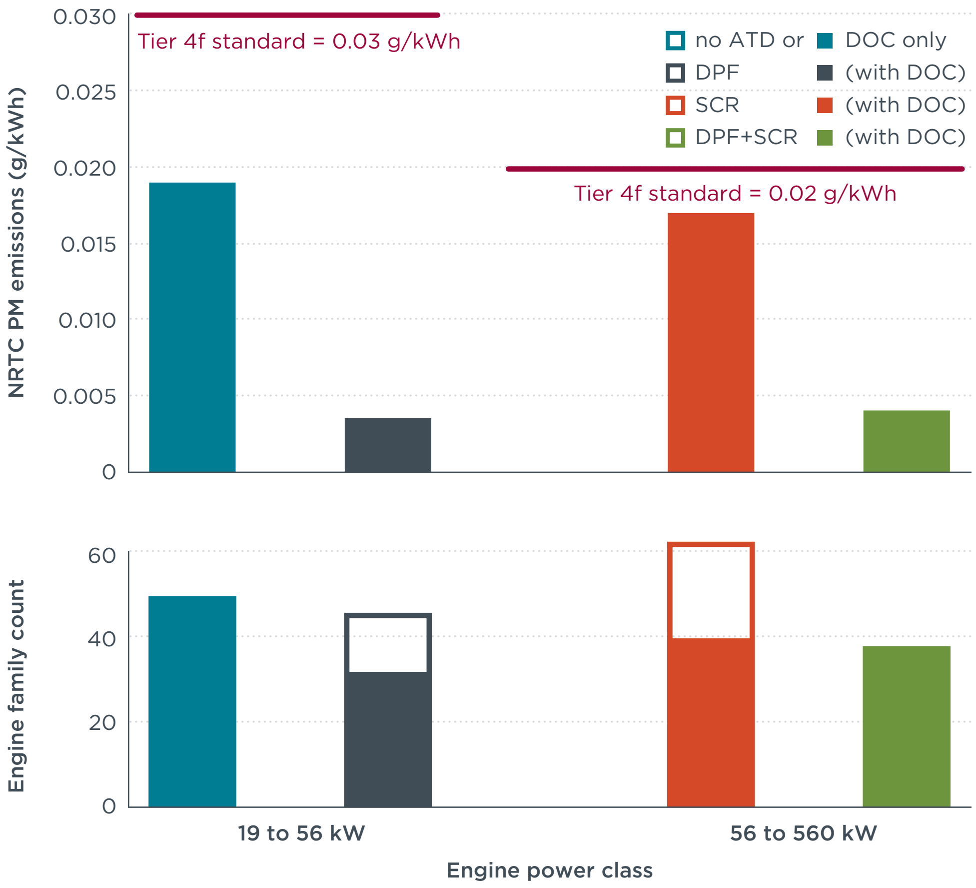

Figure 13. Tier 4f engine certification counts (bottom panel) and average transient test cycle PM emission rates (top panel) by emissions control technology package for model year 2016 engine families[11]

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[11] The total number of Tier 4f certified engine families is 96 for the 19–56 kW power class and 101 for the 56–560 kW power class.

Engines between 19 and 56 kW face emission standards of similar stringency in the U.S. Tier 4f regulatory program, though limits are relaxed relative to those for larger engines (56–560 kW). Main emission control technologies applied to meet Tier 4f standards for this size range include cooled EGR for NO_x control and oxidation catalysts and/or particulate filters for PM control. SCR technology has yet to be deployed for non-road engines of this size and is not required to meet the Tier 4f NO_x+NMHC standard of 4.7 g/kWh. In regards to PM control, about half of Tier 4f certified engine families are reported as including particulate filters in engine designs, with the remaining utilizing oxidation catalysts only (see Figure 13). As was the case with larger engines, Tier 4f engines without DPFs have significantly higher PM emission rates over the NRTC than DPF-equipped engines (factor of ~5 to 6). A detailed list of Tier 4f emission control technology packages by engine manufacturer can be found in the Appendix.

Engines between 37 and 56 kW are regulated at similar levels in the EU Stage IV program, and technology packages follow those for similarly sized Tier 4f compliant engines. In contrast, emission standards for engines between 19 and 37 kW remain at Stage IIIA levels in the European Union, and can be met without the need for advanced aftertreatment technologies.

Naturally aspirated, indirect injection engines remain common in the < 19 kW power class with the implementation of Tier 4f standards. Aftertreatment technologies are not required to meet emission standards, and the expense of such technologies is generally prohibitive given the relatively low cost of these engines.

For large non-road engines with power ratings greater than 560 kW, Tier 4f engine designs generally include both cooled EGR and an oxidation catalyst or SCR. Engines designed for use in generator sets are subject to more a stringent Tier 4f PM and NO_x standards than other engines in this power class and are more likely to incorporate SCR systems into emission control designs. General engine design elements common to most Tier 4f in this power class include electronically controlled, high-pressure direct fuel in injection systems and turbocharging with charge air cooling.

Stage V

Stage V emission standards were proposed by the European Commission on September 25, 2014, and are expected to be adopted by the end of 2016 (EC, 2014b). As proposed, Stage V standards will be phased in beginning in 2018, with all new engines required to meet Stage V emission requirements as of January 1, 2020 (ICCT, 2016). Highlights of the Stage V program include:

- Tightening of PM emission limits to 0.015 g/kWh and introduction of a particle number limit of $1x10^{12}$ #/kWh for engines between 19 and 560 kW.
- Introduction of Tier 4f equivalent emission standards for previously unregulated engine sizes (< 19 kW and > 560 kW).
- Inclusion of manufacturer run in-use testing and monitoring program.

The key technology response to the Stage V program will likely be near universal application of particulate filters to meet tightened PM and new PN standards for engines between 19 and 560 kW. For engines between 56 and 560 kW, emission control systems are expected to converge on a common design incorporating an oxidation catalyst, particulate filter, and SCR. In this case, the regulatory burden of the Stage V program will be greater for manufacturers who did not include DPFs in Stage IV engine designs.

For engines between 19 and 56 kW, DPFs will similarly be necessary to meet PM and PN limits, though proposed NO_x emission standards remain relaxed relative to engines between 56 and 560 kW, and will not require SCR systems.

Because Stage V emission standards for engines greater than 560 kW and less than 19 kW are set equal to U.S. Tier 4f values, technology packages for these engine sizes are expected to follow those developed in response to the Tier 4f program and discussed in the previous section.

CONCLUSIONS

The technical complexity of non-road diesel engines has advanced significantly over the past 20 years in response to increasingly stringent regulatory programs in the United States and European Union. Engines sold today are required to meet PM and NO_x emission limits that are approximately 95% lower than Tier 1/Stage I limits introduced in the mid-1990s. The developments that have enabled these emission reductions have largely been predicated on the transfer and integration of engine and emission control technologies developed for on-road engines into non-road engine designs.

Following the implementation of regulatory control programs in both regions, initial improvements in the emissions performance of non-road diesel engines were largely realized through in-cylinder approaches that aimed to limit the amount of pollution formed during the combustion process. Important engine technologies adopted during initial regulatory tiers/stages include more sophisticated, higher-pressure fuel injection systems incorporating electronic controls for advanced injection strategies, turbochargers with charge air cooling systems, and exhaust gas recirculation. Using these and related technologies, non-road engine manufacturers were able to meet regulatory limits through the Tier 3/Stage IIIB phases of non-road engine emissions control programs without the need for aftertreatment control technologies.

Beginning in 2011 with the implementation of Tier 4i/Stage IIIB standards, in-cylinder controls were no longer sufficient to meet emissions requirements for many non-road engine power classes, and aftertreatment devices became common in non-road engine designs. While emission control technology pathways for on-road HD diesel engines have largely converged on a common design incorporating cooled EGR, DOC, DPF, and SCR, emissions control packages vary considerable for non-road diesel engines. For larger engines, manufacturers have generally adopted emission control packages based on SCR for NO_x control and oxidation catalysts for PM control. Particulate filters are used in some engine designs, though generally not required to meet Tier 4f/Stage IV emission requirements. For smaller engines, cooled EGR and oxidation catalysts are generally sufficient to meet current emission limits.

While significant advances have been made to control emissions from non-road diesel engines, this source category remains a significant source of air pollutant emissions. As of 2011, non-road vehicles and equipment were responsible for ~20-45% and ~15-20% of mobile source $PM_{2.5}$ and NO_x emissions, respectively, in the United States and European Union. The introduction of more stringent Tier 4f/Stage IV emission control requirements in each region during succeeding years should help to reduce emission rates from new non-road diesel engines. However, current non-road regulatory programs lag behind comparable programs for on-road diesel engines, and are not stringent enough to compel the use of the best available technologies for the control of PM and NO_x emissions from diesel engines: DPF and SCR systems. This is especially true of particulate filters, whose use seems to actually have decreased with the transition from Tier 4i/Stage IIIB to Tier 4f/Stage IV regulatory programs. In the European Union, the implementation of proposed Stage V standards should lead to the universal application of DPFs for engines between 19 and 560 kW.

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APPENDIX

Tier 4i/Stage IIIB and Tier 4f/Stage IV emission control technology packages for major non-road engine manufacturers

Manufacturer	Tier 4i/Stage IIIB	Tier 4f/Stage IV	[a]Source
Agco	37-75 kW: cEGR+DOC > 75 kW: DOC+SCR	37-56 kW: cEGR+DOC 56-75 kW: DOC+SCR >75 kW: cEGR+DOC+SCR	1
Caterpillar	45-560 kW: cEGR+DOC+DPF >560 kW: cEGR+DOC	37-56 kW: DOC+DPF 56-75 kW: cEGR+DOC+SCR 90-560 kW: cEGR+DOC+DPF+SCR >560 kW: cEGR+DOC	2
Cummins	56 – 130 kW: cEGR+DOC 130-560 kW: cEGR+DOC+DPF >560kW: cEGR+DOC	19-56 kW: cEGR+DOC 56-130 kW: cEGR+SCR/cEGR+DOC+SCR 130-560 kW: cEGR+DOC+SCR/ cEGR+DOC+DPF+SCR/DOC+DPF+SCR	1
Deutz	19-56 kW: cEGR 56-520 kW: cEGR+DOC+DPF 56-520 kW: Ag engines = SCR only	19-56 kW: cEGR+DOC 56-520 kW: cEGR+DOC+DPF+SCR	2
FPT Industrial	75-560 kW: SCR	75-560 kW: DOC+SCR	1, 2
JCB	56-130 kW: cEGR	37-56 kW: cEGR 56-560 kW: SCR +cEGR	1
John Deere	<56 kW: No aftertreatment technology 56-130 kW: cEGR+DOC+DPF 130-560 kW: cEGR+DOC+DPF	19-56 kW: DOC+DPF 56-130 kW: cEGR+DOC+SCR 130-560 kW: cEGR+DOC+DPF+SCR	2
Kohler	No aftertreatment technology	19-56 kW: cEGR +DOC	1
Komatsu	56-130 kW: cEGR +DOC 130-560 kW: cEGR +DOC+DPF	37-56 kW: cEGR+DOC 56-130 kW :cEGR+DOC+SCR 130-560 kW:cEGR+DOC+DPF+SCR	1
Kubota	37-56 kW: cEGR 56-130 kW: cEGR+DOC+DPF	19-56 kW: cEGR +DOC/ cEGR+DOC+DPF 56-130 kW: cEGR+ DOC+DPF+SCR	1
Liebherr	75-560 kW:cEGR+DPF+DOC for earthmoving and material-handling machinery, SCR for mobile and crawler cranes	>130 kW: SCR	2
Mitsubishi	56-560 kW: cEGR+DOC+DPF	19-37 kW: cEGR+DOC/DOC+DPF 56-75 kW: cEGR+DOC+DPF	1
MTU	< 560kW: SCR > 560kW: cEGR	100-460 kW: cEGR+SCR 560-730 kW: cEGR+DOC	2
New Holland	> 80 kW: SCR ; < 80kW: EGR+DOC+DPF	75-560 kW: SCR +DOC 56-75 kW: cEGR +SCR 19-56 kW: iEGR+DOC+DPF	2
Perkins Engine Co.	56-560 kW: cEGR+DOC+DPF	< 56kW: DOC+DPF >56 kW: cEGR+DOC+DPF+SCR/cEGR+DOC+SCR	1,2
Scania	SCR	<560 kW: cEGR+DOC+SCR/cEGR+SCR >560 kW: SCR	1
Volvo Penta	130-560 kW: SCR	75-560 kW: cEGR + SCR	2
Yanmar	37-56 kW: cEGR 75-130kW: cEGR+DOC+DPF/cEGR+DPF	8-19kw: cEGR 19-56kW: cEGR+DOC+DPF/cEGR+DPF	1

[a] *Data sources include (1) engine information contained in EPA and California Air Resources Board engine certification documentation*[12],[13] *and (2) Publicly available resources accessed from manufacturers' websites.*

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