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Estimated cost of diesel emissions control technology to meet future Euro VII standards

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Introduction

Despite several announcements from manufacturers regarding the transition to zero-emission technologies, 99% of heavy-duty vehicles (HDVs) in the European Union (EU) are still powered with internal combustion engines.[1] Nitrogen oxide (NO_x) emissions from diesel engines have a substantial negative impact on air quality through the formation of particulate matter (PM2.5) and ground level ozone. Heavy-duty vehicles account for around 40% of NO_x emissions from road-transport in the EU (European Commission, 2018), while representing only 2.4% of the fleet (International Council on Clean Transportation, 2021). To cope with this issue, heavy-duty pollutant emission standards, currently at their sixth stage (Euro VI), have introduced increasingly stringent limits on pollutant emissions—including NO_x emissions—from heavy-duty engines. These policy interventions have forced manufacturers to innovate in the design of emission-control technologies to limit the concentration of pollutants in HDV exhaust, with additional costs incurred at each level of adopted stringency.

The European Commission is currently developing the requirements for the upcoming Euro VII standards. Cost-benefit analyses are a central element of European policy making, and Euro VII will not be the exception. Thus, it is important to have solid estimates on the incremental costs that manufacturers will have to incur to comply with new limits. This study aims to close that knowledge gap.

The Euro VII standards will likely require lower emission levels over a wider range of on-road operating conditions compared to what is currently mandated. Particular focus will be given to ensure that NO_x emissions remain at low levels under low-load conditions corresponding to urban driving and at low temperatures when the selective catalytic

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reduction (SCR) process is less efficient. Consequently, manufacturers will likely have to invest in additional technologies to comply with such new regulatory requirements.

Several technologies are currently being developed and proposed by industry stakeholders as potential solutions to meet Euro VII limits. In this paper, we assess the total manufacturing costs of the emission control systems—including both engine and aftertreatment technologies—that will likely be required to meet these limits. All estimates are based on a typical heavy-duty engine for a heavy-duty truck, which is the most representative HDV segment in Europe. Our bottom-up cost assessment builds upon ICCT's experience in this type of analysis (Cui et al., 2018; Posada et al., 2016, 2020). In particular, this study is largely based on ICCT's most recent assessment estimating the costs of diesel emission-control technologies to meet future heavy-duty pollutant standards in California (Posada et al., 2020). This study updates some of the previous cost estimates for individual components and captures the specificities of the technology pathways in the EU. The latter were informed by a thorough literature review and a continuous consultation with industry stakeholders.

Regulatory background

The evolution of the Euro standards stringency on NO_x emissions, up to the levels under discussion for the Euro VII stage, is summarized in Figure 1. NO_x emissions control is expected to be the main driver of incremental costs to meet the new standards. The Euro VII NO_x emissions limit is based on proposals presented by the CLOVE consortium,[2] which has been contracted by the European Commission to advise on the development of future pollutant emission standards. An official Euro VII proposal is expected in November 2021.

In its latest proposal from April 2021, the CLOVE consortium considered introducing a set of limits, accounting for different operating conditions including short trips, cold-start, and hot conditions.[3] The NO_x emissions limit of 80 mg/kWh would have to be demonstrated with a 90th percentile moving average window over the World Harmonized Transient Cycle, corresponding to hot conditions. A limit over the engine dynamometer cycle was not put forward by the CLOVE consortium. However, given that the 90th percentile evaluation is also currently used in the in-service conformity testing of Euro VI trucks, the 80 mg/kWh limit was used in Figure 1 to estimate the reductions in NO_x emissions from Euro VII over the transient engine dynamometer cycle.

2 The consortium for ultra-low vehicle emissions (CLOVE) consists of the Laboratory of Applied Thermodynamics (LAT) at the Aristotle University of Thessaloniki, Emisia, FEV, Ricardo, TNO, Graz University of Technology and VTT Technical Research Center of Finland.

3 Presented by the CLOVE consortium in the April 2021 Advisory Group on Vehicle Emission Standards (AGVES) meeting

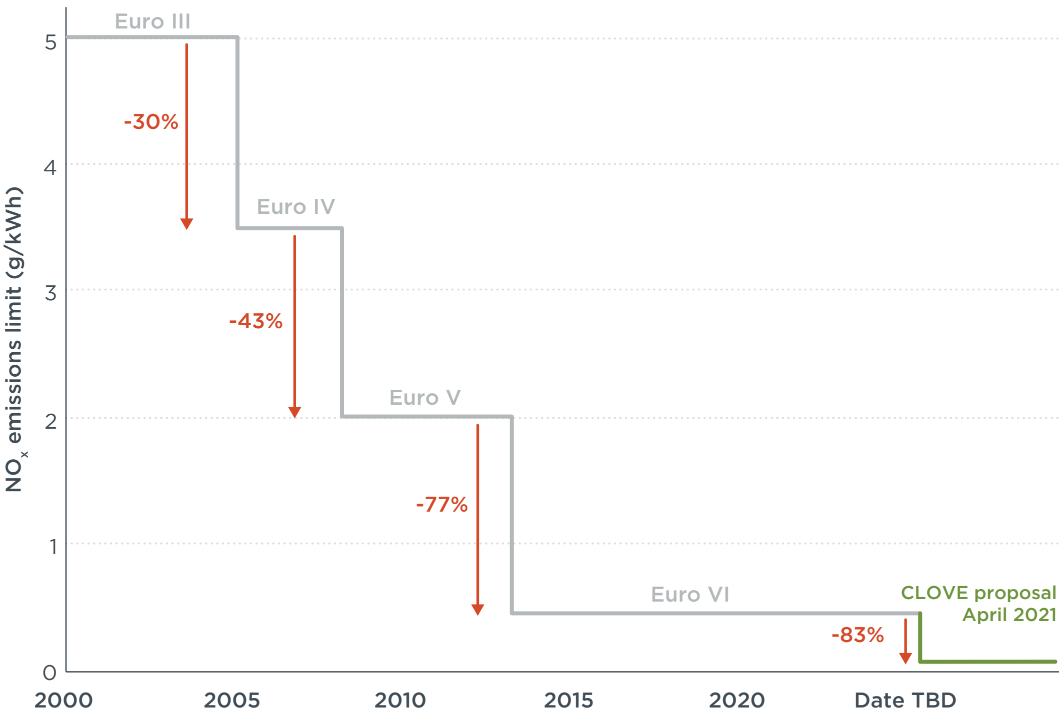

Figure 1. Evolution of the heavy-duty Euro pollutant emissions standards over the transient engine dynamometer cycle.

Compared to the previous stages, and based on CLOVE's proposal, the Euro VII standards will likely introduce additional considerations to ensure the real-world benefits of the regulation. To this end, a modification of the on-road test used in type-approval, in-service conformity, and market surveillance is expected, with an emphasis on shorter trips, low-load, and cold-start operation. These conditions are not evaluated by current on-road tests, leading to high emissions in urban operation (Badshah & Rodríguez, 2021). This upcoming modification of the on-road test procedure could have an even larger impact on the technology requirements and associated costs than the numerical values of the NO_x limits over the World Harmonized Transient Cycle presented in Figure 1.

While the date of application of the Euro VII standard is yet to be determined, it is expected that the new standards will come into effect between 2025 and 2030. This determines the analysis period of this study.

International context

The development of the Euro VII standards is one of several recent policy initiatives to update HDV pollutant emission standards globally. In 2020, the California Air Resources Board (CARB) adopted the Heavy-Duty Omnibus Regulation which sets increasingly stringent pollutant emission limits for 2024 and 2027. It also introduced several important amendments, including a new low-load engine test cycle, to better capture urban driving conditions, as well as extended durability and warranty provisions (California Air Resources Board, 2020). At the federal level, the U.S. Environmental Protection Agency (U.S. EPA) is pursuing the Cleaner Trucks Initiative to update NO_x emissions standards for heavy-duty trucks, with the intent to issue a proposed rulemaking in 2021 (U.S. Environmental Protection Agency, 2020). In China, the preparatory groundwork to develop China VII standards has also begun (VECC, 2021).

Although the limits considered in CARB's Heavy-Duty Omnibus Regulation are significantly more stringent than those put forward by the CLOVE consortium for Euro VII, these two new sets of standards aim to achieve similar levels of relative improvement from previous standards, as shown in Figure 2. According to the CLOVE consortium's latest proposal, the new set of limits should achieve a 90% reduction in NO_x emissions under low-load and cold start operation, corresponding to urban driving conditions. This relative improvement is similar to what is mandated by CARB's 2027 limit. Given that the aftertreatment technologies currently used to meet Euro VI and EPA 2010 standards are very similar, it can therefore be expected that similar technology upgrades will also be required to meet the new standards in both regions, yielding similar levels of incremental costs. However, the potential introduction of a wider range of operating conditions in the on-road test provisions under Euro VII, which might not be captured by CARB's low-load cycle, can lead to diverging technology pathways. Therefore, this study includes technology packages that go beyond those analyzed in the context of CARB's Heavy-Duty Omnibus Regulation.

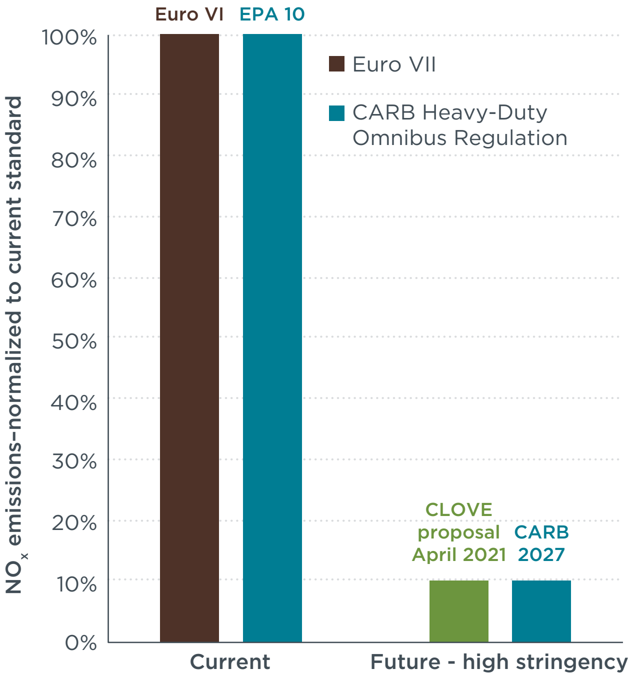

Figure 2. Comparison of the targeted NO_x reduction aimed by the CARB Heavy-Duty Omnibus Regulation and the CLOVE proposal for Euro VII.

To ensure that emission control systems maintain their performance as vehicles age, it is important to set adequate durability and warranty requirements as part of the pollutant emission standards. Sulfur oxides, unburned hydrocarbons, and lube-oil ash, among others, are known to have a poisoning effect on catalysts, which has a deteriorating impact on durability. Catalysts also tend to show deterioration with aging at high operating temperatures, although these high temperatures also increase their conversion efficiencies, therefore requiring a careful trade-off (Manufacturers of Emission Controls Association, 2019).

To this end, current Euro VI and EPA 2010 standards require that HDVs meet the pollutant emission limits at a full useful life (FUL) of 700,000 km.[4] It is expected that Euro VII standards will increase the useful life requirements; the CLOVE consortium recent proposal put forward a FUL of 1,200,000 km. For this study, we derived two possible scenarios for the final Euro VII proposal based on the targets of the CARB Heavy-Duty Omnibus Regulation to assess the sensitivity of EATS costs to durability requirement. In our "low ambition" scenario, we assumed that Euro VII would mandate

4 Euro VI: 700,000 km or seven years, whichever is the sooner. This applies to vehicles of category N3 with a maximum technically permissible mass exceeding 16 tonnes. EPA'10: 435,000 miles or 10 years, whichever comes first, for vehicles above 33,000 pounds gross vehicle weight rating.

an increase of 38% in FUL, based on the 2027 requirement of CARB regulation. In our "high ambition" we consider an increase of 84% in FUL, based on the CARB's target for 2031, as shown in Figure 3. The proposal from the CLOVE consortium is also showed.

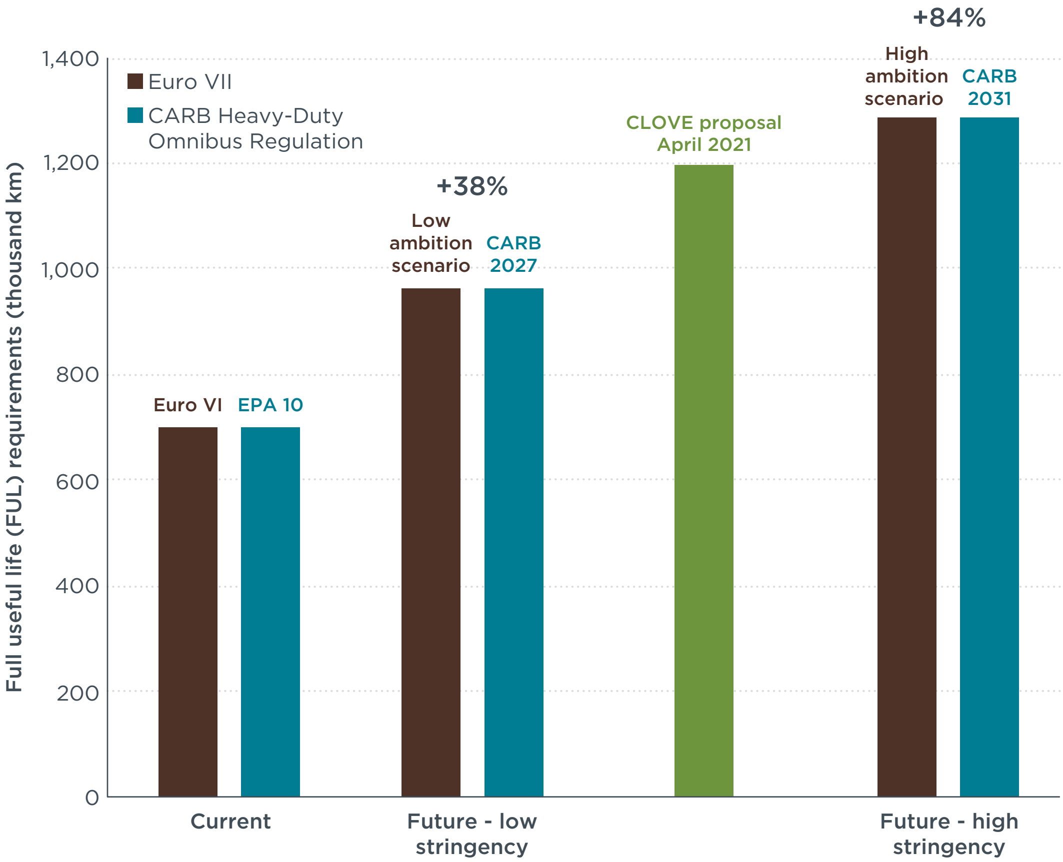

Figure 3. Current and future full useful life (FUL) requirements introduced by the CARB Heavy-Duty Omnibus Regulation and our scenarios for the sensitivity of EATS costs to durability requirements.

Emissions control technologies to meet Euro VII

Several technologies are available for emissions control in diesel engines. The current emissions control systems used to meet the Euro VI limits rely mainly on selective catalytic reduction (SCR) for NO_x emissions control. While SCR is very efficient under favorable engine operating conditions at bringing down NO_x emissions to very low levels, it has limitations in achieving similar performance under low-load and cold-start conditions, such as those encountered in urban driving (Badshah & Rodríguez, 2021). This requires the introduction of additional engine control and aftertreatment technologies. There are four main ways these technologies can help to achieve this:

» Reducing engine-out NO_x emissions

» Accelerating the SCR warm-up

» Keeping the SCR warm

» Improving the NO_x conversion efficiency of the warmed-up system

While some technologies can lead to a penalty in fuel economy, this is not the case for all of them. Many technologies exist that can simultaneously reduce NO_x and CO_2 emissions, and many more can reduce NO_x emissions without increasing CO_2 emissions. A comprehensive list of available technologies and their impact on both NO_x and CO_2 emissions is available in a previous ICCT study (Rodríguez & Posada, 2019). Here, we only review the individual technologies that were included in possible emission control packages to comply with the Euro VII standards.

Current Euro VI systems

While engine and HDV manufacturers have pursued slightly different technology pathways to meet the Euro VI standards, they typically rely on similar combinations of engine and aftertreatment technologies for emissions control. Present-day diesel engines are commonly equipped with common-rail injection. The engines are equipped with either variable geometry, two-stage, or asymmetrical twin-scroll turbochargers. Cooled high-pressure exhaust gas recirculation (HP-EGR) is widely used to reduce engine-out NO_x emissions with the SCR system being sized accordingly to be compliant. However, some manufacturers—in what is called the SCR-only approach—avoid the use of external EGR, resulting in higher engine-out emissions, and rely heavily on the SCR system for compliance. While there is little publicly available information on the chemical composition of commonly used SCR systems, it is widely understood that copper-based zeolites are the dominant technology, with a lower market penetration of vanadium-based SCR systems.[5] To comply with the 10-ppm ammonia limit, averaged over the World Harmonized Transient Cycle, ammonia slip catalysts (ASC) are widely used. For particle control, diesel particulate filters (DPF) are present in all Euro-VI compliant systems, heavily relying on a diesel oxidization catalyst (DOC) for passive and active regeneration. The complete exhaust aftertreatment system is all packed into a single underfloor box.

A typical Euro VI heavy-duty diesel aftertreatment system, which is used as the baseline of this study to assess incremental costs, is sketched in Figure 4.

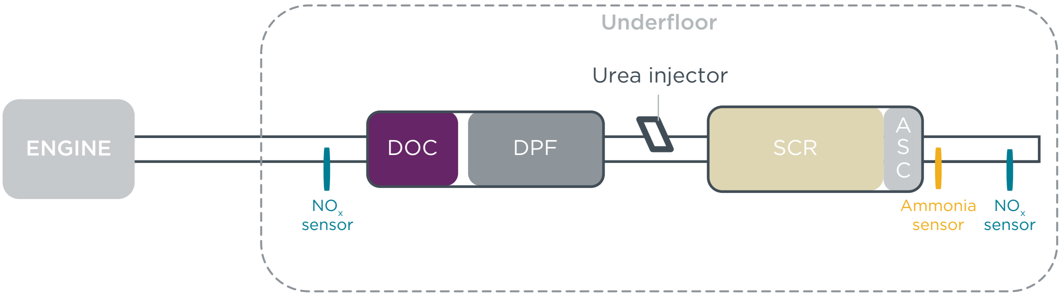

Figure 4. Typical Euro VI aftertreatment system layout. Components composed of multiple bricks in series are presented as a single unit.

Technologies proposed to meet Euro VII

Although the system described above already yields low NO_x emissions levels when the SCR reaches its maximum conversion efficiency of over 99% (Sharp et al., 2021), it is not as efficient at controlling NO_x emissions under low-load and low-speed conditions (Posada et al., 2020). To meet the potentially more stringent requirements from Euro VII, several upgraded emissions control technologies and aftertreatment configurations have been proposed by industry suppliers and manufacturer associations.

Based on this thorough literature review, and after consultations with industry experts, we assessed the costs of the most likely technologies that will be used to comply with future Euro VII standards. These technologies are summarized in Table 1.

5 Consultations with industry experts

Table 1. Technologies proposed to meet the Euro VII NO_x emissions limits.

Technology	Description
Close-coupled SCR (ccSCR)	Accelerates the catalyst warm-up. The total SCR volume is split in two, with one part moved upstream and close-coupled in the engine compartment, where the temperature of the exhaust gases is higher.
Close-coupled DOC (ccDOC)	Placed upstream of the close-coupled SCR stage, when applicable, to improve the SCR performance via NO_2 production.
SCR on particulate filter (SCRF)	Performs the SCR function on a filter substrate. Filtration is ensured in the upstream section of the SCRF brick, while the SCR function is performed downstream. Compared to a DPF + SCR configuration, the lower thermal mass enables improved thermal management. The SCRF does not use PGM as an oxidation catalyst, as the catalytic agent used on the SCRF is that of the SCR. That is, the SCRF acts as an uncatalyzed DPF with an SCR wash coat applied to it.
Passive NO_x adsorber (PNA)	Reduces the amount of NO_x in the SCR during warm up. Engine-out NO_x emissions are stored on the adsorber washcoat at low temperature (lean conditions) and released to the SCR at higher temperatures (rich conditions).
Electric catalyst heater (ECH)	Accelerates the catalyst warm up to light-off temperature and reduces cooling under low-load operation.
48-V system	Provides increased power to the electric catalyst heater for improved thermal management.
Cylinder deactivation (CDA)	Increases the exhaust temperature at low load to achieve faster SCR warm-up. CDA also enables increased fuel efficiency.
EGR cooler bypass	Reduces heat losses upstream of the SCR under cold-start conditions.
Heated urea dosing	Enables urea injection at lower exhaust temperatures and reduce the need for additional fuel burn for thermal management.

Selected layouts

We aimed at selecting a number of emissions control packages that cover most engine control and aftertreatment technologies proposed by industry stakeholders to meet the future Euro VII requirements. However, demonstrating that the emissions control configurations enable compliance with the proposal from the CLOVE consortium is outside of the scope of this analysis.

Compared to the baseline Euro VI system in Figure 4, all our configurations include features to accelerate the warm-up of the engine aftertreatment system (EATS) and to provide additional degrees of freedom for its thermal management to maintain temperature. We expect our proposals to yield a range of NO_x emissions reduction potentials coherent with the limit proposed by the CLOVE consortium (Figure 1).

Overall, compliance to the Euro VII limits will also likely require a reduction in engine-out NO_x emissions, necessitating enhanced engine control. Previous research suggested that bringing engine-out NO_x emission levels from around 5 g/kWh to 2 g/kWh would provide an additional 200 second delay for the EATS to reach its maximum NO_x conversion efficiency in order to meet the CARB 2027 limit under the heavy-duty diesel transient cycle (Hadl et al., 2021). Several technologies can enable this reduction in engine-out emissions. At low-loads, CDA has been shown to reduce engine-out NO_x by around 50% (Morris & McCarthy, 2020). Furthermore, the use of existing EGR systems in combination with the support of intake throttle valves enables higher EGR rates, lowering engine-out NO_x emissions immediately after the cold start (Hadl et al., 2021).

In our low-stringency emission control package, the Configuration 1 system sketched in Figure 5, a light-off SCR (LO-SCR) was placed upstream of the DOC and DPF, while still inside of the underfloor box. This leads to less space constraints than if it was in a close-coupled position in the engine compartment and avoids the cost premium on substrates associated with close-coupled elements. However, the downside is that the SCR warm-up is not as fast, requiring additional thermal management devices. Therefore, a heated urea injector was included upstream of the first SCR stage to allow low-temperature urea dosing. Additionally, a DOC was placed upstream of the EATS box, close-coupled in the engine compartment (ccDOC), facilitating the thermal management of the underfloor EATS box, and increasing the concentration of NO_2 to increase the conversion efficiency of the SCR system. Finally, an additional NO_x sensor and an additional ammonia sensor were added compared to the Euro VI-compliant system. Engine control technologies were unchanged compared to Euro VI. The resulting proposal is close to the HDV ultra-low NO_x demonstrator developed by the Association for Emissions Control by Catalyst and its partners (Bosteels, 2020).

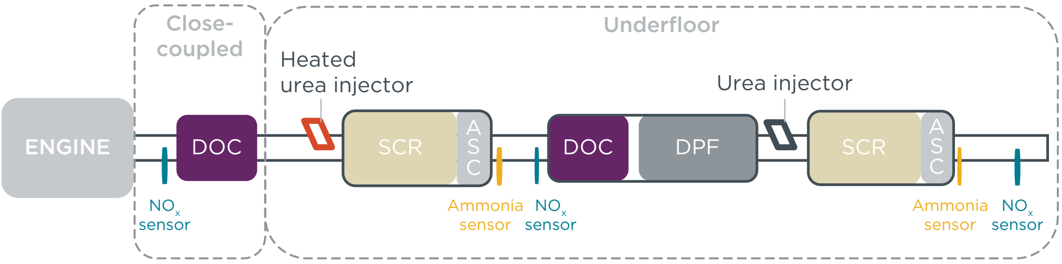

Figure 5. Potential emissions control configuration for future Euro VII requirements, Configuration 1.

In the Configuration 2 system, sketched in Figure 6, a platinum-group passive NO_x adsorber (PNA) was considered in a close-coupled position for low-temperature NO_x emissions control. An SCR on-filter (SCRF) replaced the DPF and part of the original SCR volume, compared to the Euro VI system of Figure 4. By combining the DPF and SCR functions in a single brick, the total catalyst volume can be reduced, resulting in a lower thermal mass which enables faster catalyst warm-up. Enhanced engine control technologies were also considered for this configuration, namely CDA and EGR cooler bypass, to enable fast warm-up and active thermal management to stay warm. Finally, an additional ammonia sensor was added to the Euro VI EATS.

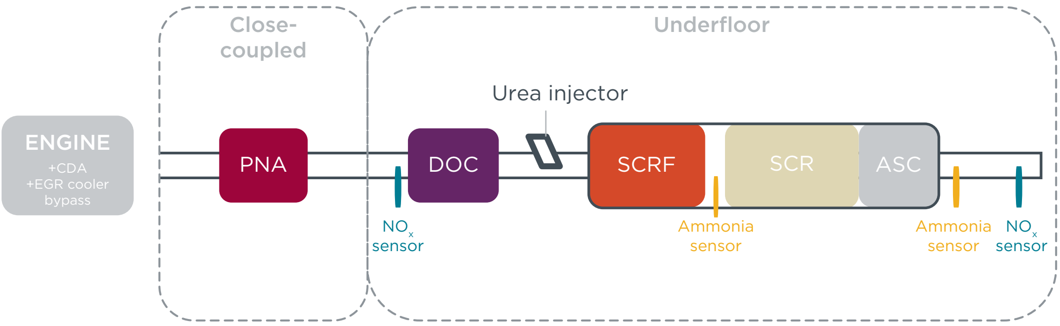

Figure 6. Potential emissions control configuration for future Euro VII requirements, Configuration 2.

Finally, Configuration 3, sketched in Figure 7, corresponds to the higher-stringency layout. As in the previous configuration, CDA and EGR cooler bypass were added for enhanced engine control. In this configuration, an SCR stage was close coupled (ccSCR) in the engine compartment, representing approximately one quarter of the total SCR volume, based on the optimum found by previous research (Harris et al., 2019). Additionally, an electric catalyst heater (ECH) was placed upstream of the close-coupled DOC for even faster warm-up. Two applications were considered for the ECH. In the first case, its power was capped at around 7 kW, limited by the constraints imposed by the 24-V network currently installed on European trucks. The heating power was deemed sufficient to substitute the functionality of the heated urea injector—which requires around 2 kW of heating power—while also complementing the CDA and EGR cooler bypass in the thermal management of the EATS. In the second case, a 48-V system was considered, enabling around 14 kW of heating power, significantly accelerating the warm-up of the EATS and enabling a more important role in thermal management in addition to the engine technologies already described. It was assumed that only half of the 48-V technology cost can be attributed to pollutant emissions control, the rest being attributed to CO_2 emissions reduction. In this case, it was also assumed that there was no need for an additional heated urea injector.

According to (Hadl et al., 2021), such a configuration with two SCR stages and an ECH can comply to the CARB 2027 targets, even under the low-load cycle.

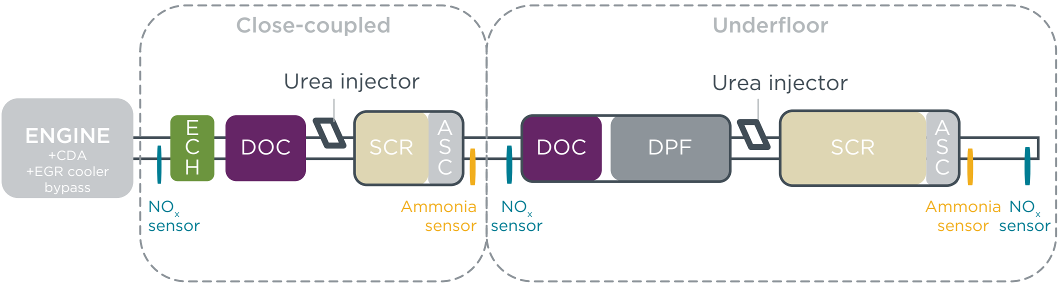

Figure 7. Potential emissions control configuration for future Euro VII requirements, Configuration 3.

The emissions control packages described above served as the basis for assessing the total system costs and incremental costs of meeting the potential Euro VII targets compared to the baseline Euro VI compliant system. Table 2 summarizes the technologies used in each configuration.

Table 2. Selected Euro VII emission control system proposals for which total manufacturing costs were assessed in this study.

Technologies	Baseline (Euro VI)	Configuration 1	Configuration 2	Configuration 3
Engine-out				
EGR loop	Cooled HP-EGR	Cooled HP-EGR	Cooled HP-EGR / EGR cooler bypass	Cooled HP-EGR / EGR cooler bypass
Cylinder deactivation	-	-	CDA	CDA
Electric network	24 V	24 V	24 V	24 V or 48 V
Aftertreatment				
Oxidation catalyst	DOC	DOC	DOC	DOC
Particulate filter	DPF	DPF	SCRF	DPF
NO_x and ammonia control	SCR and ASC	SCR and ASC	SCR and ASC	SCR and ASC
Cold-start and low-load NO_x control	-	ccDOC underfloor LO-SCR	PNA	ccDOC, ccSCR ECH
Aftertreatment configuration	Figure 4	Figure 5	Figure 6	Figure 7

Cost estimation methodology

The cost estimation methodology was largely based on a previous ICCT study, which we refer to as the *reference study*, carried out in the contexts of CARB's Heavy-Duty Omnibus Regulation (Posada et al., 2020). In this section, we summarize key cost estimates from the reference study, provide an update on the costs of several components based on the discussions with industry experts, and compare ICCT's estimates with other publicly available sources.

Literature review and comparison

As part of the development of the CARB Heavy-Duty Omnibus Regulation, the National Renewable Energy Laboratory (NREL) gathered incremental cost estimates for potential diesel emissions control technologies to meet the 2027 limit of 0.02 g/bhp-hr via a series of surveys sent to suppliers and manufacturer associations (Lynch et al., 2020). The study was based on the emission control systems proposed by Southwest Research Institute (Sharp, 2019).

While the response to the survey did not include a bottom-up cost assessment of each technology, the overall costs were still broken down into individual components, enabling comparison with the reference study.

Results from both studies differed considerably regarding indirect costs (up to several orders of magnitude), resulting in large deviations in total system costs. However, indirect costs in the NREL study were mainly driven by warranty costs, which is not relevant to Euro VII considerations. Direct manufacturing costs (DMC) were similar in both studies. Two of the EATS configurations assessed in NREL's survey, namely their average-cost and low-cost configurations, were close to one used in the ICCT reference study. These consisted of a close-coupled light-off SCR/ASC stage, a DOC, a DPF and an underfloor SCR/ASC stage. In terms of engine controls, one of the NREL concepts was equipped with CDA while the other combined EGR cooler bypass, charge air cooler bypass, and turbine bypass. Component by component incremental costs for these three layouts can therefore be compared, as shown in Figure 8.

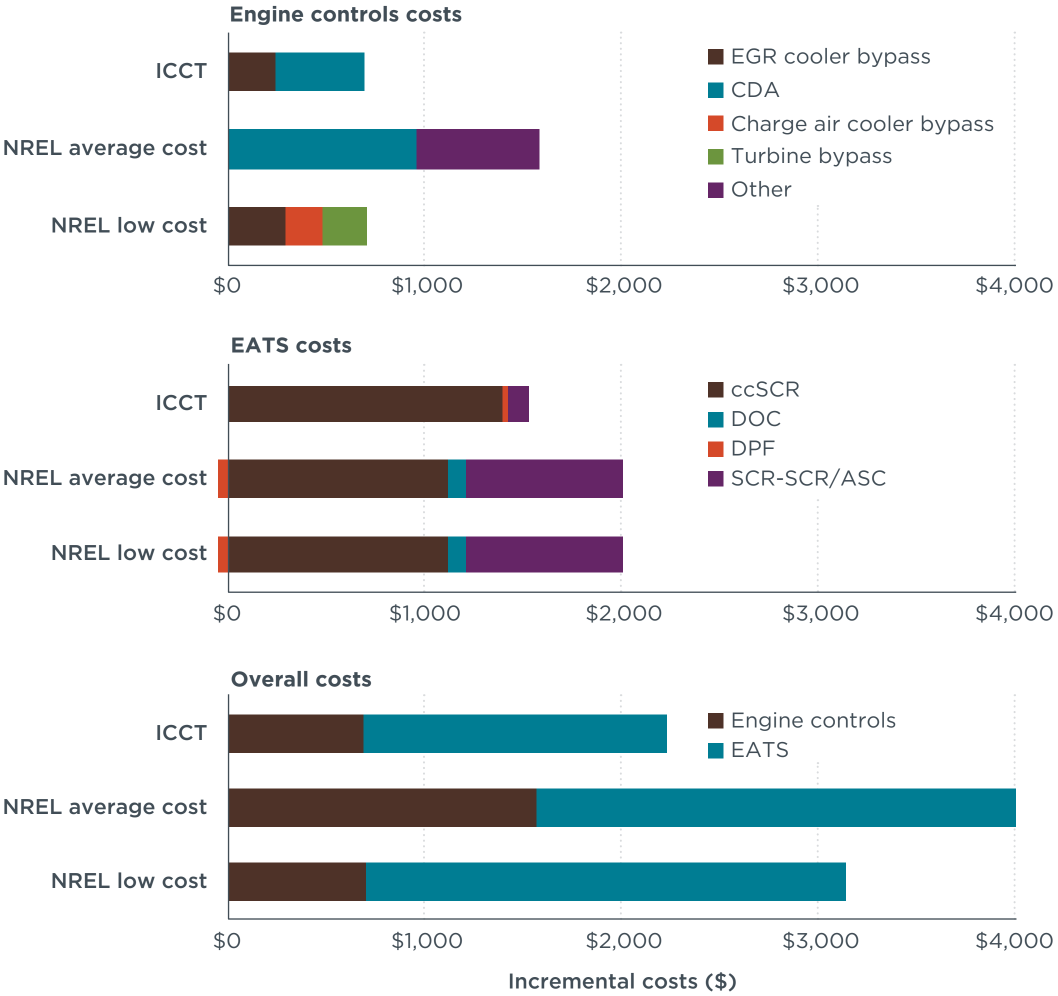

Figure 8. Comparison of the incremental direct technology cost estimates obtained by NREL (Lynch et al., 2020) and ICCT (Posada et al., 2020) for compliance to the California Heavy-Duty Omnibus Regulation.

Overall, similar orders of magnitude were obtained in the incremental cost estimates of both studies, although there were some significant differences for a few technologies. For instance, the NREL survey's cost estimate for CDA was about double that of the ICCT's reference study, or $952 and $450, respectively. Most importantly, for the underfloor SCR/ASC stage, the incremental cost estimates from NREL's survey were seven times higher than those estimated by the ICCT, or $784 and $107, respectively.

According to the ICCT's methodology, the incremental costs from the underfloor SCR correspond to a 10% increase in catalyst volume. Using the same rationale, the incremental costs gathered by NREL would correspond to a 74% increase in volume. While we believe this is higher than the volumes needed to meet the CARB limits, it is difficult to gain more insight into how the survey response was obtained. Therefore, we did not adjust ICCT's reference study estimates using NREL's estimates, and only used the latter for estimating the costs of PNAs.

Component cost estimates

Most of the technologies summarized in Table 2 were assessed in the reference study. Cost assumptions were mostly carried forward from the reference study, with some EU-specific adjustments, and were updated to account for manufacturer learning between 2019 and 2021, according to the methodology described below. When missing, costs were obtained from literature and validated by consultations with industry experts to ensure that all assumptions are coherent with the stringency of the CLOVE consortium's proposed emissions limits. The costs of passive NO_x adsorbers, electric catalyst heating and 48-V systems were not covered and are therefore based on estimates from other studies, as discussed below.

All costs were based on a 13-liter, 330-kW engine for heavy-duty truck applications. Total costs for the engine control and aftertreatment systems were broken down into direct manufacturing costs and indirect costs. It is worth noting that we focused on manufacturing costs only. Costs not covered include operational costs, such as the cost of diesel exhaust fluid (AdBlue), and maintenance costs. Additionally, the price impacts for the customers were not assessed here, as pricing strategies do not necessarily follow manufacturing costs. We obtained estimates for the direct manufacturing costs via a bottom-up cost assessment for each of the aftertreatment component being evaluated, with each assumption representing a cost item.

Diesel oxidation catalysts (DOC)

Table 3 summarizes the main assumptions for the DOC costs. All catalyst volumes were defined using the swept volume ratio (SVR), which is the ratio of catalyst volume to engine displacement volume. For our Configuration 1 and 3 systems (Figure 6 and Figure 7, respectively), where the DOC is close-coupled in the engine compartment, we included a 25% premium on substrate costs based on feedback from industry experts. This markup accounts for the expected substrate redesign to feature thinner walls, higher porosity, and increased resistance to dynamic temperature conditions.

Table 3. Diesel oxidation catalyst assumptions. Source: Reference study and EU-specific expert review.

Parameter	Value
Swept volume ratio (SVR)	0.75
PGM loading	1.25 g/L
Pt:Pd loading	4:1
Substrate cost	€5.9/L
Substrate cost – close-coupled	€7.4/L
Wash coat cost	€10.9/L
Canning cost	€4.2/L

Diesel particulate filters (DPF)

Table 4 summarizes the main assumptions for the DPF. For DPF systems in Euro VII applications, and based on feedback from industry experts, we assumed a 10% price premium on the substrate costs for improved ash capacity and filtration efficiency compared to the baseline system.

Table 4. Diesel particulate filter assumptions. Source: Reference study and EU-specific expert review.

Parameter	Value
Swept volume ratio (SVR)	1.4
PGM loading	0.097 g/L
Pt:Pd loading	3:1
Substrate cost – Euro VI	€11.3/L
Substrate cost – Euro VII	€12.6/L
Wash coat cost	€10.9/L
Canning cost	€4.2/L

Selective catalytic reduction (SCR)

The costs of SCR systems were estimated for copper-zeolite catalysts, as summarized in Table 5, Table 6, and Table 7. For the Euro VI system, the total SCR volume was assumed to be the same as for the EPA 10 system, that is SVR = 2.65. In Configuration 1 (Figure 5), we assumed no increase in the total SCR volume. The total volume was split equally between the LO-SCR and downstream SCR stages, resulting in both having SVR = 1.33. No premium was added on the substrate costs for the LO-SCR, as it was placed upstream of the underfloor EATS box. Additionally, the cost of the heated urea injection system was accounted for in the cost of the LO-SCR, as shown in Table 6. The rest of the urea dosing system and sensors costs are unchanged between the LO-SCR and underfloor SCR stages. The cost of the urea tank and dosing control unit were accounted for in the underfloor SCR costs only.

Table 5. Underfloor SCR/ASC assumptions. Source: Reference study and EU-specific expert review.

Parameter	Value
Baseline (Euro VI)	
Swept volume ratio (SVR)	2.65
ASC SVR	0.5
Configuration 1	
Swept volume ratio (SVR)	1.33
ASC SVR	0.25
Configuration 2	
Swept volume ratio (SVR)	1.81
ASC SVR	0.31
Configuration 3	
Swept volume ratio (SVR)	2.92
ASC SVR	0.5
Common to all	
ASC PGM loading (Pt only)	0.11g/L
Substrate cost	€5.9/L
Wash coat cost	€10.9/L
Canning cost	€4.2/L
Urea system	
Urea tank volume	12 x engine displacement
Urea tank cost	€1.7/L
Urea level sensor	€40
Urea dosing pump	€99
Urea dosing system (injector, pipe, mounting)	€148
Dosing control unit	€84
Urea tank accessories (brackets, bolts, spacers)	€30
Tubing	€102
Mixer	€147
Temperature sensor	€12.5 each
NOx sensor	€67 each
NH3 sensor	€101 each

In Configuration 3 (Figure 7), which we assumed to have the highest NO_x reduction potential of all three options, we assumed a 10% increase in the volume of the underfloor SCR stage for increased NO_x conversion efficiency. This is also expected to improve the SCR system durability (Sharp et al., 2021). Additionally, as compared to Configuration 2, the LO-SCR was close-coupled (ccSCR) in the engine compartment and we therefore added a premium of 25% on substrate costs. This cost markup, based on feedback from industry experts, captures the expected substrate redesign to feature thinner walls, higher porosity, and increased resistance to dynamic temperature conditions. In the closed-couple configuration, a smaller volume was assumed to accommodate for space constraints and reduce the thermal mass of the catalyst for faster warm-up. The ccSCR stage of Configuration 3 therefore has a SVR of 1.0, based on the reference study and according to previous research from Southwest Research Institute (Sharp et al., 2021).

Table 6. Light-off SCR/ASC assumptions. Source: Reference study and EU-specific expert review.

Parameter	Value
Configuration 1 (underfloor EATS box)	
Swept volume ratio (SVR)	1.33
ASC SVR	0.25
Substrate cost	€6/L
Configuration 3 (close-coupled in the engine compartment)	
Swept volume ratio (SVR)	1.0
ASC SVR	0.31
Substrate cost	€7.4/L
Common to all	
ASC PGM loading (Pt only)	0.11g/L
Wash coat cost	€10.9/L
Canning cost	€4.2/L
Urea system	
Urea dosing pump	€99
Urea dosing system (injector, pipe, mounting)	€150
Heated urea dosing system (injector, pipe, mounting)	€294
Tubing	€102
Mixer	€147
Temperature sensor	€12.5 each
NOx sensor	€67 each

In Configuration 2 (Figure 6), the SCRF replaced the DPF and part of the underfloor SCR stage. As abovementioned, this reduced the required catalyst volume by 10%-15%, resulting in a lower thermal mass (Posada et al., 2020). Hence, according to the reference ICCT study, we assumed that the SCR stage had SVR = 2.0, and subsequently set the SCR volume so that it yielded a 10% reduction in the total catalyst volume. This resulted in the SCR stage of Configuration 2 having SVR = 1.81. Table 7 summarizes the assumptions for the SCRF. The SCRF has high substrate costs as it has to ensure the filtering function on a smaller volume than with a traditional DPF, leading to higher material and manufacturing costs.

Table 7. SCRF assumptions. Source: Reference study.

Parameter	Value
Swept volume ratio (SVR)	2.0
Substrate cost	€21/L
Wash coat cost	€11/L
Canning cost	€4.2/L

Passive NO_x adsorbers (PNA)

Passive NO_x adsorbers are one option for improved NO_x emissions control at low load, storing NO_x before the SCR warms up to its light-off temperature and releasing it subsequently. While this makes it a promising option to meet future Euro VII requirements, research also found that PNAs require high rates of active sulfur regeneration, which can result in CO_2 penalties and durability issues.[6] Despite the

6 Consultations with industry experts

uncertainty on the commercial viability of this technology, it has been assessed in the past in the context of CARB's Heavy-Duty Omnibus Regulation (Sharp, 2019). Thus, we included PNAs in Configuration 2 (Figure 6).

As the costs of the PNA were not assessed in the reference study, we obtained the cost assumptions for these technologies from previous studies. The PNA cost estimate from NREL's survey (Figure 8) was used as our base assumption, as shown in Table 8. For the engine size analyzed in this study, we estimate this technology's cost at € 1,900 (Lynch et al., 2020). Although NREL presented a single, averaged value for the cost of PNAs, there was actually a wide range of estimates from their survey, covering different technology pathways in terms of precious metal loading—most notably rhodium—amongst others.

Table 8. PNA assumptions. Source: Lynch et al. (2020)

Parameter	Value
Direct manufacturing costs	€1,907

Electric catalyst heaters (ECH)

Electric catalyst heaters were first developed in the 1990s as a way to increase the exhaust gas temperature and in turn catalyst efficiency, but never reached significant market penetration. However, due to today's increased levels of hybridization, e-catalysts are being considered again as way to control emissions in light- and medium-duty vehicles with no associated fuel consumption penalty due to the improved thermal management (Vitesco Technologies, 2020).

Improved thermal management will be crucial in meeting more stringent NO_x emissions limits over a wider range of operating conditions. The addition of an ECH has been shown to substantially accelerate the SCR warm-up under California's low-load cycle and the cold phase of the Heavy-Duty Diesel Transient Cycle while exhibiting low tailpipe N_2O emissions (Hadl et al., 2021). In this regard, ECH act complementary to other active thermal management technologies such as CDA and EGR cooler bypass.

Previous estimates suggest that a heating power between 4 kW and 7 kW would be sufficient to complement CDA in some low-load and cold-start conditions, and would enable faster urea dosing (Hadl et al., 2021; Vitesco Technologies, 2020; Sharp et al., 2017). At this power rating, sufficient power could be supplied to the ECH by the 24-V networks currently installed in European truck. However, according to our consultations with industry experts, if the ECH is to ensure the full thermal management, it will require higher power ratings of up to 14 kW, requiring a 48-V system to provide the sufficient power. For the electric catalyst heater in Configuration 3, we used the cost assumptions shared with us during consultations with industry stakeholders. The cost of the heating device would be around €210, while the controller and power electronics would amount to around €630, for a total cost of approximately €840, as summarized in Table 9.

Table 9. Electric catalyst heater assumptions. Source: EU-specific expert feedback

Parameter	Value
Resistive coil (heater)	€210
Power electronics	€630

48-V system, EGR cooler bypass and cylinder deactivation (CDA)

Today, trucks in Europe are equipped with 24-V electrical networks to power engine and other accessories. Discussions are currently open as to whether 48-V systems, which are now common in passenger cars and light commercial vehicles, should also be implemented in HDVs. Several CO_2 and pollutant emissions reduction technologies would benefit from mild hybridization and, according to our consultations with industry experts, the adoption of such mild hybrid systems would likely be driven by compliance with the CO_2 emissions standards.

In terms of exhaust emission control, the main application of 48-V systems would be to provide more power to the ECH for improved thermal management. As discussed in the previous section, up to 14 kW peak power could be provided for catalyst heating, resulting in faster SCR warm-up for better NO_x control under low-load and cold-start conditions. Research on light-duty vehicles also suggests that a mild hybrid system would enhance PNA performance by stabilizing engine torque fluctuations, which can interrupt PNA regeneration (Demuynck et al., 2019). We therefore assessed 48-V systems as one technology option for emissions control to meet future Euro VII requirements.

According to consultations with industry experts, several architecture options are currently available for the mild hybrid system integration. Under a P1 architecture, which is currently viewed by some industry stakeholders as the most cost-effective option for compliance with the upcoming CO_2 emissions targets, a full 48-V system would cost around $2,500. Since only half of the power provided by the 48-V system would be consumed by the ECH, with the other half consumed by other electrified accessories and auxiliaries, we attributed half of the technology cost to emissions control. The 48-V system cost covers the elements presented in Table 10. We assumed that the battery size and costs will mainly be driven by the requirements on CO_2 emissions reduction and therefore do not include it in the costs associated with emissions controls.

Table 10. 48-V Mild hybridization assumptions. Source: EU-specific expert review.

Components	Full system value
DC/DC converter	€2,100
Starter	
Motor-generator	
Liquid cooling system	

Finally, the cost assumptions for the engine control technologies are summarized in Table 11. As in the reference study, and due to technical similarities, the cost of CDA for heavy-duty applications was assumed to be similar as for light-duty vehicles in which it is widely used and for which costs are well documented (Isenstadt et al., 2016). The cost for heavy-duty applications was assumed at the upper end of light-duty vehicle costs to account for potential additional technologies, such as automatic lash adjusters. The costs for the EGR cooler bypass were obtained from light-duty vehicle teardowns and scaled to heavy-duty applications based on engine displacements (Posada et al., 2020).

Table 11. Engine controls assumptions. Source: Reference study and EU-specific expert review.

Parameter	Value
Bypass valve cost (light-duty)	€155
Bypass pipe cost (light-duty)	€62
CDA cost	€63/cylinder

Cost reduction by learning

The costs of in-cylinder and aftertreatment technologies are assumed to reduce with time as manufacturers improve their processes and benefit from larger production volumes. In the meantime, truck prices have increased by about 1% per annum over the past few years, resulting in aftertreatment costs representing an increasingly small share of a total truck price (Manufacturers of Emission Controls Association, 2020).

In this study, cost reduction is accounted for using the set of learning curves in Figure 9, initially developed by the U.S. Environmental Protection Agency as part of their regulatory impact assessment of the Phase 2 GHG and fuel efficiency standards (U.S. EPA & U.S. DOT, 2016) and updated for this study to obtain parity in 2021. The direct manufacturing costs for each technology are therefore decreased using a multiplier, obtained from the corresponding curve from U.S. EPA & U.S. DOT (2016). Therefore, as well as estimating current technology costs, we also estimated the projected costs of emission control technologies in MY 2025 and 2030, which we consider as the earlier and later possible implementation dates of the Euro VII standards, respectively.

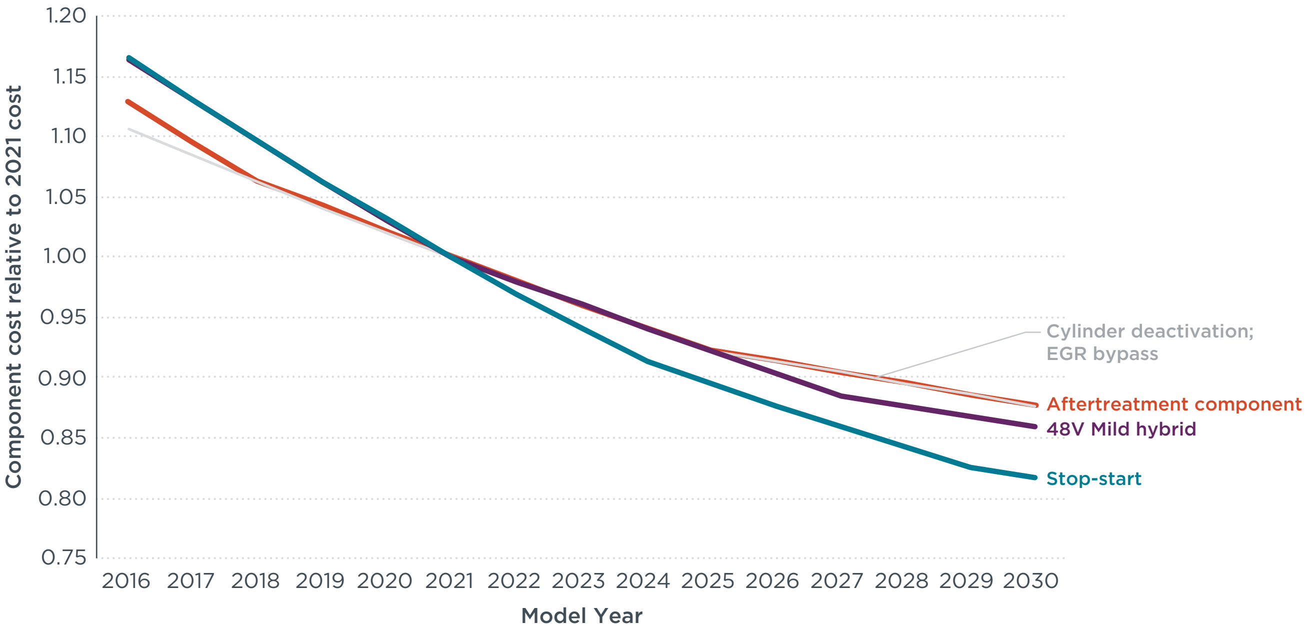

Figure 9. Manufacturer learning curves for selected emissions-control technologies, relative to 2021 (U.S. EPA & U.S. DOT, 2016).

Indirect costs and total costs

As performance requirements become more and more stringent with new iterations of the Euro standard, additional research and development is required. Additionally, as system design becomes more and more complex, increased calibration and integration efforts are required, both of which come at additional costs. We expect these indirect costs to represent an important proportion of the incremental costs required to meet the Euro VII limits. In this study, they are accounted for via the use of indirect costs multipliers (ICM), which were initially developed by the U.S. Environmental Protection Agency as part of their regulatory impact assessment (U.S. EPA & U.S. DOT, 2016). These ICMs account for different levels of complexity (low, medium, or high) and different timescales (near-term or long-term), depending on the maturity of the technology. Therefore, each DMC item is multiplied by the relevant ICM, as summarized in Table 12.

Table 12. Indirect cost multipliers (ICMs) for selected emissions-control technologies (U.S. EPA & U.S. DOT, 2016).

ICM Complexity	Near term (out to 2025)			Long term (post-2025)			Notes
	Warranty	Non-warranty	Total	Warranty	Non-warranty	Total	
Low	0.006	0.149	0.155	0.003	0.122	0.125	EATS components near term through 2025
Medium	0.022	0.213	0.235	0.016	0.165	0.181	CDA, EGR bypass near term through 2025
High1	0.032	0.249	0.281	0.016	0.176	0.192	48-V system near term through 2025
High2	0.037	0.398	0.435	0.025	0.265	0.290	

Warranty costs are assumed to reduce with learning and are therefore applied to learned DMC. Non-warranty costs—that is, all other indirect costs—on the other hand, are assumed to remain constant and are therefore applied to the base DMC evaluated in 2021. For each cost item, the corresponding learned direct costs, learned warranty indirect costs, and fixed non-warranty indirect costs are added to obtain total manufacturing costs, using the following formula, according to the reference study.

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

Where TC_{year} = total manufacturing costs for a given year

DMC_{base} = base (2021) direct manufacturing costs

LF_{year} = learning factor for the given year, obtained from Figure 9

$ICM_{non\text{-}warranty}$ = non-warranty indirect cost multiplier from Table 12

$ICM_{warranty}$ = warranty indirect cost multiplier from Table 12

base = base year (2021)

year = evaluation year

Durability considerations – sensitivity analysis

Finally, we assessed the sensitivity of the EATS costs to the yet-to-be-determined durability requirements of Euro VII. As confirmed by consultations with industry experts, either higher volumes or enhanced substrate designs will be required to ensure that catalyst performance is maintained throughout the extended full useful life requirement of Euro VII.

As part of the policy developments in California, the Manufacturers of Emission Controls Association derived durability factors that scale the catalyst costs to account for the incremental costs associated with meeting an increased FUL requirement. For the three Euro VII durability scenarios outlined in Figure 3, we assessed the associated costs of increased technology requirements using the cost factors provided by the Manufacturers of Emission Controls Association for a 12L - 13L heavy-duty engine emission control system. In the “current” durability scenario, the full useful life requirement is that of Euro VI, and we therefore assume no increase in catalyst costs. As part of the sensitivity analysis, we also considered the “low-ambition” and “high-ambition” durability increase scenarios of Figure 3, for which the additional requirements on catalyst technology are estimated to incur a 10% and 20% increase in costs,[7] respectively. Additionally, in both cases, we assumed sensor replacement is required once over the system lifetime, effectively doubling the sensor costs. The sensitivity on durability requirements was assessed on the 2025 total manufacturing costs.

Sensitivity of costs to precious metal prices

Platinum group metals are widely used as catalytic agents in aftertreatment technologies and represent a significant proportion of these technology costs. As platinum group metal prices largely vary with time and can be quite volatile, we expect this to have a potential impact on the costs of aftertreatment systems. Figure 10 shows the evolution of platinum group metal prices over the past 15 years (Johnson Matthey, 2021). Most technologies assessed in this study rely on a mix of platinum (Pt) and rhodium (Rh). While the price of platinum has remained relatively constant over the years, the price of palladium (Pd) has increased by 130% in the past three years. Still, it is hard to predict how these prices will vary in the future due to their high volatility, but it is expected that manufacturers of aftertreatment systems can adopt strategies to manage the risk of the price fluctuations. For instance, manufacturers would generally adjust the ratio of the different platinum group metals according to market price variations to

7 Values averaged over the estimates provided by Manufacturers of Emission Controls Association.

aim at a constant overall cost. Additionally, they can mitigate the volatility in prices by accumulating stocks of these precious metals. For technologies that would rely on the use of rhodium as the primary platinum group metal, however, the technology costs would likely be exposed to large variations as s the price of rhodium has increased drastically by more than 1000% in the past three years. Note, however, that this observation did not influence the final results of this study, as platinum group metal prices cannot be projected in the future within reasonable levels of uncertainty.

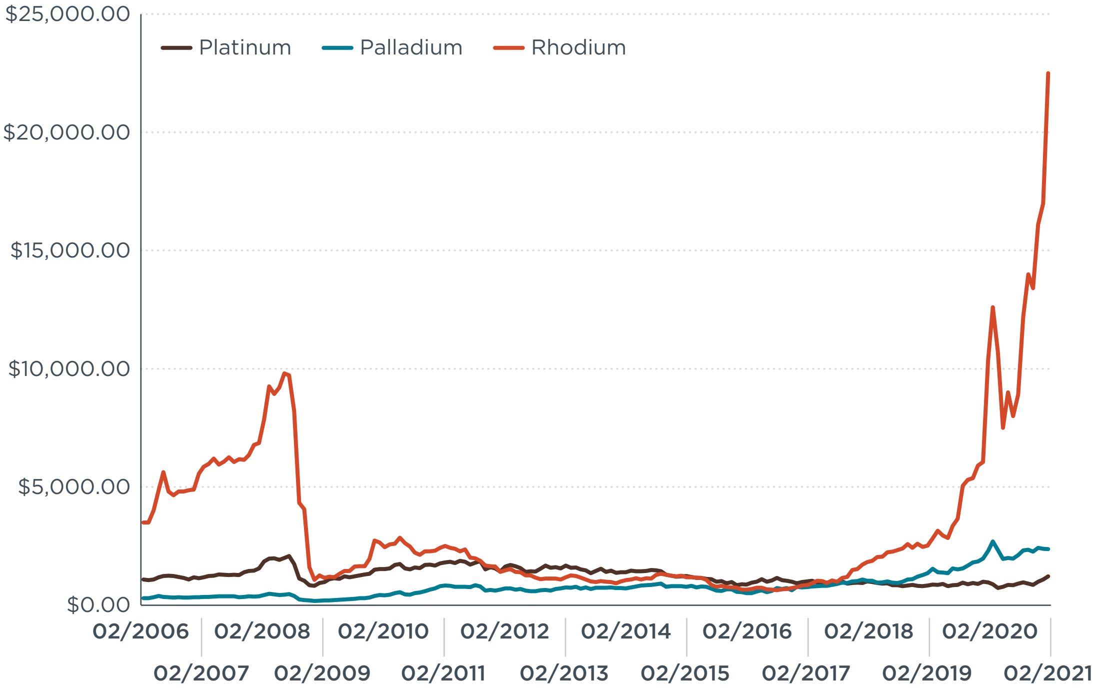

Figure 10. Evolution of platinum group metal prices over the past 15 (1 $/Oz = 37 €/g) (Johnson Matthey, 2021).

Costs of emissions control systems

Engine control costs

The direct, indirect, and total costs of the additional engine control technologies considered to reduce engine-out NO_x emissions according to future Euro VII requirements are summarized in Table 13. Direct costs were obtained using the assumptions in Table 11, while indirect costs account for research and development as well as increased system integration and control costs. It was assumed that CDA is applied to all cylinders, although it can also be applied to a fraction of them for reduced costs. Based on power distribution, the cost of the 48-V system attributed to emissions control is only half of the total technology costs, the rest being attributed to CO_2 emissions reduction to comply to the heavy-duty CO_2 emissions standards. We assessed current technology costs, as of 2021, as well as learned costs for MY 2025 (near-term) and 2030 (long-term).

Table 13. Estimated total manufacturing costs of engine control technologies and mild hybridization to meet future Euro VII requirements, today and in MY 2025 and 2030.

Technology	2021			2025			2030		
	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
Bypass (pipe and valve)	€208	€49	**€257**	€192	€49	**€241**	€182	€37	**€220**
Cylinder deactivation	€363	€85	**€448**	€335	€85	**€420**	€318	€65	**€383**
48-V mild hybridization	€1,050	€295	**€1,345**	€968	€292	**€1,261**	€902	€199	**€1,101**

Aftertreatment system costs

Similarly, our cost estimates for the aftertreatment systems required to meet future Euro VII standards are presented in Table 14, based on the assumptions described in the previous section of this paper. Direct costs were obtained using the assumptions in Table 3 through Table 9 and updating them using the manufacturer learning curves of Figure 9. The costs listed in Table 14 correspond to the current durability scenario and do not include the incremental costs associated with meeting the future FUL requirements of Euro VII.

Table 14. Estimated total manufacturing costs of aftertreatment systems to meet future Euro VII requirements, today and in MY 2025 and 2030.

Technology	2021			2025			2030		
	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
Baseline – Euro VI									
System	€3,089	€479	**€3,568**	€2,852	€477	**€3,329**	€2,711	€385	**€3,096**
Configuration 1									
ccDOC	€628	€97	**€726**	€580	€97	**€677**	€551	€78	**€630**
LO-SCR/ASC	€1,141	€177	**€1,318**	€1,053	€176	**€1,230**	€1,001	€142	**€1,143**
DOC	€615	€95	**€710**	€567	€95	**€662**	€539	€77	**€616**
DPF	€639	€99	**€738**	€590	€99	**€688**	€560	€80	**€640**
SCR/ASC	€1,502	€233	**€1,735**	€1,386	€232	**€1,619**	€1,318	€187	**€1,505**
System	€4,525	€701	**€5,226**	€4,177	€699	**€4,876**	€3,970	€486	**€4,534**
Configuration 2									
PNA	€1,830	€284	**€2,114**	€1,689	€283	**€1,972**	€1,606	€228	**€1,834**
DOC	€615	€95	**€710**	€567	€95	**€662**	€539	€77	**€616**
SCRF	€913	€142	**€1,055**	€843	€141	**€984**	€801	€114	**€915**
SCR/ASC	€1,745	€271	**€2,016**	€1,611	€270	**€1,881**	€1,531	€218	**€1,749**
System	€5,103	€791	**€5,894**	€4,711	€789	**€5,500**	€4,478	€636	**€5,114**
Configuration 3									
E-catalyst heater	€806	€125	**€931**	€744	€125	**€869**	€707	€100	**€808**
ccDOC	€628	€97	**€726**	€580	€97	**€677**	€551	€78	**€630**
ccSCR/ASC	€936	€145	**€1,081**	€864	€145	**€1,009**	€821	€117	**€938**
DOC	€615	€95	**€710**	€567	€95	**€662**	€539	€77	**€616**
DPF	€639	€99	**€738**	€590	€99	**€688**	€560	€80	**€640**
SCR+SCR/ASC	€2,024	€314	**€2,338**	€1,869	€313	**€2,181**	€1,776	€252	**€2,028**
System	€5,648	€875	**€6,523**	€5,214	€873	**€6,087**	€4,956	€704	**€5,660**

Full system incremental costs

Table 15 summarizes our estimates for the incremental costs of the full emissions control systems we assessed for Euro VII, as compared to our estimate for the current Euro VI-compliant system in Figure 4. Since the ICCT's previous estimate of Euro VI-compliant systems costs (Posada et al., 2016), cost reductions have occurred due to manufacturer learning, different use of PGM, and other improvements. We assessed current technology costs, as well as costs in 2025 (near-term) and 2030 (long-term).

Table 15. Estimated incremental costs of the full systems to meet Euro VII limits in 2021, 2025, and 2030.

System	2021	2025	2030
Configuration 1	€1,658	€1,547	€1,438
Configuration 2	€3,032	€2,831	€2,621
Configuration 3 - without 48-V	€3,661	€3,418	€3,167
Configuration 3 - with 48-V	€5,006	€4,678	€4,268

Overall, we estimated that the 2021 incremental costs for the full emissions control system to meet Euro VII range from €1,658 to €3,661 and €5,006 with and without a 48-V system, respectively. Configuration 1 incurred the lowest incremental costs, both in terms of EATS and engine control technologies. Configuration 2 was more costly due to the high costs of the PNA, while Configuration 3 incurred the highest incremental costs, whether it included the 48-V system or not, due to more extensive technology deployment. Overall, the assumed manufacturer learning would yield cost reductions of around 14% between now and 2030.

Sensitivity of costs to durability requirements

To account for the uncertainty in the future durability requirements of Euro VII, we estimated the sensitivity of the EATS costs to the FUL requirement in 2025. For the different scenarios in Figure 3, we assessed the additional costs associated with increasing the durability of the catalysts and the costs of sensor replacement (see *Durability considerations – sensitivity analysis* section). The resulting EATS costs are shown in Figure 11. Under our low ambition durability scenario, whereby we assumed a 38% increase in FUL to about 970,000 km is required, the EATS costs for 2025 increased from approximately €4,900–€6,100 to €5,500–€6,900, representing a cost premium of between 12% and 14%. This increase resulted from a 10% premium on catalyst costs as well as a single replacement of all sensors in the EATS once during the system lifetime. Under the high ambition durability scenario, a 20% premium was applied to all catalysts, as well as sensor replacement. This translated into an increase in EATS costs to approximately €5,800–€7,200, representing a cost premium of between 18% and 22%. The high ambition scenario would bring the FUL requirement in the EU to about 1,300,000 km (800,000 miles).

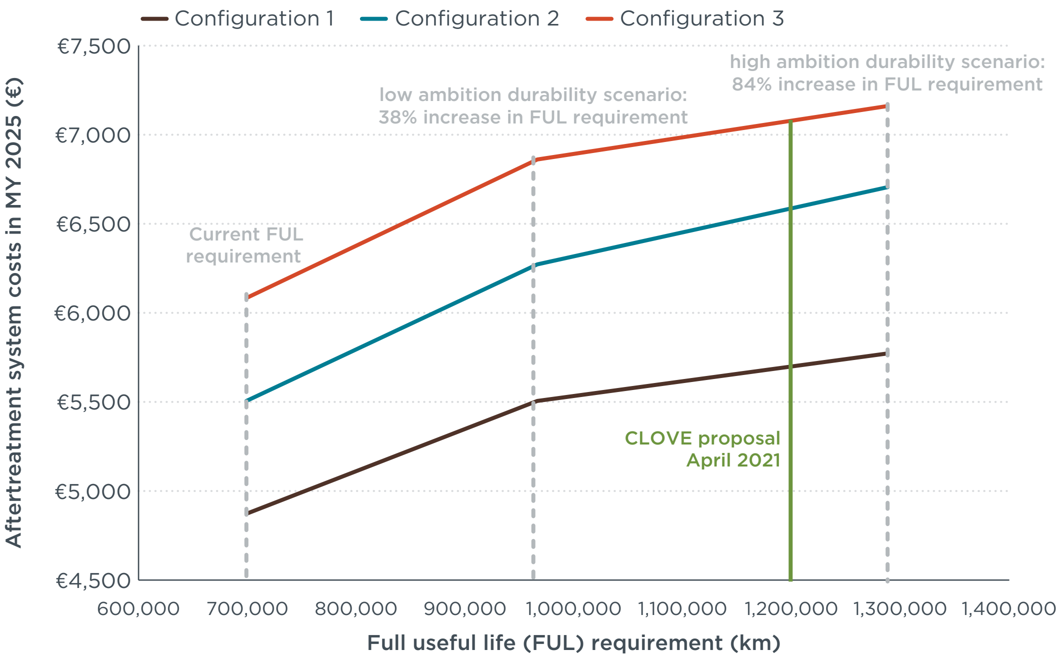

Figure 11. Sensitivity of the evaluated potential Euro VII EATS costs to the potential full useful life durability requirements of Euro VII, for model year 2025.

Production volumes

Other trends not considered in this report might also affect the future costs of emission control systems. For instance, technology costs are largely dependent on the production volumes and the ability to benefit from economies of scale. As truck makers have started to announce ambitious electrification targets for their new vehicle fleets starting in 2030, mainly driven by compliance to the CO_2 emissions standards, diesel trucks might lose significant market shares to zero-emission technologies in the coming years. The production volumes of diesel emissions control technologies might therefore drop accordingly and the engine control and aftertreatment technologies discussed in this report would become more expensive. This might create a significant challenge for truck and emissions control manufacturers. However, such risks can be mitigated by horizontal integration, working closely with engine manufacturers, and creating partnerships with other truck manufacturers.

Incremental costs to meet future Euro VII requirements

Finally, we estimated the incremental costs of our potential Euro VII emissions control systems, as compared to the baseline Euro VI-compliant system, given the different durability scenarios discussed above. Figure 12 shows the estimated incremental costs of Configurations 1 through 3 (both with and without a 48-V system) in MY 2025 and 2030. The main bars represent the low-ambition durability scenario (middle case, FUL = 970,000 km), while the lower and upper end of the error bars account for the current (FUL = 700,000 km) and high-ambition scenario (FUL = 1,300,000 km) requirements, respectively. Under the high-ambition durability scenario, we estimated the incremental costs of compliance to the Euro VII standards to range between approximately €2,400 and €5,800 in 2025, and between €2,300 and €5,000 in 2030. The current proposal of the CLOVE consortium to require a FUL of 1,200,000 km would yield very similar levels of incremental costs.

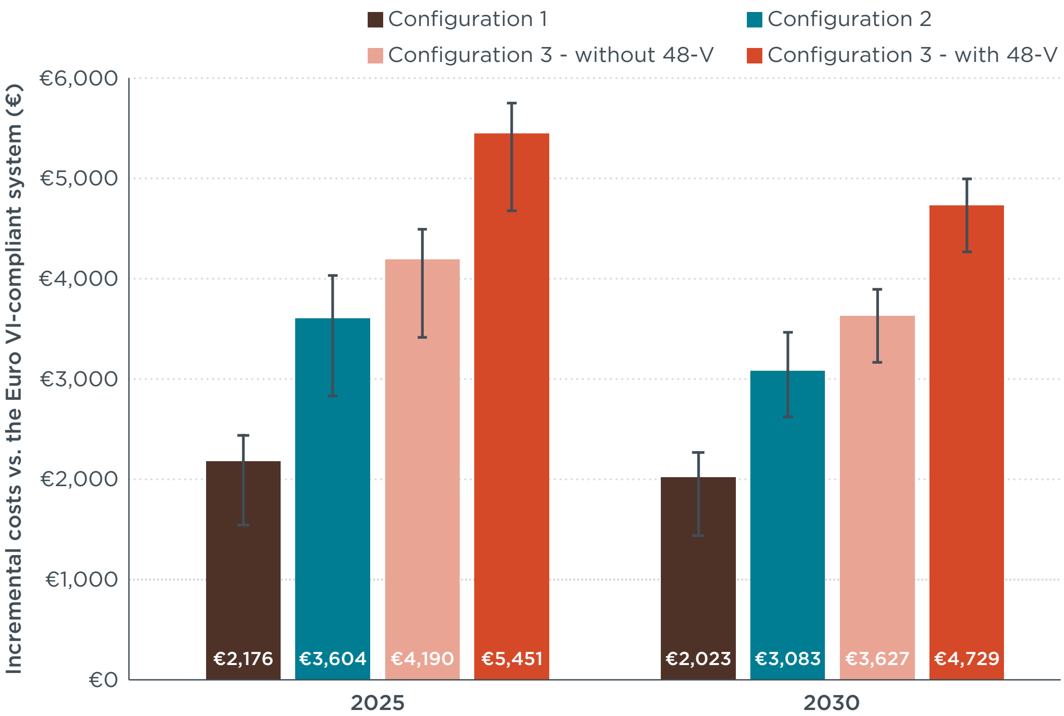

Figure 12. Estimated incremental costs of our potential Euro VII emissions control systems as compared to a Euro-VI compliant system. The main bar corresponds to our "low ambition" durability increase scenario (FUL = 970,000 km), while the lower and upper ends of the error bars represent the current (FUL = 700,000 km) and "high ambition" (FUL = 1,300,000 km) durability increase scenarios, respectively.

Conclusions

The Euro VII pollutant emissions standards are an important opportunity to require a significant reduction in pollutant emissions from HDVs to levels that will drive the adoption of emission control technologies that are already commercially available or that have a high technology readiness level. In particular, technologies that enable very low NO_x emission levels under cold start and at low load—conditions representative of urban driving operation—are essential to reduce the health impacts of HDV exhaust. This study provides estimates of the costs associated with the deployment of such technologies for heavy-duty trucks. The key findings are as follows.

» **The technologies required to achieve ultra-low pollutant emissions are already in production or close to commercialization.** These include both engine control and aftertreatment technologies, which focus on improving the efficacy of the emissions control system at cold start and during low-load operation. On the engine and powertrain side, technologies such as cylinder deactivation, EGR cooler bypass, and 48-volt systems could enable better low-load engine-out NO_x control, faster catalyst warm-up, and stay-warm thermal management strategies. Most of these technologies are already common in light-duty vehicles. On the aftertreatment side, we expect that compliance with stricter NO_x emissions limits will require the use of close-coupled catalysts, increased catalyst volumes, dual urea injection, heated urea dosing, and electric catalyst heaters, as well as high filtration substrates, amongst others.

» **We expect these technologies will increase the price of heavy trucks in less than 5%.** Overall, we estimated the incremental costs of meeting the Euro VII standards compared to a Euro VI-compliant emissions control system will be between €1,500 and €4,700 in 2025, and between €1,400 and €4,300 in 2030. Therefore, Euro VII will likely result in a cost increase between 2% and 5% relative to the current price of new Euro VI tractor-trucks. Overall, we expect engine-out emissions control to represent 0%-41% of the incremental costs of compliance to Euro VII, while the rest accounts for improvements in the EATS.

» **Increasing the requirements of the durability of aftertreatment systems to 1.3 million kilometers will increase full system costs in approximately €1,000, or 1% of the truck price.** We estimated that increasing the required full useful life requirements of aftertreatment systems from the current 700,000 km to 970,000 km and 1,300,000 km would lead to average additional costs of approximately €700 and €1,000, respectively, in 2025. This corresponds to an increase between 12% and 22% in the cost of Euro VII aftertreatment systems.

Acronyms and abbreviations

ASC	Ammonia slip catalyst
CARB	California air resource board
cc	Close-coupled
CDA	Cylinder deactivation
DMC	Direct manufacturing costs
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EATS	Engine aftertreatment system
ECH	Electric catalyst heater
EGR	Exhaust gas recirculation
FUL	Full useful life
HDV	Heavy-duty vehicle
ICM	Indirect cost multipliers
LO	Light-off
NREL	National renewable energy laboratory
PNA	Passive NO_x adsorber
SCR	Selective catalytic reduction
SCRF	SCR on filter
SVR	Swept volume ratio

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