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ESTIMATED COST OF DIESEL EMISSIONS-CONTROL TECHNOLOGY TO MEET FUTURE CALIFORNIA LOW NO_x STANDARDS IN 2024 AND 2027

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EXECUTIVE SUMMARY

Emissions of nitrogen oxides (NO_x) from heavy-duty diesel engines are a significant contributor to ambient air quality issues and ozone pollution in many regions of the United States. Although the U.S. Environmental Protection Agency's (EPA) 2010 emissions standard for heavy-duty engines went a long way toward reducing diesel emissions, there is still a significant gap between real-world and certified NO_x emissions from these engines. In California, achieving real-world NO_x emissions control from a growing fleet of heavy-duty vehicles (HDVs) is imperative to meet 2024 air quality targets. The California Air Resources Board (CARB) is developing new regulations to address weaknesses in the current federal standard and improve the air quality of millions of residents breathing unhealthy air. An important element for consideration in this regulatory process is to assess the cost of emission control technologies to comply with the envisioned regulatory changes.

CARB regulators have announced their intention to improve the state's HDV engine emission standards. Key changes include a phased-in introduction of lower NO_x emissions, with long-term targets set 90% below current limits, and the adoption of low-load cycle (LLC) to supplement the traditional federal test protocol (FTP) and ensure NO_x emissions compliance under urban low-speed operating conditions. The board also proposed increasing the useful life or durability requirements and warranties to better reflect HDV operating life in the United States and ensure long-term real-world emissions control.

The more-stringent emission targets and the other regulatory requirements can be met with improvements to current emission control systems and adoption of new hardware components. Improvements needed to achieve the targets include close-coupled selective catalytic reduction (SCR) systems and heated urea injection. Close-coupled SCR systems are needed to address NO_x emissions during low-load operation. Heated urea injection reduces the need to heat the exhaust mass flow, allowing for injections at lower exhaust temperatures.

The cost of the technology required to meet CARB's envisioned regulatory changes in 2024 and 2027 is the focus of this analysis. The cost-estimation methodology follows the steps outlined in previous ICCT work for light-duty vehicles, heavy-duty vehicles, and nonroad engines. Each technology involved in emissions control, in-cylinder, and aftertreatment components, is studied independently. In-cylinder technology cost is presented as a single value. Aftertreatment cost values are dissected for each of the main system components and parts. The cost information for each item comes from bottom-up assessments, available literature, trade publications, suppliers, and expert reviews. Indirect cost values are determined from methodologies developed by the EPA and added to the detailed manufacturing costs. The effect of time and production learning are also accounted for in 2024 and 2027. The impact of increased useful life requirements is also estimated. However, the effect of changes in warranty requirements is out of the scope of this report. The main output of this analysis is the incremental cost of meeting future requirements in 2024 and 2027 compared with a baseline EPA 2010 technology case.

KEY FINDINGS

The costs of meeting EPA 2010 standards in 2019 have declined significantly compared with previous cost estimates. Costs of aftertreatment technology needed to meet the EPA 2010 standard have dropped by about 25%. Total direct and indirect aftertreatment manufacturing costs in 2019 are estimated in this analysis to be $2,800 for a class 6–7 HDV with a 7.0 liter engine and $4,400 for a class 8 HDV with a 13.0 liter engine.

Meeting the envisioned CARB 2024 targets would require very modest increases in technology complexity and costs. Technology changes are expected to occur in the urea dosing system of current aftertreatment system architectures. The incremental cost of achieving a 75% reduction in NO_x emissions under the FTP and meeting new LLC standards is estimated to range between $100 and $1,000 for a class 6–7 vehicle with a 7.0 liter engine and between $100 and $1,100 for a 13.0 L class 8 HDV (Table ES-1).

Table ES-1. Incremental total cost of the proposed 2024 CARB standards, as compared with EPA 2010 standards in 2024 (in 2019 U.S. dollars).

Regulatory step	HDV class 6–7 7.0 L engine	HDV class 8 13.0 L engine
Baseline technology costs EPA 2010 in 2024	$2,570	$3,997
Total costs to meet CARB 2024	$2,675 – $3,575	$4,102 – $5,090
Incremental costs to meet CARB 2024	**$105 – $1,005**	**$105 – $1,093**

Meeting the envisioned CARB 2027 targets would require significant changes in current technology and costs, driven by 90% lower FTP NO_x targets, low-load cycle requirements, and longer useful life mandates. The technology changes are focused on improving thermal management and increasing the aftertreatment system NO_x reduction efficiency and durability. To achieve that, cylinder deactivation and EGR bypass would be added to future engines. Aftertreatment changes would include the addition of a close-coupled SCR and changes to the urea dosing system. Higher useful life would be addressed with changes to catalyst volume and wash coat formulations, and sensor replacement. For class 6–7 HDVs with 7.0 L engines, this would result in additional $1,800 – $2,600 of total emission control costs compared with systems meeting the EPA 2010 standards in 2027. For class 8 HDVs with 13.0 L engines we estimate an increment in total cost ranging from $2,200 to $3,200 compared with systems meeting the EPA 2010 standards in 2027 (Table ES-2).

Table ES-2. Incremental cost of the proposed 2027 CARB standards, as compared with EPA 2010 standards in 2027 (in 2019 U.S. dollars).

Regulatory step	HDV class 6-7 7.0 L engine		HDV class 8 13.0 L engine	
Baseline technology costs EPA 2010 in 2027	$2,431		$3,769	
Total costs to meet CARB 2027	Low-cost durability case	High-cost durability case	Low-cost durability case	High-cost durability case
	$4,214–$4,288	$4,925–$4,996	$5,919–$6,031	$6,864–$6,988
Incremental costs EPA 2010 to CARB 2027	**$1,803–$1,877**	**$2,514–$2,585**	**$2,170–$2,282**	**$3,115–$3,239**

INTRODUCTION

Nitrogen oxides (NO_x) are precursors to $PM_{2.5}$ and ground-level ozone, both of which are known to have adverse effects on public health. Long-term exposure to $PM_{2.5}$ and ozone is associated with increased risk of premature death from cardiovascular, lung, and kidney diseases (Burnett et al., 2018; Turner et al., 2016). In addition, direct NO_2 exposure is associated with increased asthma incidence among children and asthma emergency department visits (Anenberg et al., 2018).

Heavy-duty diesel vehicles are a major source of NO_x emissions. In California, HDVs are responsible for more than 70% of NO_x emitted by on-road mobile sources (CARB, 2019). Nationwide, HDVs are responsible for roughly 60% of NO_x emissions from on-road mobile sources (U.S. EPA MOVES2014a).

Reduction of NO_x emissions can lead to substantial public health benefits from improved air quality, including fewer hospitalizations and emergency room visits, fewer missed days at work, and lowered risk of premature death from cardiovascular, lung, and kidney diseases (U.S. EPA, 2018b)(EPA, 2018c). These benefits are the main drivers for decreasing NO_x emissions from HDVs.

Regulatory agencies in the United States have put in place rules aimed at reducing NO_x emissions from heavy-duty diesel engines. In 2000, the U.S. Environmental Protection Agency (EPA) adopted heavy-duty engine emission standards for model years 2007–2010 and later engines. The EPA 2010 emissions regulation was intended to reduce NO_x emissions by 90% compared with the model year (MY) 2004 standard. As a result, total fleet NO_x emissions in the United States have dropped by more than 40% (EPA, 2018a). The ICCT estimates that achieving these standards could avoid 2,100 premature deaths from $PM_{2.5}$ and 700 deaths from ozone exposure in the United States annually in 2040.

The adoption of the EPA 2010 heavy-duty regulations resulted in widespread deployment of advanced NO_x emission control systems with positive vehicle emission reductions. This has been confirmed by remote sensing data from HDVs in California. Data covering a wide span of vehicle model years shows significant improvements in average NO_x emissions, moving from close to 20 g NO_x/kg of fuel for vehicle MY 2004 to a range of 3.8–13.9 g NO_x/kg of fuel for post MY 2010 (Bishop, 2019).

At the same time, in-use emissions testing has shown that there is still a gap between real-world NO_x emissions and certified levels. Portable emissions measurement system (PEMS) testing data on post-MY 2010 line-haul and delivery trucks shows that brake-specific NO_x emissions reach an average of 0.45 g/bhp-hr, or twice the engine certification standard (Besch, 2018; Duncan & Hamady, 2019; Quiros et al., 2016). Remote sensing data from HDVs in California show that the best performers, at 3.8 g NO_x/kg of fuel, emit about 3.3 times more than the engine certification standard would permit (Bishop, 2019).

A recent analysis of PEMS data for U.S. HDVs reveals that a disproportionate amount of NO_x emissions occur during urban driving. Urban-driving NO_x emissions form HDVs are five times higher than the engine emissions standard of 0.2 g/bhp-hr. For class 8 trucks the data shows an even larger gap, almost seven times the standard (Badshah et al., 2019).

As a result, air quality is still a significant problem in certain regions of the United States. In California, more than 12 million of the state's 40 million residents are exposed to unhealthy levels of pollutants. The Los Angeles South Coast Air Basin and San Joaquin Valley are the two areas most affected, classified as "extreme" under the national eight-hour ozone standard (U.S. EPA, 2019).

Reducing the environmental and health impact of the current and future fleet of HDVs in California would entail reducing the amount of NO_x emitted from those vehicles. In the South Coast Air Basin, reductions of 70% of NO_x emissions from today's levels would be needed by 2023 to meet the national ambient air quality standard for ozone (Heroy-Rogalski, Lemieux & Robertson, 2019).

CARB'S LOW NO_x PROPOSAL

CARB envisions a two-step approach to reduce HDV NO_x emissions. In the first phase, applicable from 2024–2026, the engine certification NO_x limit would be reduced by 75% from 0.2 g/bhp-hr to 0.05 g/bhp-hr. The low-load cycle (LLC) would also be introduced in this timeframe. This supplemental engine dynamometer cycle is intended to incentivize NO_x emissions control within the operating areas that have been more challenging for MY 2010 and later engines: low-speed and low-load conditions. These low-load conditions are typically found during urban driving, or at speeds of less than 25 mph.

In the second phase, from 2027 onward, CARB would introduce more-stringent NO_x emissions standards. CARB's intention of reducing NO_x emissions from HDVs by 90% translates to a certification value of 0.02 g/bhp-hr. The LLC limit will fall somewhere between one and three times this value. Meeting these reductions is expected to require the introduction of engine and aftertreatment hardware upgrades. Therefore, the planned LLC NO_x limit applicable starting in 2027 has not been announced and will be based on a technology demonstration program being carried out by Southwest Research Institute (SwRI) to be completed in the spring of 2020. Table 1 provides a summary of the CARB low NO_x envisioned changes. CARB also proposed changes to warranty requirements, but that is outside the scope of our analysis.

Table 1. Summary of CARB key proposed changes to engine emission standards compared with current EPA 2010 standard. The standards apply to medium duty and HD diesel-cycle engines.

Test cycle		Current EPA 2010 standard	CARB MY 2024–2026	CARB MY 2027 and beyond
Engine FTP emission limit ($g\ NO_x$/bhp-hr)		0.2	0.05 (75% reduction)	0.02 (90% reduction)
Low-load cycle (LLC) emission limit ($g\ NO_x$/bhp-hr)		-	0.2	(1–3) x FTP limit
Durability	**Class 8 HDV**	435,000 miles	435,000 miles	600,000 miles by 2027 800,000 miles by 2031
	Class 6–7 HDV	185,000 miles	185,000 miles	360,000 miles by 2027 450,000 miles by 2031

The technology deployment required to achieve the low levels of NO_x emissions specified in the proposed changes builds upon the architecture of current emission-control systems. Under the right temperature conditions, a well-designed selective catalytic reduction (SCR) system can convert NO_x with more than 99% efficiency. Low exhaust temperatures however, like those found during cold-start and extended low-load operation, can significantly reduce the SCR conversion efficiency and are responsible for the majority of NO_x emissions from HDVs. Keeping the SCR substrate in the right temperature range and accelerating the light-off process are key goals for low-load NO_x control. Thus, technology interventions in engine and aftertreatment systems are necessary to reduce emissions under these conditions.

Subsequent sections of this paper discuss the potential of technology to meet these future standards. Engine enhancements, aftertreatment system improvements, and the estimated costs for both are explored.

EMISSION-CONTROL TECHNOLOGIES ON A GLOBAL SCALE

Since 2007, a growing number of national governments have implemented Euro VI or EPA 2010 heavy-duty tailpipe emission standards as a response to air quality and health concerns. These standards require an almost identical emissions-control architecture (Posada et al., 2016). Meeting Euro VI and EPA 2010 HDV standards requires a diesel oxidation catalyst (DOC), a wall-flow diesel particulate filter (DPF), and a selective catalytic reduction (SCR) system, governed by an array of sensors, actuators, and controllers. As of 2018, all diesel heavy-duty vehicles sold in the United States, Europe, Canada, and Japan were fitted with these advanced emissions-control systems.

By 2023, the advanced emissions-control technologies market is expected to double in response to adopted and announced emission standards. India, China, Brazil, and Mexico have announced the adoption of Euro VI-equivalent standards between 2020 and 2023. China and India account for 30% of the new HDV diesel global market. The ICCT estimates that by 2023 almost 80% of all new heavy-duty diesels will meet Euro VI/EPA 2010 equivalent standards requiring advanced aftertreatment systems (Miller, 2019).

SCOPE OF WORK

This report focuses on the diesel HDV emissions-control technology required for today's engines to meet the current—MY 2024 and MY2027. We focus on cost impacts derived from changes to FTP standard limits, the adoption of the new supplemental low-load cycle with corresponding limits, and longer useful life requirements. We focus our analysis on two engines sizes, a 7.0 liter engine representative of class 6 and 7 HDVs in the United States and a 13.0 liter engine representative of Class 8 HDVs in the United States.

This assessment does not consider the final cost to customer but instead tries to assess the per-vehicle direct manufacturing cost and indirect costs of technologies that engine manufacturers will have to deploy to comply with future regulations. This study does not cover the cost impact of market size consideration from adopting low NO_x standards in some states compared with a federal regulatory change. Also, Operating costs are not discussed here.

EMISSION-CONTROL TECHNOLOGIES FOR LOW NO_X

This section presents various strategies for reducing vehicle NO_x emissions to meet current and future standards. CARB's proposed standards would focus on the engine and vehicle operating areas where NO_x is more challenging to control: low load and low vehicle speed that are characteristic of urban driving. During low-load urban driving the exhaust gas temperature is not high enough for proper SCR operation. This challenge can be met with numerous technologies that focus in these key areas: reducing engine-out NO_x, accelerating the SCR warm-up process, keeping the SCR warm, and increasing the SCR NO_x conversion efficiency. These technologies and their qualitative impact on CO_2 emissions are listed in Table 2, adapted from Rodriguez and Posada (2019).

The following sections explore in greater detail some of the more promising technologies listed in Table 2, particularly those that have minimal impact on CO_2 emissions or simultaneously reduce NO_x and CO_2 emissions. Although the technologies described may be used in the future to meet strict NO_x limits, manufacturers may choose other pathways to meet these limits.

Table 2. Technologies available to meet future low NO_x standards. Adapted from Rodriguez and Posada (2019).

		Short description	Impact on CO_2 / GHG	Low NO_x into SCR	Fast warm-up	Stay warm	High conv. efficiency
Engine technologies	**Air gap insulated manifold**	Insulates the exhaust manifold and reduces heat losses before the SCR inlet during cold-start.	⇨		X		
	Cylinder deactivation	Deactivating cylinders at low loads increases exhaust temperatures of the firing cylinders.	⇩		X	X	
	Dual urea dosing	Improves NO_x conversion in high-load operation and enables the use of close-coupled SCRs.	⇨				X
	Ducted fuel injection	Eliminates trade-off between soot and NO_x, allowing higher EGR rates and less-frequent DPF regeneration.	⇨	X			
	EGR (backpressure)	Exhaust gases recirculation (EGR) reduces NO_x formation during combustion by diluting the intake air.	⇧	X			
	EGR pumps	Allow accurate control of EGR rates and eliminate the increase in backpressure to drive the EGR flow.	⇩	X			
	Coolers bypasses	Bypassing hardware with high thermal inertia reduces heat losses upstream of the SCR during cold-start	⇨		X		
	Electric boosting	Electric motors built into the turbo improve transient response, reducing NO_x peaks. 48V required.	⇩		X		
	Fast idle	Accelerates warm-up by increasing the flow of hot exhaust gases in cold-start.	⇧		X		
	Mild-hybrid (48 Volts)	Increases exhaust temperatures (higher engine load), improves transient NO_x, and enables other measures.	⇩	X	X	X	
	Post / late injection	Increases the exhaust temperature and reduces engine-out NO_x at the cost of higher fuel consumption.	⇧	X	X	X	
	Stop/start	Prevents cooling of the SCR during idle by stopping the flow of cool exhaust gases. 48V required.	⇩			X	
	Variable valve actuation	Enables temperature management by early exhaust valve opening, intake valve closing modulation.	⇩		X	X	
Aftertreatment technologies	**Burner**	Burns additional fuel in the exhaust and increases exhaust temperature at the inlet of the SCR.	⇧		X	X	
	Close-coupled SCR	Positioning an SCR unit close to the engine makes possible significantly faster warm-up.	⇨		X		
	Electric catalyst heating	Accelerates warm-up and ensures operating temperature independent of engine load.	⇧		X	X	
	Heated urea dosing[a]	Enables urea dosing at lower temperatures without formation of deposits in the SCR inlet	⇨		X		X
	Improved SCR chemistries	Improved formulations increase the NO_x performance at low temperatures and reduce N_2O formation.	⇩		X		X
	Larger SCR volume	Larger SCR volumes can increase conversion efficiency but require more thermal management	⇨				X
	Passive NO_x adsorbers	Trap NO_x during cold-start and release it once the SCR is warm enough. Require periodic regeneration.	⇧	X			
	SCR on DPF (SCRF)	Integrating the SCR into the DPF substrate enables faster warm-up as it puts the SCRF closer to the engine.	⇨		X		
	Seventh injector	Injects fuel directly in the exhaust which is oxidized by the DOC increasing the exhaust temperature.	⇧		X	X	

[a] Heated urea dosers (HUDs) enable dosing at exhaust temperatures in the range of 130°C–150°C compared with a temperature limit of 180°C–200°C for conventional dosers. HUDs reduce the need for additional fuel burn used for thermal management of aftertreatment systems. The small amount of energy required to heat up the urea injector is compensated by enabling more-efficient thermal control and efficient engine calibrations at low-load conditions.

ENGINE CONTROLS

Pollutants like particulate matter (PM), hydrocarbons (HCs), and carbon monoxide (CO) are formed in diesel engines due to air-fuel mixing challenges and incomplete fuel combustion, while NO and NO_2 (NO_x) are formed during the combustion process and driven by high-temperature combustion conditions. Advanced engine design can manipulate in-cylinder combustion dynamics to minimize the formation of these pollutants, reducing engine-out emissions. The temperature, speed, and composition of the mix entering the chamber influence burn conditions, as does the fuel delivery timing strategy. Engine redesigns, which do not add significant hardware costs but do require investment in R&D, seek to improve combustion efficiency and minimize pollutant formation through engine geometries that improve mixing of air and fuel.

Conventional strategies to reduce engine-out emissions focus on improved fuel injection, improved air handling, and exhaust gas recirculation (EGR). A new set of technologies that is entering the diesel engine space as a potential solution for emissions control and fuel efficiency, which has been widely used in light-duty gasoline engines, are variable valve actuation and cylinder deactivation (CDA). For the purpose of cost evaluation, we focus on CDA technologies as well as EGR handling, air-charge cooler, and turbo bypass.

EGR cooler, air-charge cooler, and turbo bypass

An EGR system recirculates a portion of exhaust gas back to the engine's cylinders. This provides diluent to the air handling system and reduces NO_x formation by lowering peak combustion temperature within the cylinder. EGR coolers are often included for further temperature control. EGR is the most widely used technology for in-cylinder NO_x reduction in diesel-powered engines. The EGR fraction, or the share of recirculated exhaust gas in the total intake charge, is tailored to each engine operating condition and, in the latest systems, varies from zero to 50% of incoming air.

EGR systems for HDV applications can be high-pressure or low-pressure, cooled or uncooled, each with trade-offs and varying effectiveness under different operating conditions. A compromise between these is a dual-loop system, which combines a low-pressure cooled system with a high-pressure uncooled system (Posada, Chambliss, & Blumberg, 2016).

Current systems use a valve, a virtual flow meter based on valve opening and other signals, and sometimes a variable geometry turbocharger to control EGR flow rates and bypass. Not all EGR rates are available or controllable under all engine loads and speeds. By bypassing the EGR cooler, EGR can be used earlier in the warm-up phase of engine operation, reducing cold-start NO_x emissions. Similarly, disabling cooled EGR during low-load conditions can increase or maintain combustion temperatures.

Electric EGR pumps that perform independently of engine speed can further improve current EGR performance. This could be used to further reduce NO_x or improve fuel consumption without NO_x increases (Dorobantu, 2019; Eaton, 2019b). As long as other enabling technologies are already included with the powertrain—48V mild hybrid, for example—this technology improvement is essentially cost-neutral as it eliminates the need for an EGR valve and a flow meter while enabling the use of a less-expensive single-stage fixed geometry turbocharger.

Bypassing the charge air cooler or turbo reduces heat losses. Bypassing the cooler keeps the compressed charge hot, which helps raise exhaust temperatures at low vehicle speeds and idle conditions. Bypassing the turbine also maintains higher exhaust temperatures by avoiding heat losses through exhaust gases expanding through the turbine. Transient response challenges that may result from turbine bypass systems can be resolved with electric assist motors integrated into the turbocharger or by the addition of an electric boost compressor. These strategies require mild 48V hybridization.

Cylinder deactivation

Cylinder deactivation encompasses a range of technologies that disable one or more cylinders during engine operation. This effectively creates a smaller engine displacement in which cylinders operate at higher loads (Isenstadt, German, & Dorobantu, 2016). CDA is already used in light-duty vehicles, primarily for fuel economy improvement from operating active cylinders in more efficient zones. Diesel engines also realize efficiency benefits from CDA. Additionally, since CDA increases exhaust gas temperatures it can rapidly warm the aftertreatment system and maintain that warmth, even under low-load conditions (Dorobantu, 2019; Eaton, 2019a; Ramesh et al., 2018).

Faster warm-up and longer stay-warm periods enabled by CDA can lead to 35%–45% reductions in tailpipe NO_x emissions (Dorobantu, 2019; M. Joshi et al., 2018). Although fuel consumption can increase slightly by 0%–3.4% under some loads when NO_x emission reductions are prioritized, studies show that fuel consumption decreases by 4%–10.6% over several drive cycles (Dorobantu, 2019; M. Joshi et al., 2018; Ramesh et al., 2018). According to a recent study performed by SwRI, CDA realized a 44% reduction in work-specific NO_x while simultaneously reducing fuel consumption by 2.8% over the low-load cycle on a modern aftertreatment system (Neely, Sharp, Pieczko, & McCarthy, Jr, 2019). The same study shows that CDA contributed to a 32% reduction in work-specific NO_x with a simultaneous 2.5% reduction in CO_2 on the same aftertreatment system over the FTP.

Additional technologies that reduce fuel consumption and NO_x

The technologies listed above provide NO_x emissions reduction while lowering the impact of thermal management on fuel consumption. Two additional technologies, engine stop-start systems and 48V mild-hybrid systems, can provide more flexibility for thermal management and achieve higher fuel-efficiency gains. These two technologies have not been tested on engine dynamometers as part of the CARB technology potential program (SwRI, 2019). We present here the potential for those technologies to help reach the CARB-envisioned targets, though they are not included in our cost estimates.

Stop-start engine technologies stop the engine and halt the flow of cool exhaust gases through the aftertreatment system during idle or extended periods of low load. This stoppage of flow prevents aftertreatment components from cooling below the point at which the catalysts become ineffective. In this way, stop-start enables the aftertreatment system to stay warm longer.

The increased number of engine starts demands a more robust starter and electrical system as does the need to provide power while stopped for accessories and auxiliary components, such as the pump of the cooling system, the cooling fan, the AC unit, and others. Consequently, stop-start requires 48V mild hybrid electric vehicle system (MHEV). A 48V MHEV system also enables electric boosting, electric EGR pumping, and a suite of other fuel-saving benefits, including braking energy recovery and rapid catalyst heating. From an operations perspective the 48V would also enable hoteling capabilities. In the light-duty sector, MHEVs are expected to offer more than half of the benefits of a full hybrid system, or 15%–20% fuel savings, at less than half the cost, or $800–$1,400 (Isenstadt et al., 2016).-

AFTERTREATMENT CONTROL

Aftertreatment systems treat engine-out NO_x, PM, HC, and CO in the exhaust stream. Selective catalytic reduction (SCR) using urea as a reagent controls NO_x emissions in the exhaust. The diesel particulate filter (DPF) controls soot while the diesel oxidation catalyst (DOC) controls the soluble organic PM fraction and reduces HC and CO emissions. These technologies can also be used in combination with other strategies to lower other pollutant emissions. For example, DOCs can support SCR catalytic functions, and SCR systems enable in-cylinder strategies to reduce PM emissions and increase fuel efficiency.[1]

This section provides an update on improvements made to the EPA 2010 architecture as of 2019 and provides an introduction to the technologies that have been identified as able to meet the CARB-envisioned MY 2024 and 2027 targets.

Baseline EPA 2010 standard in 2019

Today's systems are certified to meet EPA 2010 engine emission standards, which set a NO_x certification limit of 0.2 g/bhp-hr and an in-use NO_x emissions limit of 0.45 g/bhp-hr. These systems are warrantied up to 5 years or 100,000 miles but have a durability requirement of 435,000 miles.

Today's baseline aftertreatment emissions control architecture required to meet EPA 2010 emission standards combines a DOC, DPF, a main SCR brick, and a smaller, integrated ammonia slip catalyst (ASC) (MECA, 2019). The system also includes four temperature sensors, two NO_x sensors, and a urea storage and delivery system. Although these aftertreatment components are largely the same as those described in a previous ICCT report (Posada et al., 2016), global market expansions and production improvements have made today's systems smaller and less expensive (MECA, 2019). Details of today's catalysts and aftertreatment system components can be found in the Methodology section.

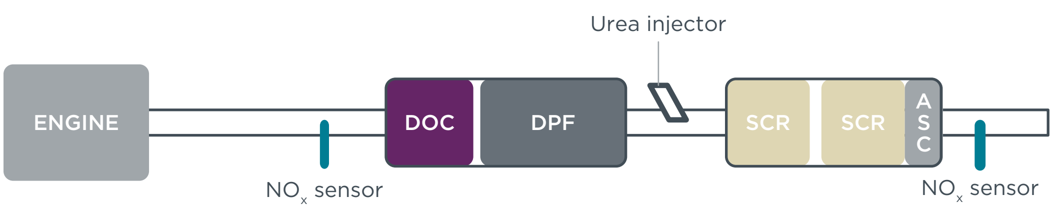

Figure 1. EPA 2010 aftertreatment system layout.

CARB proposal 2024–2026

Experimental and modeling results and the most recent engine certification data show that meeting the envisioned 2024 targets under the FTP can be achieved with engine calibration strategies and small changes to current aftertreatment systems.

1 For optimal NO_x conversion, SCR systems require a higher concentration of NO_2 than is emitted out of the engine. Besides oxidizing engine-out CO and HC emissions, DOCs are designed to oxidize NO into NO_2. DOCs increase the engine-out NO_2/ NO_x ratio, typically from around 1:10 to a ratio of 1:2 that enhances NO_x reduction downstream in the SCR system. An SCR with high NO_x conversion efficiency can allow the engine to be tuned for high combustion temperatures, which are conditions where higher concentrations of NO_x are generated. At high temperature combustion conditions fewer particulates are formed, and higher fuel efficiency is achieved. As a result, advanced aftertreatment systems can enable low NO_x emissions at low fuel consumption.

Meeting the supplemental low-load cycle requirements could require only minimal aftertreatment component changes.

The Manufacturers of Emission Controls Association (MECA) analyzed the tailpipe NO_x emissions over the composite FTP cycle of current emission control systems and modeled the impact of additional technologies that further reduce NO_x emissions (MECA, 2019). The association's engine testing demonstrated that modern SCR formulations in a traditional aftertreatment system can yield tailpipe NO_x emissions over the hot-start FTP of close to 0.02 g/bhp-hr.

MECA analyzed cold-start FTP emissions and additional technology deployment through modeling of catalysts aged to represent 435,000 miles (700,000 km) of operation. Specifically, they modeled architectures with close-coupled SCRs, dual urea dosing and heated urea injectors. They did not attempt to optimize engine calibration or other thermal management strategies. The modeling results over the composite FTP suggest that currently available emission control systems can achieve weighted composite FTP NO_x emissions of less than 0.04 g/bhp-hr and that emissions can be further reduced to approximately 0.03 g/bhp-hr by increasing the SCR catalyst volume to the level found on 2019 trucks.

Engine certification data from the EPA show that several diesel engine families from three manufacturers have already been certified to 0.05 g/bhp-hr over the composite FTP without increased CO_2 emissions (U.S. EPA, 2019a). Those diesel engines are in the 12–13 L engine displacement range and are produced by Volvo, Cummins, and Detroit Diesel. Ford certified a 6.7 L engine at this NO_x emissions range.

Meeting the LLC mandates will require engine calibration and urea injection strategy changes. SwRI experimental data shows that engine-out NO_x calibrations and urea injection strategy changes are required to meet a 0.34 g/bhp-hr standard on a stock engine and aftertreatment system while running on an older version of the LLC that had zero load during idling operation. MECA's modeling of LLC engine-out NO_x levels on currently available emission systems shows that the adoption of heated urea dosing and improved urea dosing strategies[2] to increase ammonia storage on SCR systems can be used to meet the requirements. The results indicate that currently available emission controls, with the addition of heated urea dosing and 50% ammonia storage level on the SCR, can reduce tailpipe NO_x emissions down to 0.18 g/bhp-hr over a low-load certification cycle. Figure 2 shows one potential aftertreatment configuration for meeting the proposed CARB 2024 targets.

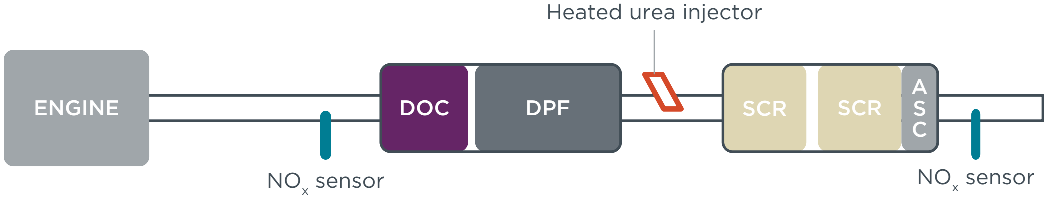

Figure 2. Potential aftertreatment configuration (No. 1) of a CARB 2024 compliant system.

The challenges of in-use NO_x emission compliance in addition to low-load cycle testing requirements may drive the adoption of an alternative technology pathway. The alternative would split the volume of the existing underfloor SCR into two: One

2 Urea delivery can be tailored via closed-loop control for ammonia storage optimization. This control is possible with feedback from available NO_x and NH_3 sensors. This enables accurate dosing to maximize ammonia storage in the SCR and achieve high NO_x conversion while minimizing overdosing of the catalyst that can result in ammonia slip and increased N_2O emissions.

part would remain downstream, while the other would be located upstream, before the DOC (Geller, 2019). This strategy is already used in light-duty applications (MECA, 2019; VW, 2019). This configuration for HDVs would use two urea injectors, one heated injector for the first SCR, and a conventional injector for the underfloor, downstream SCR. The DOC and DPF components remain the same. This second configuration is illustrated in Figure 3.

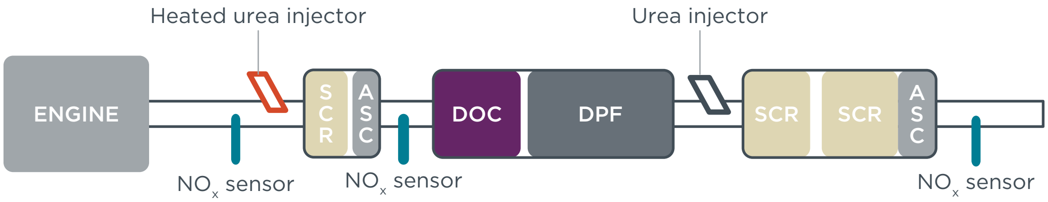

Figure 3. Potential aftertreatment configuration (No. 2) of a CARB 2024 compliant system.

This second pathway also has many similarities to what is expected to be required to meet the proposed 2027 NO_x limits, thereby providing manufacturers with additional cost reduction opportunities through manufacturing learning.

CARB proposal 2027 and beyond

To reach CARB's envisioned low NO_x levels — below 0.02 g/bhp-hr — significant emission reductions from cold start and high conversion efficiencies for the entire FTP test and supplemental low-load cycle are needed. These requirements include reducing the time to achieve SCR light-off and maintaining adequate temperatures for the whole cycles. Three main strategies are expected to be used to meet this 90% reduction in NO_x limits:

» First, adding heat to quickly warm up SCR catalysts. Late in-cylinder fuel injection, heated catalysts, mini-burners, and heated urea dosing increase the thermal energy needs during periods when the SCR would be too cold for high NO_x conversion. Some of these technologies enable and improve engine efficiency and decrease fuel consumption, so there may be no net increase in fuel consumed. As mentioned above, heated urea dosing reduces the need to heat the exhaust gases, enabling low-load fuel efficiency gains; 48V electrical systems enable electric catalyst or heated urea dosing. The energy supply for this heating could in part come from recuperated braking energy, which reduces real-world fuel consumption from fast light-off.

» Second, NO_x suppression while catalysts are cold involves reducing SCR inlet NO_x mass during the warm-up period via a passive NO_x adsorber, or via in-cylinder emission controls with EGR or late fuel injection. Once the SCR has reached light-off, adsorbed NO_x is released and reduced in the SCR system, or engine controls switch to higher engine-out NO_x.

» Third, adding SCR volume and positioning some of the additional volume close to the engine exposes such close-coupled SCR (ccSCR) to higher temperatures, thereby enabling faster light-off of the ccSCR.

At the request of CARB, SwRI has been studying the potential of meeting the envisioned standards through a combination of these strategies. SwRI studied a series of aftertreatment configurations and engine calibration and hardware changes. In this section we summarize those architectures that have achieved the most promising results for emissions control under the different test cycles. We focus on just three of the most promising architectures for subsequent cost assessment. The system components studied by SwRI were aged to 435,000 miles (Sharp, 2019).

Configuration 1

Today's systems consist of DOC, DPF, a single urea doser, and the combined SCR and SCR/ASC bricks (MECA, 2019). The main difference with the 2nd configuration for ARB 2024 is that the 2027 system requires larger SCR substrate volumes, a different washcoat, and adds an ammonia sensor in the underfloor section. The simplest improvement to meet future 2027 standards adds a close-coupled SCR (ccSCR) next to the turbocharger outlet. This system includes a urea doser and SCR/ASC upstream of the DOC for fast light-off. In these configurations, one heated urea injector is located in front of the ccSCR, composed of SCR/ASC, which comes before the filter, while the second urea injector remains in front of the downstream SCR. The two injectors better control the desired ammonia and also manage NO_2 slip for passive soot regeneration of the DPF (A. Joshi, 2019). Based on engine testing, this system can meet CARB's 2027 NO_x limits over the composite FTP and LLC (Neely et al., 2019; Sharp, 2019).

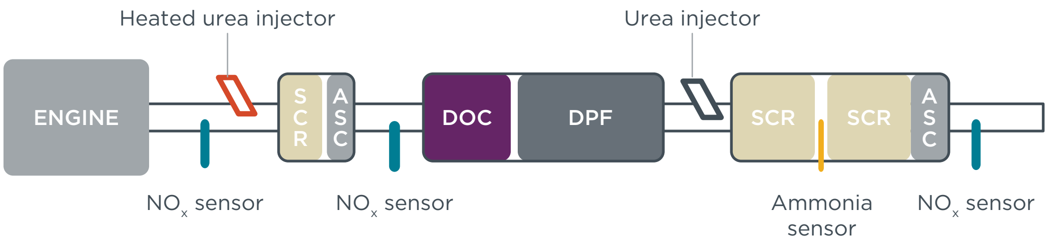

Figure 4. Aftertreatment – Configuration 1 (ccSCR + DOC + DPF + SCR/ASC) to meet CARB 2027 standards under FTP and supplemental low-load cycle. Adapted from SwRI (Sharp, 2019).

Configuration 2

The second configuration retains the first section of configuration 1 and introduces an integrated SCR system on a DPF substrate, known as SCR on DPF or SCRF. The SCRF replaces the DPF and part of the SCR with a compact design. The SCRF allows for improved thermal management due to lower thermal inertia. The second doser also enables switching off urea dosing during filter regeneration, which helps manage the pressure drop across the soot-loaded SCRF. Despite the advantages of using SCRF, it presents filter regeneration challenges not present with separate DPF+SCR bricks, as NO_2 preferentially reacts with ammonia and therefore is not available for passive filter regeneration (A. Newman, 2018). This system has not yet been experimentally investigated as thoroughly as Configurations 1 and 3.

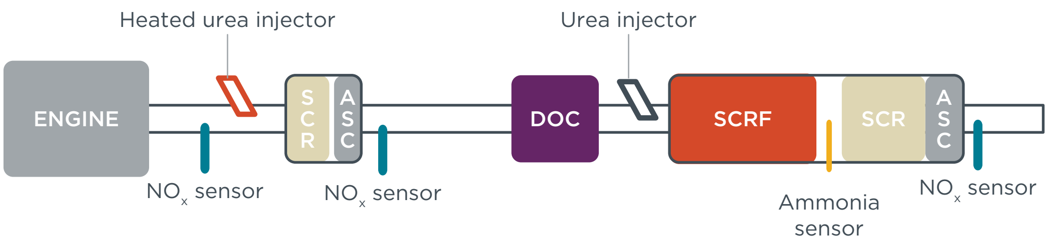

Figure 5. Aftertreatment configuration 2 to meet CARB 2027 standards under FTP and supplemental low-load cycle. Adapted from SwRI (Sharp, 2019).

Configuration 3

Further modifying Configuration 1 by combining the separate DOC and DPF into one catalyzed soot filter (CSF). CSF are characterized by performing the DOC function in the front section of the filter substrate. The precious metal loading is not uniform. The CSF was selected as it promises lower thermal inertia ahead of the downstream SCR, which helps to achieve low NO_x emissions over the low-load cycle. In addition, CSF provides lower backpressure than the DOC+DPF combination, reducing CO_2 penalties according to recent modeling by SwRI (Sharp, 2019).

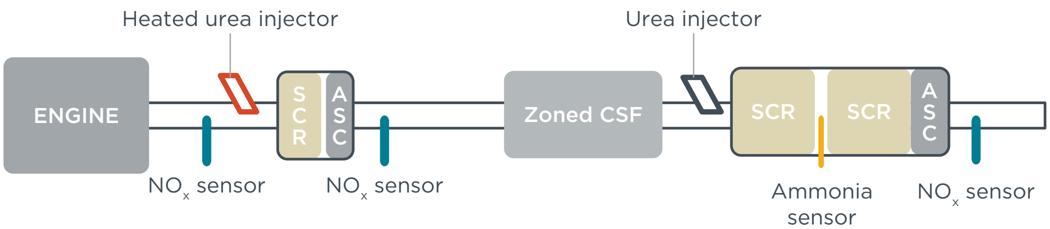

Figure 6. Aftertreatment configuration 3 to meet CARB 2027 standards under FTP and supplemental low-load cycle. Adapted from SwRI (Sharp et al., 2019).

Aftertreatment system integration with in-cylinder controls

Achieving low NO_x emissions with these aftertreatment configurations under different engine test cycles requires proper integration with engine technologies to maximize the benefits offered.

SwRI selected the systems of Configuration 1 and Configuration 3 for further testing with CDA and NO_x optimization under the FTP and LLC cycles (Neely et al., 2019; Sharp, 2019). At a CO_2 penalty of 2.1%–2.6%, the systems achieved 80%–84% lower specific NO_x emissions than the baseline EPA 2010 compliant system over the cold FTP. In the hot FTP, NO_x emissions decreased by 90%–91% with 1% fuel savings. The composite FTP yielded an 88.8% NO_x reduction, or 0.018 g/bhp-hr, with respect to the baseline with a CO_2 reduction of 0.5%.

Low-load cycle results were similarly positive. SwRI researchers measured 89%–91% reductions in NO_x emissions, or 0.12–0.16 g/bhp-hr, with respect to the baseline and 1.6%–5% reductions in CO_2. These LLC results exclude thermal management, which typically increases CO_2 emissions but lowers tailpipe NO_x. When thermal management is used, LLC NO_x is 96%–97% lower, or 0.036–0.053 g/bhp-hr, than the baseline, and CO_2 emissions are between 2% lower and 1.4% higher (Sharp, 2019).

These first sets of results are promising, especially considering that many of the aftertreatment system components are commercially available or similar to currently available components. They demonstrate the feasibility of meeting CARB's 2027 NO_x emission standards with today's technologies.

Summary of engine and aftertreatment technologies to meet current and proposed standards

There are numerous trade-offs that can be made when designing the best aftertreatment system to meet future NO_x standards. Many issues can be addressed with combinations of currently available aftertreatment and engine technologies. Still, technologies currently under development present unique solutions that manufacturers are also considering.

Table 3 summarizes the current and potential technology solutions proven in the engine certification tests to meet the envisioned CARB low NO_x standards in 2024 and 2027. For engine-out control we are considering EGR cooler bypass, charge air cooler bypass, and CDA as part of the overall solution. For aftertreatment technologies we cover the SwRI technologies best suited to meet both future FTP limits and the LLC requirements. We estimate only the costs for these potential architectures in the following sections.

Additional technologies that have not been tested and priced here have equal or higher potential to enter the market and enable meeting the 2027 NO_x targets and fuel-efficiency requirements. Technologies such as 48 V mild hybrid technologies can reduce fuel consumption and greenhouse gas emissions by taking over engine accessory loads and enabling electric turbochargers, electric EGR systems, and electrically heated catalyst and urea injectors, These technologies contribute to lowering engine-out NO_x emissions and improving aftertreatment thermal load management such as SCR light-off and keep-warm actions. Thus, many other technology pathways exist that would help achieve the targets in a cost-effective manner.

Table 3. Current and potential future technology options to meet CARB-proposed low NO_x standards in 2024 and 2027.

Technologies	EPA 2010 technology	CARB 2024	CARB 2027
Engine-out			
Fuel injection	Common rail fuel injection (P>2,200 bar)	Common rail fuel injection (P>2,200 bar)	Common rail fuel injection (P>2,200 bar)
Air induction	Turbochargers (waste gate, VGT and two-stage)	Turbochargers (waste gate, VGT and two-stage)	Turbochargers (waste gate, VGT and two-stage)
NO_x control	EGR high pressure	EGR high pressure	EGR high pressure and EGR cooler bypass
Cold start and low load NO_x control	-	-	Cylinder deactivation (CDA) – Provides strong fuel consumption benefits
Aftertreatment			
Oxidation catalyst	DOC	DOC	DOC or CSF
Particulate matter filtration	DPF	DPF	DPF, CSF or SCRF
NO_x reduction and ammonia slip control	SCR and ASC	SCR and ASC	Increased volume SCR (or SCRF) and ASC
Cold start and low-load NO_x control	-	Heated urea injection (HUI) for downstream SCR	Close-coupled SCR/ASC with HUI
Aftertreatment configurations	DOC+DPF+SCR/ASC	Configuration 1: DOC+DPF+SCR/ASC Configuration 2: SCR/ASC+ DOC+DPF+SCR/ASC	Configuration 1: ccSCR/ASC+ DOC+DPF+SCR/ASC Configuration 2: ccSCR/ASC+ DOC+SCRF+SCR/ASC Configuration 3: ccSCR/ASC+ CSF+SCR/ASC

COST ESTIMATION METHODOLOGY

The cost estimation methodology follows the steps outlined in previous ICCT work on this area (Dallmann, Posada, & Bandivadekar, 2018; Posada et al., 2016). ICCT's methods for estimating emission-control costs have been built on methodologies developed by the EPA for regulatory impact assessments of on-road and off-road engines and vehicles (U.S. EPA, 2000; U.S. EPA, 2004). Each in-cylinder and aftertreatment component is studied independently. In-cylinder technology cost is presented as a single cost value. Aftertreatment cost values are dissected for each of the main system components and parts. The cost information for each item comes from bottom-up cost assessments, available literature, trade publications, suppliers, and expert reviews.

The cost estimation methodology develops in three main steps. The first covers identifying publicly available direct manufacturing cost values from regulatory impact assessments and trade publications. Those initial numbers are corrected with the latest cost information such as catalyst prices and loadings to generate initial cost values. The second step is a review of initial direct manufacturing costs by expert reviewers. The third step covers correcting direct manufacturing costs with indirect cost multipliers to account for research and development and marketing, among others. Durability aspects are also investigated under two potential technology solution cases.

The values presented here provide a carefully developed estimate of the manufacturing costs of emission control technologies. Exact cost numbers are out of reach of this process. Understandably, manufacturers are unwilling to openly share information regarding component costs because of competitiveness concerns.

INITIAL COST ESTIMATES

The initial data for this report come from an ICCT report that estimated the cost of EPA 2010 and Euro VI technology (Posada et al., 2016). The ICCT HDV emissions-control cost report of 2016 provided an itemized description of component costs to meet the EPA 2010 standards. The data used to develop the 2016 report was based on information published between 2010 and 2015. Those values were reviewed again for this study with the latest developments, which, according to recent announcements by emissions control technology manufacturers, result in lower costs than the MY 2010 technologies as modern systems are smaller and lighter (MECA, 2019).

The costs of future technologies build upon the estimates of today's system, modified with additional components we think manufacturers are most likely to select to comply with future standards. These choices are based on reports of engine and aftertreatment testing, scholarly articles, and supplier input, where available. Our selections consider lead time, product availability, supplier/manufacturer experience, and future warranty and durability requirements.

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

Once cost estimates of both current, or baseline, and future aftertreatment systems and engine controls were established, these estimates were sent to industry experts for feedback. Experts consisted primarily of parts suppliers specializing in various aspects of engine control or aftertreatment components. Expert inputs were incorporated as appropriate, particularly for costs that are uncertain or outdated. Wherever possible, expert input was verified with publicly available sources.

Where no new information could be found in the literature or from expert input, costs from the previous ICCT analysis were carried forward with adjustments for manufacturer learning.

Initial characteristics of today's baseline system and future systems were adjusted after a thorough review of available publications and industry presentations. Additional adjustments followed from direct expert consultations. As an example, the swept volume ratio (SVR) parameter, used to relate the size of a catalyst substrate to the engine size as well as future component characteristics, was updated to better reflect the current status of emission control technologies.

The following are the major updates from the previous report.

For today's DOC, total platinum group metal (PGM) loading is 1.25 g/L, or around 35 g/ft^3 on average, 11% lower than assumed in the ICCT's previous cost analysis (Chatterjee, Naseri, & Li, 2017; Sethuraman, Sitamraju, Lopez-De Jesus, & Markatou, 2019; Wolff, T., 2015; Yang, Sukumar, Naseri, Markatou, & Chatterjee, 2017). Platinum is the primary metal used, at a 4:1 ratio of platinum to palladium ratio (Pt:Pd) (Sethuraman et al., 2019), as opposed to the 2:1 ratio used in previous DOC cost estimates (Posada et al., 2016). Today, six-month average platinum prices are about 10% lower, and palladium prices are 150% higher than PGM price values used in the 2016 ICCT report (Johnson Matthey, 2019). The overall size of the DOC is around the same as in the previous report, at about 0.75 times engine displacement volume (Vd) (Hruby, Huang, Duddukuri, & Dou, 2019). Wash coat, substrate, and canning costs are approximately unchanged. On balance, today's DOC costs approximately the same as in the ICCT's previous estimate.

Today's DPF is about 15% smaller, at an average of 1.4 times the engine displacement as presented in available publications (Gao et al., 2019; Harris et al., 2019; Hruby et al., 2019; Johannesen, 2016; Johansen, Widd, Zuther, & Viecenz, 2016). PGM loading is an average of 0.097 g/L, or around 2.7 g/ft^3 (Chatterjee et al., 2017; Sethuraman et al., 2019) at a 3:1 Pt:Pd ratio, similar to light-duty applications (Posada, Bandivadekar, & German, 2012). Substrate costs have come down to about half of their original prices reflecting manufacturer learning.

Because of the development of today's SCR+SCR/ASC configuration, the 2016 ICCT report underestimated the swept volume ratio (SVR) of the full SCR system. Current systems are 2.5–3 times engine volume, which includes the ASC SVR of 0.5 (personal communication with supplier companies, 2019). For the ASC, PGM loading is reduced from 0.2 g/L to 0.11 g/L, or from 5.7 g/ft^3 to 3.1 g/ft^3 (Chatterjee et al., 2017). Substrate costs were assumed to match DOC substrate costs separated from wash coat costs. Wash coat costs are assumed to be around $13/L of catalyst volume, a reduction with respect to the previous values due to manufacturer learning since 2010, and confirmed by expert reviews. As with the DOC and DPF, canning costs are assumed constant.

Several other hardware component cost assumptions have changed. Where prices were collected from commercial sources, it was assumed that aftermarket prices have a 2.5 times markup over direct manufacturing costs (Posada et al., 2016). Modern diesel exhaust fluid (DEF), or urea, tanks are made of plastic, not metal, costing about 30% less based on aftermarket prices with an assumed 2.5 times markup (Everblue Solutions, 2019). Aftermarket prices for urea doser pumps show prices ranging from $170–$420, or $68–$168 in direct manufacturing costs. The resulting direct manufacturing cost thus averages about $118, 25% higher than previous estimates. Aftermarket prices for urea dosing control units/modules are $100–$275 for Bosch's Denoxtronic 2.2 Dosing Control Unit. Additional costs of $325–$350 are incurred by adding heating elements and mechanical construction needed to withstand an environment closer to the engine. Lastly, temperature, NO_x, and NH_3 sensors experienced significant price reductions related to the expansion of the global aftertreatment market. Aftermarket prices for these sensors were found by collecting a range of prices associated with new parts for sale on e-commerce websites.

Table 4 through Table 9 summarize all the cost assumptions and parameters used in the analysis. Cost itemization for CSF, SCRF, and ccSCR/ASC were not considered previously by the ICCT. However, they rely heavily on conventional parts, so many costs carry over. All prices cited are direct manufacturing costs.

Table 4. DOC assumptions.

Parameter	Value	Sources
Swept Volume Ratio	0.75	(CARB, 2019; Hruby et al., 2019)
Catalyst loading	0.53–1.41 g/L	(Chatterjee et al., 2017; Sethuraman et al., 2019; Wolff, T., 2015; Yang et al., 2017)
Pt:Pd loading	4:1	(Sethuraman et al., 2019)
Substrate cost	$7/L	Prior report, expert review
Wash coat cost	$13/L	Expert review
Canning cost	$5/L	Prior report, expert review

Table 5. DPF assumptions.

Parameter	Value	Sources
Swept Volume Ratio	1.0–1.7	(Gao et al., 2019; Harris et al., 2019; Hruby et al., 2019; Johannesen, 2016)
Catalyst loading	0.06–0.13 g/L	(Chatterjee et al., 2017; Sethuraman et al., 2019)
Pt:Pd loading	3:1	Expert review
Substrate cost	$12–$15/L	Expert review
Wash coat cost	$13/L	Prior report, expert review
Canning cost	$5/L	Prior report, expert review

Table 6. Catalyzed soot filter (CSF) assumptions.

Parameter	Value	Sources
Swept Volume Ratio	1.75	(CARB, 2019)
PGM loading	0.6 g/L	PGM mass is sum of DOC & DPF (Sethuraman et al., 2019)
Pt:Pd loading	7:2	Average of DOC & DPF
Substrate cost	$12–$15/L	Same as DPF
Wash coat cost	$13/L	Same as DPF
Canning cost	$5/L	Same as DPF

Table 7. SCR/ASC assumptions.

Parameter	Value	Sources
Swept Volume Ratio	1.5–3.0	(CARB, 2019; Gao et al., 2019; Harris et al., 2019; Johannesen, 2016; Naseri, Conway, Hess, Aydin, & Chatterjee, 2014; Sharp, 2019), expert review
ASC SVR	0.4–0.7	(Johansen et al., 2016; Naseri et al., 2014; D. A. Newman, 2018; Sharp, 2019; Wolff, T., 2015)
ASC PGM loading (Pt only)	0.05–0.11 g/L	(Chatterjee et al., 2017; Wolff, T., 2015)
Substrate cost	$13–$15/L	Expert review
Wash coat cost	$13/L	Expert review
Canning cost	$5–$10/L	Prior report, expert review
Urea system		
Urea tank volume	12*Displacement	Prior report
Urea tank cost	$2/L	(Everblue, 2019)
Urea level sensor	$48	Prior report, expert review
Urea dosing pump	$118	e-commerce websites, expert review
Urea dosing system (injector, pipe, mounting)	$175	Prior report, expert review
Dosing control unit	$100	e-commerce websites, expert review
Mixer	$120–$200	Expert review
Temperature sensor	$15 each	e-commerce websites, expert review
NOx sensor	$70–$90 each	e-commerce websites, expert review
NH_3 sensor	$120 each	Expert review. Similar to NO_x sensor but lower volume sales

Table 8. ccSCR/ASC assumptions.

Parameter	Value	Sources
Swept volume ratio	1.0	(CARB, 2019; Sharp, 2019; Wille & Kalwei, 2018)
ASC SVR	0.31	(Wille & Kalwei, 2018)
ASC PGM loading (Pt only)	0.106 g/L	(Chatterjee et al., 2017; Naseri et al., 2014; Wille & Kalwei, 2018)
Substrate cost	$15/L	Expert review. Price increase to withstand higher thermal loads and cycles.
Wash coat cost	$13/L	Expert review
Canning cost	$5/L	Expert review
Urea system		
Heated urea dosing system (injector, pipe, mounting)	$325–$350	Prior report (with higher-cost heating system), expert review

Table 9. SCRF assumptions.

Parameter	Value	Sources
Swept volume ratio	2.0	(Wolff, T., 2015)
Substrate cost	$25/L	Enhanced substrate, expert review
Wash coat cost	$13/L	Prior report, expert review
Canning cost	$5/L	Same as SCR

Finally, Table 10 lists the assumptions used to estimate costs of future engine control technologies. Most of these costs are based on previous light-duty teardowns, with costs scaled based on appropriate parameters. For example, CDA requires actuators, changes to the camshaft, and changes to the cylinder head of a diesel engine (FEV, 2015). A relationship between engine displacement and cost scaling was derived based on trends in cost scaling from those teardowns. Although this method is inexact, it provides a starting point from which to estimate actual costs.

Table 10. Engine controls assumptions.

Parameter	Value	Source
Bypass valve light-duty cost	$56	(FEV, 2015)
Bypass pipe light-duty cost	$22	(FEV, 2015)
CDA heavy-duty cost	$38–$75/cylinder	(Isenstadt et al., 2016)
Scaling	0.7*(Displacement)^0.6	Based on engine component cost trends in (FEV, 2015)

COST REDUCTIONS BY LEARNING

The expansion of the market for emission control technology components experienced in the past decade is a key factor helping reduce the costs of all current emission control components. As part of its regulatory impact analysis process, the EPA developed manufacturer learning curves modeling decreases in manufacturing costs over time as production volumes scale and manufacturing processes improve. A similar approach was used for the Tier 3 and heavy-duty greenhouse gas rules (U.S. EPA, 2014, 2016). When a technology only recently enters the market, it follows a steep learning curve with significant cost reductions. However, as the market saturates with a given technology, most of the cost reductions from learning have already occurred, so further cost reductions take place slowly if at all.

Manufacturers continuously learn how to produce components more cheaply. As evidenced by today's aftertreatment systems, technological innovation and incremental progress have led to significant reductions in aftertreatment system and component costs (MECA, 2019). We reflect these cost reductions from learning processes using learning curves adapted from the EPA Heavy-Duty Phase 2 Greenhouse Gas and Tier 3 Motor Vehicle Emission Rules (U.S. EPA, 2014, 2016).

Learning cost-reduction rates are applied on different levels dependent on how complex or commercially available a technology is. For example, aftertreatment technologies have been in production lines since 2007, while some electrification technologies—CDA and 48V systems—are commercially available only in the light-duty vehicle (LDV) market and are completely new to the HDV market. As the technologies considered herein are well-known, their costs are assumed to decline slowly compared with newer technologies. This trend is illustrated in Figure 7.

Costs from 2019, which are predicated on the assumptions described, decline over time according to the appropriate learning curve in Figure 7. We assume that alternative aftertreatment configurations that use relatively newer parts such as CSF and SCRF will benefit from learning at the same rate as all other such components, reflecting similarities in manufacturing. If learning occurs faster for these newer parts, our estimates will be conservative.

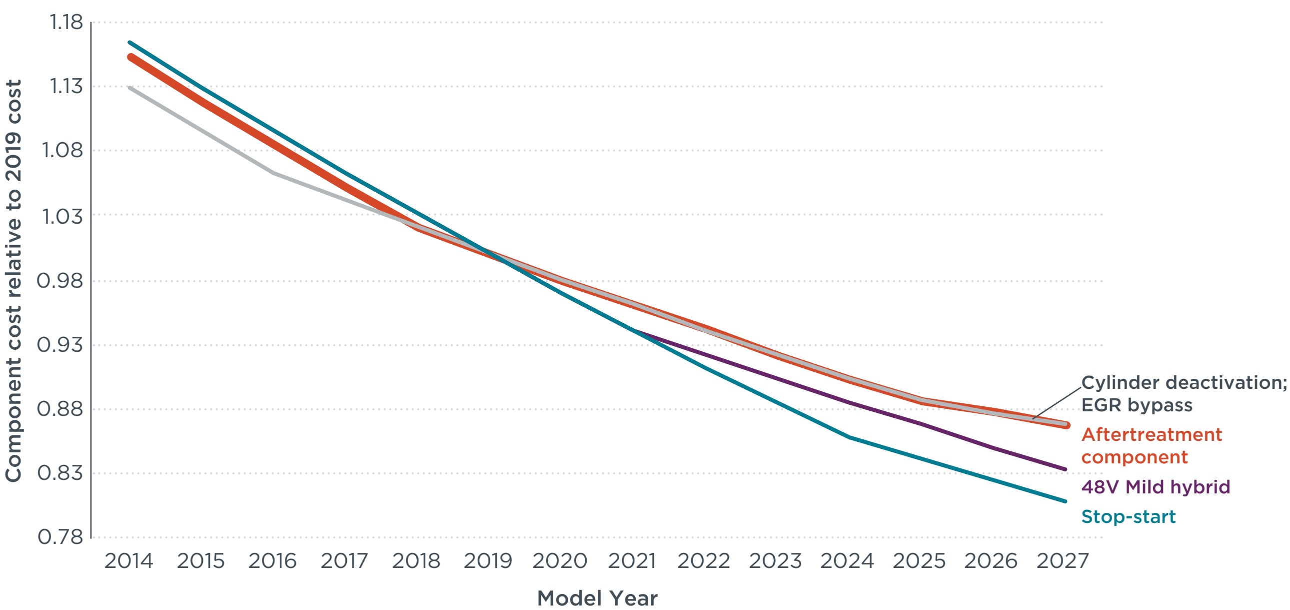

Figure 7. Learning curves for various low NO_x technologies, relative to 2019 (U.S. EPA, 2014, 2016).

INDIRECT COSTS AND TOTAL COSTS

This analysis also estimates indirect manufacturing costs and total manufacturing costs. Indirect costs include, for example, research and development, marketing, shipping, corporate operations, facility operations, and warranties. The best estimates for these costs also come from EPA rules, wherein most aftertreatment-related components are considered “near term” through 2024, thereby incurring higher indirect cost multipliers. As many indirect costs occur regardless of manufacturer learning, most of the indirect cost multipliers (ICMs) apply to the 2019 direct manufacturing cost. Warranty costs, however, are a major exception. These do decrease with learning, as the cost to replace a part declines with production cost. Table 11 summarizes these assumptions.

Table 11. Indirect cost multipliers (ICMs) for select NO_x control technologies. Adapted from U.S. EPA, 2016.

ICM complexity	Near term			Long term			Notes
	Warranty[a]	Non-warranty	Total[a]	Warranty[a]	Non-warranty	Total[a]	
Low	0.006	0.149	0.155	0.003	0.122	0.125	Aftertreatment components are near-term through 2024
Medium	0.022	0.213	0.235	0.016	0.165	0.181	CDA, EGR bypass are near-term through 2024
High1	0.032	0.249	0.281	0.016	0.176	0.192	MHEV near-term through 2024
High2	0.037	0.398	0.435	0.025	0.265	0.290	

Notes:
a. Warranty costs apply to learned direct manufacturing costs and therefore decrease with learning.
b. Total ICM is in the first year, after which warranty costs decrease with learning, but nonwarranty costs stay constant.

Algorithmically, the direct costs of technology, which decline over time with learning, are summed with associated indirect warranty and indirect nonwarranty costs from Table 11 to determine total retail cost excluding taxes as follows.

$$TC_{year} = (DMC_{base} \times LF_{year}) + (DMC_{base} \times ICM_{non\text{-}warranty}) + (DMC_{base} \times LF_{year} \times ICM_{warranty})$$

Where: TC_{year} = total technology cost in given evaluation year
DMC_{base} = base year direct manufacturing cost (as estimated in this study)
LF_{year} = learning factor in given evaluation year (see Figure 7)
$ICM_{non\text{-}warranty}$ = non-warranty indirect cost multiplier (see Table 11)
$ICM_{warranty}$ = warranty indirect cost multiplier (see Table 11)
base = base year
year = evaluation year

DURABILITY CONSIDERATIONS

CARB is proposing increasing the requirements for durability of emissions control components to 600,000 miles by 2027 and 800,000 miles by 2031 for class 8 HDVs and to 450,000 miles for Class 6–7 HDVs. Manufacturers will face additional costs to design and produce technology that meets those requirements.

To estimate the impact of the extended durability requirements, we assume two cases. First, the conventional case parallels the technology progression that occurred after the introduction of the EPA 2010 emission standards. Since that rule, manufacturers have made incremental improvements that together resulted in lower aftertreatment costs and smaller component sizes. This case assumes that manufacturers incrementally innovate to the point where an advanced aftertreatment system that today meets future NO_x requirements also meets future durability requirements. That is, neither an increase in size nor part replacement is required.

The second case assumes that future durability requirements will force changes in catalyst sizes and targeted component replacement. According to expert reviewers, the incremental volumes for DOCs and DPFs are expected to range between 15% and 20% to reach 2027 useful life (UL) targets and between 20% and 30% to reach 2031 final UL targets. For NO_x and NH_3 sensors, it is expected that a replacement may be needed, increasing cost by a factor of two.

Of course, today's technology will improve before the CARB proposal goes fully into effect and will continue improving thereafter. Therefore, the cost increases associated with meeting future durability requirements should be interpreted as only temporary. Learning and powertrain improvements are likely to bring down catalyst volume and component replacement rates.

EMISSION CONTROL COSTS

ENGINE CONTROL COSTS

This analysis considers costs from CDA and EGR bypass, two key engine technologies that reduce NO_x emissions by enabling and enhancing aftertreatment thermal control under cold start and low-load operation. Of these key technologies, cylinder deactivation abounds in the light-duty segment.

CDA technologies are widely deployed by manufacturers across LDV segments as meeting fuel-efficiency standards require their adoption. CDA is used by 12% of the LDV fleet in the United States (U.S. EPA, 2019b). In addition, CDA provides significant fuel savings under low-load conditions.

Because of technical similarities between light- and heavy-duty applications of CDA, heavy-duty CDA costs are expected to be roughly on a par with light-duty costs. For applications in which the number of deactivated cylinders varies, costs range from $38–$75 per cylinder (Isenstadt et al., 2016). Additional costs for heavy-duty engines could come from complementing CDA hardware with automatic lash adjusters that reduce maintenance costs of mechanical lash adjustments (Dorobantu, 2019; "Hydraulic Lash Adjuster," 2019). As a result, we estimate that CDA for heavy duty applications costs $75 per cylinder.

Bypass piping and bypass valves for high-pressure EGR cooler, charge air cooler, and turbine are assumed to scale as a function of engine displacement. The costs for all these technologies are presented in Table 12. Today's NO_x standards do not require CDA or bypasses, nor will they be required to meet the 2024 proposed standards. Both CDA and bypasses are expected for 2027. In Table 12, the costs presented include learning from today's costs.

Table 12. Costs of engine control technologies in 2027.

Technology	Direct		Indirect		Total	
	7L	13L	7L	13L	7L	13L
Bypass (pipe and valve)	$146	$211	$30	$43	$176	$254
Cylinder deactivation	$391	$391	$81	$81	$471	$471

Note: NO_x standards in 2024 are not expected to require the use of either CDA or any bypass.

AFTERTREATMENT COMPONENT COSTS

Baseline EPA2010 in 2019

Since the ICCT's original report on the cost of EPA 2010 technologies, incremental cost reductions have occurred because of manufacturer learning, transitioning to cheaper but more effective PGMs, and other improvements.

The DOC, DPF, SCR, and SCR/ASC all have three cost components: catalyst, canning, and hardware/accessories. Catalyst costs include substrate, wash coat, and PGM costs, whose costs have declined with manufacturer learning. Canning costs are assumed to have changed little for most systems since the previous cost assessment. DOC and DPF hardware costs are assumed to be largely unchanged, as these costs are mainly for mounting/attachment hardware (Table 13 and Table 14). The SCR system, on the other hand, requires much more than mounting hardware. In fact, we find SCR system hardware costs to be 50%–64% of the cost of the full SCR system, including the canned bricks (Table 15).

Table 13. DOC cost estimates for EPA 2010 technology in 2019.

Engine displacement, liters	**7.00**	**13.00**
Catalyst volume, CV (SVR=0.75)	**5.25**	**9.75**
Pt: (4/5) x 1.25 PGM g/liter x CV x $27/g	$144	$267
Pd: (1/5) x 1.25 PGM g/liter x CV x $47/g	$62	$115
Total PGM	**$205**	**$381**
Substrate ($7/L x CV)	$37	$68
Wash coat ($13/L x CV)	$68	$127
Total PGMs+ wash coat + substrate	**$310**	**$576**
Canning ($5/L x CV)	**$26**	**$49**
Accessories	$12	$14
Total manufacturing	**$348**	**$640**

Table 14. DPF cost estimates for EPA 2010 technology in 2019.

Engine displacement, liters	**7.00**	**13.00**
Catalyst volume, CV (SVR=1.4)	**9.80**	**18.20**
Pt: (3/4) x 0.097 PGM g/liter x CV x $27/g	$19	$36
Pd: (1/4) x 0.097 PGM g/liter x CV x $47/g	$11	$21
Total PGM	**$31**	**$57**
Substrate ($13/L x CV)	$132	$246
Wash coat ($13/L x CV)	$127	$237
Total PGMs + substrate+ wash coat	**$290**	**$539**
Canning ($5/L*CV)	**$49**	**$91**
Accessories – brackets	$31	$38
Regeneration system(a)	$81	$81
Total manufacturing	**$451**	**$749**

Note: (a) Regeneration systems includes differential pressure sensor, temperature sensor, wiring, additional engine control unit (ECU) processing capabilities and in some cases an oxygen sensor. It ***excludes OBD PM sensor.***

Table 15. Zeolite-based SCR+SCR/ASC cost estimates for EPA 2010 technology in 2019.

Engine displacement, liters	**7.00**	**13.00**
Catalyst volume, CV (SVR=2.7) for US2010	**18.6**	**34.6**
Precious metals not required. Base metals costs are negligible.	$0	$0
Ammonia slip catalyst (ASC) - CV (SVR=0.5), 0.11 g/L Pt x $27/g	$10	$19
Total PGM	**$10**	**$19**
Substrate ($13/L x CV)	$241	$448
Wash coat (Zeolites: $13/L x CV)	$241	$448
Total SCR catalyst: PGMs + substrate+ wash coat	**$493**	**$915**
Canning ($5/L*CV)	**$93**	**$172**
Urea tank volume, Liters (12 x Vd)	***84***	***156***
Urea Tank cost	$168	$312
Urea level sensor	$48	$48
Urea Tank accessories (brackets, bolts, spacers)	$31	$38
Urea pump	$118	$118
Urea dosing system (injector, pipe, mounting parts)	$175	$175
Tubing Stainless Steel	$84	$121
Temperature sensors (x2)	$30	$30
Mixer	$130	$200
Dosing Control Unit	$100	$100
NO_x sensors (x2)	$160	$160
Total urea system	**$1,045**	**$1,303**
Total manufacturing	**$1,631**	**$2,390**

With the updates described previously, costs for each component of a EPA 2010-compliant system were reassessed (Table 16). The following tables present these updated baseline cost estimates. Direct and indirect costs are presented. Compared with the ICCT's previous cost estimates, today's direct manufacturing system costs are about 33% less. The cost values projected for 2024 and 2027 serve as the baseline to compare the incremental cost of technologies to meet the corresponding envisioned targets in 2024 and 2027.

Table 16. Full EPA 2010 aftertreatment system direct manufacturing cost estimates in 2019, 2024, and 2027.

Engine displacement, liters	**7.00**	**13.00**
DOC direct manufacturing cost in 2019	$348	$640
DPF direct manufacturing cost in 2019	$451	$749
SCR+SCR/ASC direct manufacturing cost in 2019	$1,631	$2,390
DOC indirect manufacturing cost in 2019	$54	$99
DPF indirect manufacturing cost in 2019	$70	$116
SCR+SCR/ASC indirect manufacturing cost in 2019	$253	$371
Complete baseline total manufacturing cost in 2019	**$2,807**	**$4,365**
Complete baseline total manufacturing cost in 2024	**$2,570**	**$3,997**
Complete baseline total manufacturing cost in 2027	**$2,431**	**$3,769**

CARB proposal for 2024 and 2027

Experimental work shows that current aftertreatment systems are nearly capable of meeting the future 2024 standards, with some diesel engine families already certified to 0.05 g/bhp-hr or less over the composite FTP. Increasing SCR volume and incorporating the next generation of ASC could make today's systems compliant over the composite FTP and steady-state in 2024 (MECA, 2019). However, meeting the standards over the low-load cycle and under cold start conditions requires additional components with respect to 2019 technology. Based on the options discussed in the literature referenced above, we predict the additional components will be a heated second urea doser and accompanying sensors in 2024, with a close-coupled SCR/ASC.

The close-coupled SCR and corresponding ammonia slip catalyst (ccSCR/ASC) come with additional sensors and control hardware. Additional upstream hardware includes a heating system and proper support for heated urea dosing and additional temperature sensors. Costs for the ccSCR/ASC in 2019 are presented in Table 17.

Table 17. Close-coupled zeolite ccSCR+ASC with heated urea injection cost estimates for 2024 targets.

Engine displacement, liters	**7.0**	**13.0**
Catalyst volume, CV (SVR=1.0)	**7.0**	**13.0**
Precious metals not required. Base metals costs are negligible.	$0	$0
ccSCR ASC - CV (SVR=0.2), 0.106 g/L Pt x $27/g	$4	$8
Total PGM	**$4**	**$8**
Substrate ($15/L x CV)	$105	$195
Wash coat (Zeolites: $13/L x CV)	$91	$169
Total SCR Catalyst: PGMs + substrate+ wash coat	**$200**	**$372**
Canning ($5/L*CV)	**$35**	**$65**
Urea pump	$118	$118
Heated urea dosing system (heated injection, mounting, piping)	$325	$350
Tubing stainless steel	$34	$34
Temperature sensors (x2)	$30	$30
Mixer	$130	$175
Dosing control unit	$100	$100
NO_x sensors (x1)	$80	$80
Total urea system	**$817**	**$887**
Total manufacturing	**$1052**	**$1,324**

The 2024 underfloor SCR design has a similar cost structure as the 2019 design, with changes on catalyst volumes for the SCR and ASC components and one additional ammonia sensor. The underfloor SCR was assumed to have an SVR of 1.7, which added to the ccSCR volume results in 2019 SCR volume sizes of SVR=2.7. A similar treatment was given to the ammonia slip catalyst. The total 2024 SCR system compliant design has an underfloor ammonia slip catalyst with an SVR of 0.3. Urea tank volume is kept the same as in the 2019 design. The costs of the underfloor SCR+SCR/ASC for 2024 are shown in Table 18.

Table 18. Underfloor zeolite SCR+SCR/ASC cost estimates for 2024 targets.

Engine displacement, liters	**7.0**	**13.0**
Catalyst volume, CV (SVR=1.7)	**18.6**	**34.6**
Ammonia slip catalyst (ASC) - CV (SVR=0.3), 0.11 g/L Pt x $27/g	$6	$12
Total PGM	**$6**	**$12**
Substrate ($13/L x CV)	$150	$279
Wash coat (Zeolites: $13/L x CV)	$150	$279
Total SCR catalyst: PGMs + substrate+ wash coat	**$307**	**$569**
Canning ($5/L*CV)	**$58**	**$107**
Urea tank volume, Liters (12 x Vd)	***84***	***156***
Urea Tank cost	$168	$312
Urea level sensor	$48	$48
Urea Tank accessories (brackets, bolts, spacers)	$31	$38
Urea pump	$118	$118
Urea dosing system (injector, pipe, mounting parts)	$175	$175
Tubing Stainless Steel	$84	$121
Temperature sensors (x2)	$30	$30
Mixer	$130	$200
Dosing Control Unit	$100	$100
NO_x sensors (x2)	$160	$160
NH3 sensors (x1)	$120	$120
Total underfloor urea delivery system	**$1,165**	**$1,423**
Total manufacturing	**$1,529**	**$2,100**

The cost of the technology components to meet 90% reductions in FTP NO_x standards and additional low-load cycle requirements is presented in tables 19 to 22. Table 19 presents the cost associated with close-coupled SCR systems. It was assumed for this cost estimate that ccSCR components would retain the size of the SCR substrate compared with the 2024-compliant versions.

Table 19. Zeolite ccSCR+ASC with heated urea injection cost estimates for 2027 targets.

Engine displacement, liters	**7.00**	**13.00**
Catalyst volume, CV (SVR=1.0)	**7.00**	**13.00**
Precious metals not required. Base metals costs are negligible.	$0	$0
ccSCR+ASC (SVR=0.3), 0.106 g/L Pt x $27/g	$6	$12
Total PGM	**$6**	**$12**
Substrate ($15/L x CV)	$105	$195
Wash coat (Zeolites: $13/L x CV)	$91	$169
Total SCR Catalyst: PGMs + substrate+ wash coat	**$202**	**$376**
Canning ($5/L*CV)	**$35**	**$65**
Urea pump	$118	$118
Heated urea dosing system (heated injection, mounting, piping)	$325	$350
Tubing stainless steel	$34	$34
Temperature sensors (2x)	$30	$30
Mixer	$130	$175
Dosing control unit	$100	$100
NO_x sensors (x1)	$80	$80
Total urea system	**$817**	**$887**
Total manufacturing	**$1,047**	**$1,315**

We assume for 2027 that an SCRF, if implemented, takes the place of the DPF and the first of the downstream SCR bricks. In total the SCRF reduces aftertreatment volume by 10%–15% (D. A. Newman, 2018). Thus, we conservatively estimate the SCRF has SVR=2.0, and the remaining downstream SCR has SVR=1.8, corresponding to about a 10% reduction in total downstream aftertreatment size (including DOC). Though the SCRF currently is more challenging to manufacture than a DPF or SCR separately, we assume costs will decrease annually as manufacturers gain experience. Table 20 summarizes these cost assumptions.

Table 20. Zeolite SCRF cost estimates.

Engine displacement, liters	**7.00**	**13.00**
Catalyst volume, CV (SVR=2.0)	**14.00**	**26.00**
Substrate ($25/L x CV)	$350	$650
Wash coat ($13/L x CV)	$182	$338
Total PGMs + substrate+ wash coat	**$532**	**$988**
Canning ($5/L*CV)	**$70**	**$130**
Temperature sensors (2x)	$30	$30
Total manufacturing	**$632**	**$1,148**

If the DOC and DPF are combined into a single-brick zone-coated CSF, the combined brick may be significantly smaller than the two separate bricks (Sharp, 2019). Table 21 details the direct costs estimated for a CSF.

Table 21. CSF cost estimates.

Engine displacement, liters	**7.00**	**13.00**
Catalyst volume, CV (SVR=1.75)	**12.25**	**22.75**
Pt: (7/9) x 0.6 PGM g/liter x CV x $27/g	$156	$290
Pd: (2/9) x 0.6 PGM g/liter x CV x $47/g	$77	$143
Total PGM	**$233**	**$433**
Substrate ($15/L x CV)	$184	$341
Wash coat ($13/L x CV)	$159	$296
Total PGMs + substrate+ wash coat	**$576**	**$1,070**
Canning ($5/L*CV)	**$61**	**$114**
Accessories - brackets	$31	$38
Regeneration System [(a)]	$81	$81
Total manufacturing	**$750**	**$1,303**

Note: (a) Regeneration systems includes differential pressure sensor, temperature sensor, wiring, additional ECU processing capabilities and in some cases an oxygen sensor. It ***excludes OBD PM sensor.***

Lastly, all future aftertreatment system configurations include conventional downstream SCR+SCR/ASC, or just SCR/ASC if SCRF is present. Future downstream SCR and ASC costs are presented in Table 22. The costs for SCR/ASC alone, used in conjunction with an SCRF, are shown in italics.

Table 22. Zeolite SCR+SCR/ASC cost estimates (SCR/ASC-only costs in gray).

Engine displacement, liters	**7.0**	**13.0**
Catalyst volume, CV (SVR=2.9) for CARB2027	**20.4**	**37.9**
Precious metals not required. Base metals costs are negligible.	$0	$0
Ammonia slip catalyst - CV (SVR=0.5), 0.11 g/L Pt	$10	$19
Total PGM	**$10**	**$19**
Substrate ($13/L x CV)	$265	$493
Wash coat (Zeolites: $13/L x CV)	$265	$493
Total SCR catalyst: PGMs + substrate+ wash coat	**$541**	**$1,005**
Canning ($5/L*CV)	**$102**	**$189**
Catalyst volume, CV_{SCRF} (SVR=1.8) for ARB2027 w/SCRF	*12.66*	*23.51*
Substrate ($13/L x CV_{SCRF})	*$165*	*$306*
Wash coat (Zeolites: $13/L x CV_{SCRF})	*$165*	*$306*
Total SCR catalyst: PGMs + substrate+ wash coat	***$340***	***$631***
Canning ($5/L* CV_{SCRF})	***$63***	***$118***
Urea tank volume, liters (12 x Vd)	***84***	***156***
Urea tank cost	$168	$312
Urea level sensor	$48	$48
Urea tank accessories (brackets, bolts, spacers)	$31	$38
Urea pump	$118	$118
Urea dosing system (injector, pipe, mounting parts)	$175	$175
Tubing stainless steel	$84	$121
Temperature sensors (2x)	$30	$30
Mixer	$130	$200
Dosing control unit	$100	$100
NH_3 sensor (x1)	$120	$120
NO_x sensors (2x)	$160	$160
Total Urea system	**$1,165**	**$1,423**
Total manufacturing	**$1,808**	**$2,617**
For SCR+ASC only (SCRF) total manufacturing	***$1,568***	***$2,171***

Table 23 and Table 24 present the estimated costs of a 2024-compliant aftertreatment system in 2019 and in 2024. In the first configuration, which includes heated urea injection (HUI) with virtually no other changes, the cost is almost the same as the baseline configuration. By 2024, manufacturer learning leads to a net decrease in cost from today's baseline. The 2024 configuration 2, however, has 27%–39% higher cost today than the baseline in 2019 due to the added complexity from the ccSCR. By 2024, learning will have reduced these costs to 16%–27% more than baseline 2019 costs.

Table 23. Estimated 2024 aftertreatment costs in 2019.

Cost component	Direct		Indirect		Total	
Engine Displacement, L	**7**	**13**	**7**	**13**	**7**	**13**
2024 Configuration 1: DOC+DPF+(HUI)+SCR/SCR/ASC						
DOC	$348	$640	$54	$99	$402	$739
DPF	$451	$749	$70	$116	$521	$865
SCR/ASC	$1,730	$2,490	$268	$386	$1,998	$2,875
System	**$2,529**	**$3,878**	**$392**	**$601**	**$2,921**	**$4,480**
2024 Configuration 2: ccSCR/ASC+DOC+SCR/ASC						
ccSCR+ASC	$1,052	$1,324	$163	$205	$1,215	$1,529
DOC	$348	$640	$54	$99	$402	$739
DPF	$451	$749	$70	$116	$521	$865
SCR/ASC	$1,529	$2,100	$237	$325	$1,766	$2,425
System	**$3,381**	**$4,812**	**$524**	**$746**	**$3,905**	**$5,558**

Table 24. Estimated 2024 aftertreatment costs in 2024.

Cost component	Direct		Indirect		Total	
Engine Displacement, L	**7**	**13**	**7**	**13**	**7**	**13**
2024 Configuration 1: DOC+DPF+(HUI)SCR/ASC						
DOC	$315	$578	$54	$99	$368	$676
DPF	$408	$677	$70	$116	$477	$792
SCR/ASC	$1,562	$2,249	$267	$384	$1,829	$2,633
System	**$2,284**	**$3,503**	**$391**	**$599**	**$2,675**	**$4,102**
2024 Configuration 2: ccSCR/ASC+DOC+SCR/ASC						
ccSCR+ASC	$950	$1,195	$162	$204	$1,113	$1,400
DOC	$315	$578	$54	$99	$368	$676
DPF	$408	$677	$70	$116	$477	$792
SCR/ASC	$1,381	$1,897	$236	$324	$1,618	$2,221
System	**$3,054**	**$4,346**	**$522**	**$743**	**$3,576**	**$5,090**

Table 25 and Table 26 present total estimated costs for 2027-compliant systems. Table 25 shows that total future aftertreatment costs today are 40%–50% higher than a 2019 baseline EPA 2010 system. The cost-reduction effects from learning are presented in Table 26. These costs would be between 20% and 30% higher than today's system.

Table 25. Estimated 2027 aftertreatment system costs in 2019.

Cost component	Direct		Indirect		Total	
Engine displacement, L	**7**	**13**	**7**	**13**	**7**	**13**
2027 Configuration 1: CCSCR/ASC+DOC+DPF+SCR+SCR/ASC						
ccSCR+ASC	$1,047	$1,315	$162	$204	$1,210	$1,518
DOC	$348	$640	$54	$99	$402	$739
DPF	$466	$777	$72	$120	$538	$897
SCR+SCR/ASC	$1,808	$2,617	$280	$406	$2,088	$3,023
System	**$3,670**	**$5,348**	**$569**	**$829**	**$4,238**	**$6,177**
2027 Configuration 2: ccSCR/ASC+DOC+SCRF+SCR/ASC						
ccSCR+ASC	$1,047	$1,315	$162	$204	$1,210	$1,518
DOC	$348	$640	$54	$99	$402	$739
SCRF	$632	$1,148	$98	$178	$730	$1,326
SCR/ASC	$1,568	$2,171	$243	$337	$1,811	$2,508
System	**$3,596**	**$5,274**	**$557**	**$817**	**$4,153**	**$6,091**
2027 Configuration 3: ccSCR/ASC+CSF+SCR+SCR/ASC						
ccSCR+ASC	$1,047	$1,315	$162	$204	$1,210	$1,518
Zoned-CSF	$750	$1,303	$116	$202	$866	$1,505
SCR+SCR/ASC	$1,808	$2,617	$280	$406	$2,088	$3,023
System	**$3,605**	**$5,235**	**$559**	**$811**	**$4,164**	**$6,047**

Table 26. Estimated 2027 aftertreatment system costs in 2027.

Cost component	Direct		Indirect		Total	
Engine displacement, L	**7**	**13**	**7**	**13**	**7**	**13**
2027 Configuration 1: ccSCR/ASC+DOC+DPF+SCR+SCR/ASC						
ccSCR+ASC	$909	$1,140	$130	$164	$1,039	$1,304
DOC	$302	$555	$43	$80	$346	$635
DPF	$404	$674	$58	$97	$462	$770
SCR+SCR/ASC	$1,569	$2,271	$225	$326	$1,795	$2,598
System	**$3,184**	**$4,640**	**$457**	**$666**	**$3,641**	**$5,306**
2027 Configuration 2: ccSCR/ASC+DOC+SCRF+SCR+ASC						
ccSCR+ASC	$909	$1,140	$130	$164	$1,039	$1,304
DOC	$302	$555	$43	$80	$346	$635
SCRF	$548	$996	$79	$143	$627	$1,139
SCR/ASC	$1,360	$1,884	$195	$271	$1,556	$2,155
System	**$3,119**	**$4,575**	**$446**	**$657**	**$3,567**	**$5,232**
2027 Configuration 3: ccSCR/ASC+CSF+SCR+SCR/ASC						
ccSCR+ASC	$909	$1,140	$130	$164	$1,039	$1,304
Zoned-CSF	$650	$1,131	$93	$162	$744	$1,293
SCR+SCR/ASC	$1,569	$2,271	$225	$326	$1,794	$2,598
System	**$3,127**	**$4,542**	**$449**	**$652**	**$3,577**	**$5,194**

DURABILITY EFFECTS ON 2027 AND 2031 COSTS

This section looks at the impacts of increasing useful life requirements for emission control systems by 2027 and 2031. The 2027 proposal calls for increasing useful life to 600,000 miles from 435,000 miles for class 8 trucks and to 360,000 miles from 185,000 miles for class 6 and 7 trucks. Useful life requirements increase to 800,000 miles by 2031 for class 8 and to 450,000 miles for class 6–7. Suppliers and manufacturers have several years to make production-ready the next generation of control technology to comply with the CARB proposal for NO_x limits and durability. Increasing the SCR volume of today's aftertreatment system and coupling with a ccSCR replacement may be the simplest option for compliance in the future. After all, such a system would benefit from similarities to today's proven aftertreatment technology. Although cost reductions through learning may be lower with this architecture than the others evaluated, durability improvements may be easier to achieve because of the experience manufacturers already have with the commonplace components required for this system. On the other hand, SCRF and CSF manufacturing costs may decline faster than conventional filters and catalysts, though they could face greater useful life challenges as this technology has not been widely deployed in commercial applications.

Based on previous experience with tightening emission standards and lengthening durability requirements, manufacturers may initially increase the size of components to quickly adapt to the new regulation. As occurred under EPA 2010, learning over time will lead to more-compact components at lower manufacturing costs.

Increasing catalyst volume by 15%–20% to meet 2027 durability requirements and by 20%–30% for 2031 requirements and replacing sensors will initially increase costs in 2027 and 2031, as presented in Table 27. This is a worst-case scenario, and we expect that manufacturers will resolve durability issues in the next 7–10 years and aftertreatment system costs will decrease.

Table 27 shows that the estimated total cost to meet the most ambitious useful life requirements of 800,000 miles for Class 8 HDVs, and 450,000 miles for Class 6–7 in 2031 would result in costs that are similar to the 2027 technologies. This is a result of incremental cost associated with higher useful life requirements in 2031 being offset by manufacturing learning cost reductions.

Table 27. Estimated total emission control costs in 2027 and 2031 including corresponding extended durability requirements.

Durability case	**2027**		**2031**	
Engine displacement, L	**7**	**13**	**7**	**13**
2027 Configuration 1: ccSCR/ASC+DOC+DPF+SCR+SCR/ASC				
ccSCR+ASC (volume + NO_x /NH_3 sensors)	$1,185	$1,481	$1,157	$1,455
DOC (volume)	$409	$752	$414	$763
DPF (volume + sensors)	$526	$888	$528	$895
SCR+SCR/ASC (volume + NO_x /NH_3 sensors)	$2,229	$3,141	$2,196	$3,114
System	**$4,349**	**$6,263**	**$4,295**	**$6,227**
2027 Configuration 2: ccSCR/ASC+DOC+SCRF+SCR+ASC				
ccSCR+ASC (volume + NO_x /NH_3 sensors)	$1,185	$1,481	$1,157	$1,455
DOC (volume)	$416	$765	$424	$780
SCRF (volume)	$746	$1,361	$767	$1,400
SCR/ASC (volume + NO_x /NH_3 sensors)	$1,951	$2,625	$1,915	$2,593
System	**$4,298**	**$6,232**	**$4,263**	**$6,228**
2027 Configuration 3: ccSCR/ASC+CSF+SCR+SCR/ASC				
ccSCR+ASC (volume + NO_x /NH_3 sensors)	$1,185	$1,481	$1,157	$1,455
Zoned-CSF (volume)	864	$1,516	$871	$1,532
SCR+SCR/ASC (volume + NO_x /NH_3 sensors)	$2,229	$3,141	$2,196	$3,114
System	**$4,278**	**$6,139**	**$4,224**	**$6,101**

SYSTEM COSTS

CARB proposal 2024

Meeting the proposed 2024 NO_x standards is expected to be achieved via two pathways. One would require a heated injector in addition to the baseline configuration, or a second in which an upstream SCR would be introduced while keeping the same total SCR volume as the 2019 system.

The first configuration comes at a direct cost of around $100 in 2019 compared with today's system, but learning means that this 2024 system would actually cost less than today's baseline. The second 2024-compliant configuration would be on average one-third more costly by 2024 than the baseline EPA 2010 technology. The estimated total costs are summarized in Table 28.

Table 28. Full system costs to meet proposed 2024 standards in 2024 (From Table 24).

2024 Compliant aftertreatment costs	Total costs	
Engine displacement, L	**7**	**13**
Configuration 1	$2,675	$4,102
Configuration 2	$3,575	$5,090

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Table 29 lists estimated total costs for meeting future 2027 emission regulations, estimated for a 7.0 L and a 13.0 L engine. It combines the engine change costs (Table 12) with aftertreatment costs (Table 26), and the high-durability case (Table 27) all in the year 2027. Total costs include direct manufacturing and indirect costs.

Table 29. Full system total manufacturing costs to meet 2027 standards in 2027.

Engine costs	Low-cost durability case	High-cost durability case	Low-cost durability case	High-cost durability case
Engine displacement, L	**7**	**7**	**13**	**13**
Engine costs	**Low-cost durability case**	**High-cost durability case**	**Low-cost durability case**	**High-cost durability case**
EGR cooler bypass	$176	$176	$254	$254
Cylinder deactivation (CDA)	$471	$471	$471	$471
Total engine costs	$647	$647	$725	$725
Aftertreatment costs	**Low-cost durability case**	**High-cost durability case**	**Low-cost durability case**	**High-cost durability case**
Configuration 1	$3,641	$4,349	$5,306	$6,263
Configuration 2	$3,567	$4,298	$5,232	$6,232
Configuration 3	$3,577	$4,278	$5,194	$6,139
Full system costs	**Low-cost durability case**	**High-cost durability case**	**Low-cost durability case**	**High-cost durability case**
Configuration 1	$4,288	$4,996	$6,031	$6,988
Configuration 2	$4,214	$4,945	$5,957	$6,957
Configuration 3	$4,224	$4,925	$5,919	$6,864

INCREMENTAL COSTS TO MEET CARB PROPOSAL IN 2024 AND 2027

Future emission control systems will require a range of changes in terms of technologies to meet envisioned emission standards and test cycles. The environmental benefits provided by those technology changes would have an associated cost proportional to the stringency of the regulation. Tables 30 and 31 present our estimated absolute and incremental total costs to comply with CARB's envisioned regulations in 2024 and 2027. Incremental costs incurred by the regulatory proposal are estimated by subtracting the cost of baseline technology in compliance years 2024 and 2027 from the cost of future technology needed to meet the target.

Table 30 shows the incremental costs to meet envisioned 2024 targets. Baseline technology costs (EPA 2010 in 2024) were introduced in Table 16. The incremental cost to meet 2024 targets range from less than 5% to 30%–40% higher than today's aftertreatment systems. This implies that meeting a NO_x target that is 75% more stringent than current standards and meeting new low-load requirements would increase the cost of the emission control systems by less than the cost reductions achieved in the past 10 years of EPA 2010 implementation.

Table 30. Incremental total cost of the proposed 2024 NO_x standards as compared with EPA 2010 standards (in 2019 U.S. dollars).

Regulatory step	7 L	13 L
Baseline technology costs EPA 2010 in 2024	$2,570	$3,997
Total costs to meet CARB 2024	$2,675 – $3,575	$4,102 – $5,090
Incremental costs to meet CARB 2024	**$105–$1,005**	**$105–$1,093**

Table 31 shows the absolute and incremental cost to meet envisioned CARB 2027 targets. Two cost scenarios are presented for each engine size as a way to address the uncertainty on durability cost impact for future systems. The low-cost durability projections assume that manufacturers improve durability without significant component changes. The second case, high-cost durability, assumes component size changes and sensor replacements. Within each durability cost case and engine size, a range of cost values is presented reflecting the three technology configurations studied for the aftertreatment system.

Future emission control system costs in 2027 are 60%–100% higher than projected baseline technology costs in 2027. A combination of additional technologies and higher durability requirements result in additional $1,800–$2,600 to meet envisioned CARB 2027 standards for a class 6–7 HDV with a 7.0 L engine. For a class 8 truck with a 13 L engine, the incremental cost is estimated to range between $2,200 and $3,200. Engine-out emissions control corresponds to 10%–15% of that incremental value, while the rest reflects aftertreatment improvements.

Table 31. Incremental total cost of the proposed 2027 CARB standards as compared with EPA 2010 standards (in 2019 U.S. dollars).

Regulatory step	7 L		13 L	
Baseline technology costs EPA 2010 in 2027	$2,431		$3,769	
Total costs to meet CARB 2027	Low-cost durability case	High-cost durability case	Low-cost durability case	High-cost durability case
	$4,214–$4,288	$4,925–$4,996	$5,919–$6,031	$6,864–$6,988
Incremental costs EPA 2010 to CARB 2027	**$1,803–$1,877**	**$2,514–$2,585**	**$2,170–$2,282**	**$3,115–$3,239**

CONCLUSIONS

The challenge of meeting more-stringent emission targets, supplemental emissions testing at low load, and increased durability requirements can be meet with improvements to current emission control systems and adoption of a few new hardware components. Improvements needed to achieve the targets include close-coupled SCR systems, heated urea injection, and increased catalyst volumes. Close-coupled SCR systems are needed to address NO_x emissions during low-load operation, reducing the thermal mass to achieve quicker response from the SCR system. Heated urea injection reduces the need to heat up the exhaust mass flow, allowing for injections at lower exhaust temperatures while avoiding ammonia deposit formation.

New hardware modifications such as cylinder deactivation, already in adoption in LDV applications, are required to ensure meeting the NO_x targets under the low-load cycle. This type of technology enables better SCR thermal management by keeping the active cylinders at higher exhaust gas temperatures, eliminating the fuel consumption impact of traditional approaches such as late injections.

All of these technologies are already in production. Close-coupled catalysts were adopted for gasoline-vehicle emissions control in the United States since the Tier 2 standard was implemented in 2004. Manufacturers of diesel passenger cars in Europe have adopted twin SCR systems—close-coupled and underfloor—to meet the most stringent real-world emission standards. CDA technology has been adopted for large SUVs and light-duty trucks to improve fuel economy in the U.S. market.

We find that the expenses of meeting EPA 2010 standards in 2019 have fallen significantly from previous cost estimates. The costs of aftertreatment technology to meet the EPA 2010 standard have dropped by around 25%.

Meeting envisioned CARB 2024 targets would require very modest increases in technology complexity and costs. Technology changes are expected to occur in the urea dosing system of current aftertreatment system architectures. The costs of achieving a 75% reduction in NO_x emissions under the FTP and meeting new LLC standards are estimated to range between $100 and $1,000 for a class 6–7 vehicle with a 7.0 liter engine and between $100 and $1,100 for a 13.0 L class 8 HDV. The lower-cost option assumes a solution that is based on heated urea injection and improved catalysts. The higher-cost option assumes the adoption of close-coupled SCR systems, which would provide better emissions control during real world vehicle operation.

Meeting envisioned CARB 2027 targets would require significant changes in technology and costs, driven by 90% lower FTP targets, low-load cycle requirements, and longer useful life mandates. The technology changes are focused on improving thermal management and increasing the aftertreatment system's NO_x reduction efficiency and durability. To achieve that, cylinder deactivation and EGR bypass would be added to future engines. Aftertreatment changes would include the addition of a close-coupled SCR and changes to the urea dosing system. Extended useful life would be addressed with changes to catalyst volume and wash coat formulations and potential sensor replacement as a worst-case cost estimate in absence of sensor durability data. For class 6–7 HDVs with 7 L engines, this would result in additional total emission control costs of $1,800–$2,600 over baseline systems meeting the EPA 2010 standards in 2027. For class 8 HDVs with 13 L engines, we estimate an increment in total cost ranging from $2,200 to $3,200 compared with systems meeting the baseline EPA 2010 standards in 2027.

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