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Real-World Emissions of Euro VI Heavy-Duty Vehicles

Pablo Mendoza Villafuerte, Joachim Demuynck, and Dirk Bosteels AECC Association For Emissions Control by Catalyst

Robin Vermeulen, Rene van Gijlswijk, and Norbert Ligterink TNO

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Abstract

The Euro VI Step E emission standard for heavy-duty vehicles (HDVs) is the first step to introduce cold-start emissions analysis as part of the on-road In-Service Conformity (ISC) requirements. The intention is to reflect the engine cold-start requirements foreseen in the World Harmonized Transient Cycle (WHTC) type approval cycle. In addition, a limit is introduced for solid particle number (PN) to be measured with Portable Emissions Measurement Systems (PEMS). The new regulatory step continues using the Moving Averaging Window (MAW) data post-processing prescribed by the Euro VI regulation, with additions to consider the cold-start emissions.

In order to have a full understanding of the vehicle emissions performance during their daily operation, this study presents emissions data analysis of 25 Euro VI A-C and 3 Euro VI D vehicles. The aim is to screen for potential remaining high emission events during the day-to-day operation. The measurements were conducted throughout the year covering a variety of temperatures and road conditions. The data has been analyzed both in raw form and using an MAW post-processing consistent with the European Union (EU) regulation (either EU 582/2011 for Euro VIA-C or EU 2016/1718 for Euro VI D vehicles).

The results show that overall low oxides of nitrogen (NOx) emissions are achieved in the daily operation. There are, however, remaining high NOx emissions events, mainly within the urban operation. These are not fully considered by the regulatory procedure and therefore usually do not contribute to the final declared emissions for vehicle compliance.

The definition of the European Commission proposal for the heavy-duty Euro VII emissions regulation is ongoing, and the discussion on vehicle compliance is shifting from structured ISC on-road test trips to actual daily operations. This shift emphasizes the need to reduce pollutant emissions in a wide regime of operating conditions in order to minimize exposure of citizens to pollutants. In this context, this analysis contributes to the thorough understanding of the areas where emissions control of HDVs can still be improved.

Keywords

Heavy-duty, Ultra-low emissions, SCR, Twin dosing

Introduction

The road transport sector is considered to be an important source of oxides of nitrogen (NOx) and particulate matter (PM) [1] in European cities. Heavy-duty vehicles (HDVs) are the backbone of the European economy, and these are used throughout Europe to carry goods and people. It is therefore extremely important that they operate cleanly and efficiently.

Euro VI emission standards for HDVs were introduced in Europe in 2014 [2]. The latest step on the Euro VI emission standards is Step E, which has been introduced for new vehicles as of 1 January 2021. This step is relevant as it is the first time where analysis of the cold-start emissions (<70°C of coolant temperature) has been prescribed, as well as the first time that particle number (PN) for on-road operation will be declared for compliance.

Euro VI legislation includes a Portable Emissions Measurement System (PEMS)-based test at type approval. The PEMS is also prescribed for the in-service conformity (ISC) test of these vehicles. The ISC test is used to verify if the pollutant emissions of these vehicles are still compliant through the useful life of the vehicle as prescribed by the regulation (ISC testing is required within 18 months of the first registration on a vehicle registered in the EU that has accumulated a minimum of 25,000 km). The on-road-based PEMS test is conducted on public roads, and the trips have to comply with the prescribed boundary conditions (i.e., shares of operation and route composition, maximum altitude, etc.). The routes and duration are designed to verify the test results of the vehicle's engine certification test in the laboratory. This is achieved mainly through processing the measured on-road data and calculating an equivalence ratio, or conformity factor. The calculation is described by the Moving Averaging Window (MAW) methodology [3]. The MAW methodology is a moving average analysis where the duration of the averaging window is based on the mechanical work (or CO_2 emission) that was measured over the World Harmonized Transient Cycle (WHTC) test during type approval testing. Windows are excluded step-wise if they are covered by one of a number of prescribed conditions (i.e., below 20%/10% power threshold, above the 90th cumulative percentile, etc.). The remaining window with the highest average emission level is the basis for the evaluation of compliance of the vehicle's emissions. The maximum conformity factor allowed for NOx emissions by the regulation is currently 1.5, which means that the average emission in the highest remaining window is not allowed to be higher than 1.5 times the WHTC NOx limit of 460 mg/kWh.

The results show that overall low NOx emissions are achieved in the daily operation. This means that when all the emissions of an ISC trip are integrated and divided by the work performed during such trip, the values found are generally low. However, on day-to-day use, the length of the trip and the actual mission profile of the vehicle have a large influence on the emissions. This has been reported by different technical teams and within different levels of Euro VI vehicles, as described by Vermeulen et al. [4]. When looking into the detailed emission traces of the vehicles, either monitored within in-service prescribed routes or outside, the situation is variable, with high emission events still found mainly in urban operations. One of the main causes for this behavior is that during cold-start and low load/urban operation, the emissions control system is not reaching the activation temperature required to start reducing NOx emissions [5, 6].

This was noted by Perujo et al. [7] in an assessment that set the technical basis for the modifications that the European Commission implemented in Euro VI Step D. The study concluded that the 90th cumulative percentile boundary condition (where the 10% windows with the highest emissions are left out of the analysis) as applied concurrently to other limitations (i.e., power threshold and cold start) unnecessarily eliminates a significant portion of the vehicle operation in urban areas from the emissions assessment.

More recently, Posada et al. [8] concluded that the European MAW methodology for on-road measured emission data captures NOx emissions under the most challenging conditions, i.e., low speed and low power demands, which are characteristic of urban driving. However, according to Posada, improvements could be made to the MAW protocol to further incentivize urban NOx reductions. Such improvements include expanding window validity to all power conditions.

Moreover, for high-powered N3 truck tractors, the ISC test prescription with the two-hour length of the test and the need for at least one urban window in the evaluation has become difficult to achieve. Some artificial test execution became necessary to ensure the engine work in the urban part was sufficiently high.

The objective of the work presented here is to investigate on-road emissions of HDVs in their day-to-day operation, based on vehicles that were used in a regular manner, driven by their regular users. The data allowed looking at how these vehicles performed under normal driving conditions, including operations where high-emission events still occur. It was possible to analyze how these events are represented by the current regulatory framework.

For this, the Association for Emissions Control by Catalyst (AECC) has partnered with the Netherlands Organization for applied scientific research (TNO) in order to analyze the NOx emission performance of different Euro VI (A-C) and Euro VI D vehicles covering a wide range of applications.

Project Setup

About 25 HDV classes N2, N3, M3, and homologated as Euro VI A-C, suitable for evaluation, were identified by TNO in their database. Additionally, three Euro VI D vehicles were included to complete the analysis. These vehicles were monitored with Smart Emissions Measurement System (SEMS), and the data reflects the normal operation of the vehicles by the operators and transport companies, mainly in the Netherlands.

SEMS is a sensor-based system developed by TNO [9] and is used to measure and analyze the tailpipe NOx emissions and a range of vehicle/engine parameters during daily operations to be able to characterize the typical operation of the vehicles. In this way, days, weeks, or up to months of data is possible to be collected per vehicle. The SEMS uses an automotive NOx sensor, an ammonia sensor, GPS, and a data acquisition system to record the sensor data and CAN data from the vehicle and engine at a sample rate of 1 Hz.

The method is not certified and relies on signals of (in principle) unknown accuracy and origin. The results and sensors are therefore continuously calibrated and compared with the results of laboratory testing in cross-validation experiments. The accuracy and reproducibility of measurements with the current generation of SEMS equipment is, in most cases, within a bandwidth of 10% and, in many cases, even a smaller bandwidth.

The system can operate autonomously and wakes up at the ignition/key-on of the vehicle. The system can be stowed away so that normal operation is not hindered by the measurement; a standard setup of the SEMS can be seen in Figure 1. The recorded data is sent hourly to a central data server.

NOx Emissions Results

The data obtained through the SEMS were analyzed following the post-processing boundary conditions prescribed by the regulation including the exclusion of cold-start windows, 10%/20% power threshold, and 90th cumulative percentile; finally, the results shown also contain the results considering all windows.

The impact of the data exclusions on the emissions of the highest remaining window after each boundary condition was applied can be seen in Figure 2. This figure is showing data from the Euro VI A-C vehicles. Each vehicle is represented by two bars: light blue indicates the highest MAW emissions and

FIGURE 1 SEMS system installation.

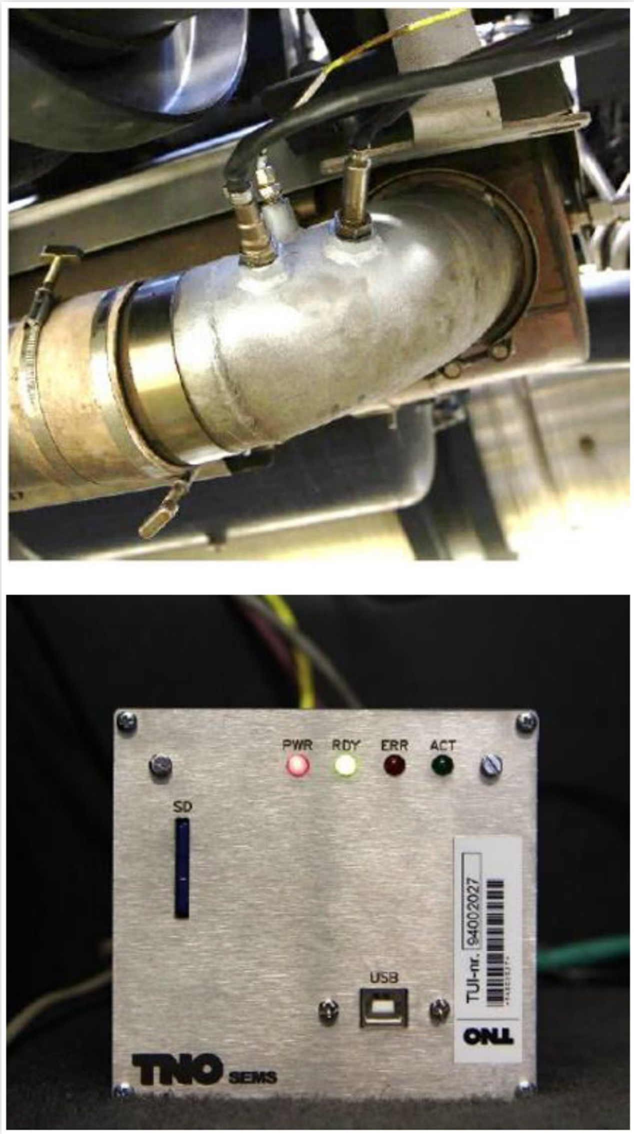
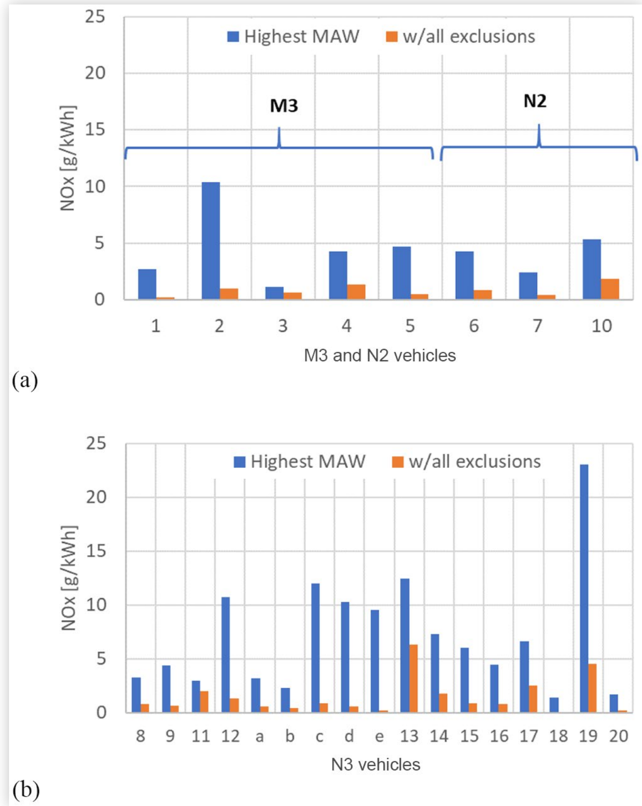


FIGURE 2 (a) Overview of the Euro VI A M3 and N2 data. (b) Overview of the Euro VI A and C N3 data. In both figures, every bar represents the average emission level in the highest window.



orange the highest window after all exclusions. The vehicle categories and mission can be found in Appendix 1.

As can be seen, the database covers a wide range of applications, from city buses to long-haul trucks and some vocational HDVs. From the results below, it can be seen that the bars representing the resulting emissions when all boundary conditions are considered (including the 90th cumulative percentile) are not representing the highest MAW emissions; in many cases, the resulting emissions after all exclusions are very low. It must not be forgotten that each MAW represents a period of at least around half-hour (i.e., the period needed to complete the WHTC work).

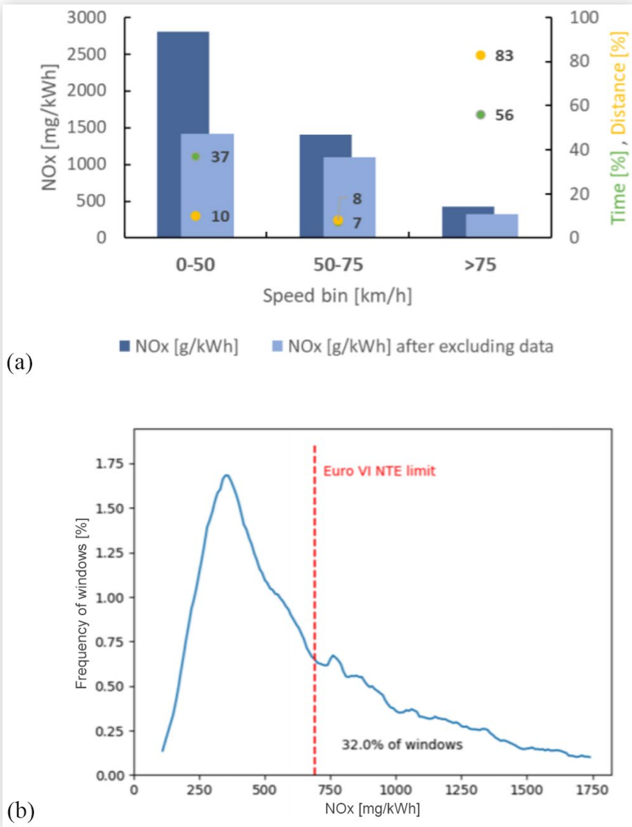
Figure 3 shows an example of the impact of the Euro VI C post-processing and the MAW distribution during the operation of an N3 vehicle (Vehicle 13). Figure 3(a) shows that this vehicle spent 37% of the time in urban operation where the maximum averaged emissions are about 6 times the current NOx limit. Figure 3(b) shows the distribution of the MAW and whether the MAW is within or above the Euro VI Not-to-Exceed (NTE) limit. As can be seen, a majority of emissions in the daily operation are below the limit, but still a significant 32% of the MAW are above the limit.

Perujo et al. [7] analyzed how the different boundary conditions had an impact on the results. The study showed how the combination of boundary conditions/exclusion criteria act concurrently and how the combination of exclusions leaves up to 78% of the NOx unaccounted in some cases.

Our study confirms that a significant amount of data is excluded from the final step in the calculation as prescribed by the regulation. To further analyze the impact of the prescribed boundary conditions, it was important to understand which levels of averaged emissions occur during the day-to-day operation and how these emissions compared to the value resulting from the legislative prescribed analysis. Part of this analysis was based on the Euro VI A-C vehicles database, which is presented in Figure 2. However it was relevant to study the latest vehicles in the market, being from the Euro VI D category.

Figure 4(a) shows the impact of data exclusions for a Euro VI D vehicle. The emissions levels achieved from the Euro VI D vehicle shown in Figure 4 are much lower than those seen from the Euro VI C vehicle above. The data has been post-processed according to the Euro VI D regulation as well as with the new Euro VI E post-processing rules considering the cold-start data. The vehicle is an N2 rigid truck that spent 37% of the time monitored under urban operation. During this

FIGURE 3 (a) Euro VI C vehicle's NOx emissions averaged data over the indicated speed bin. The dark blue bar considers all data without exclusions; the light blue bar considers the data left after applying all Euro VI C prescribed exclusions. (b) MAWs integrated emissions frequency distribution.



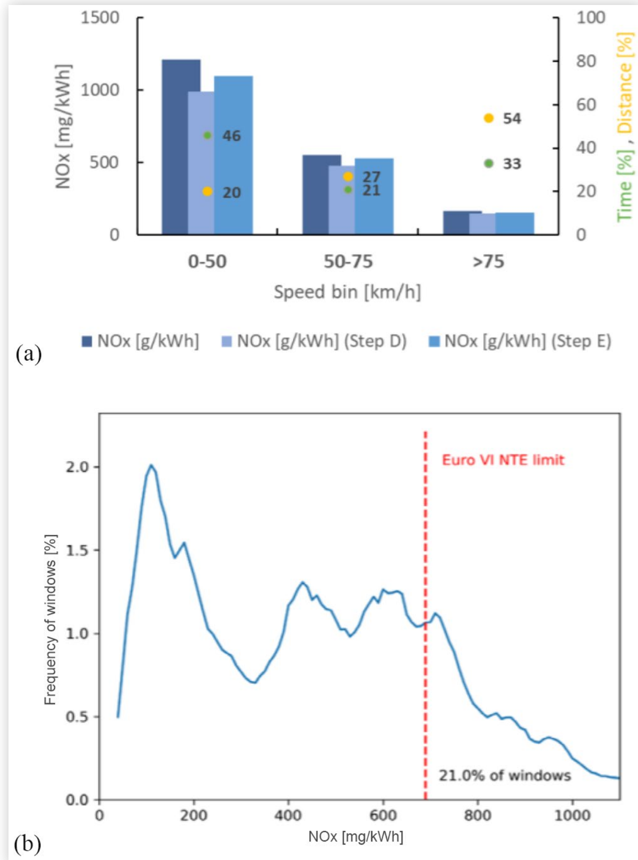
time, the average emissions were about three times the current NOx limit. If we look at the MAW distribution shown in Figure 4(b), 21% of the MAW were above the Euro VI NTE limit in this case.

To be able to determine where the data exclusions have a bigger impact, it is therefore important to look at the peak and duration of the emissions events on top of the average value. To do this, five examples were chosen: a Euro VI A N3 vocational truck used for sand haulage, a Euro VI C N3 vehicle used for national distribution, and three Euro VI D vehicles—an N2 rigid truck, an N3 tractor tanker semi-trailer, and an N3 tractor semi-trailer. This is to look at a range of vehicle applications, as well as missions, covered.

Figure 5 shows the NOx emissions of these vehicles under their normal day-to-day activities. The data represents the integrated emissions within the three speed bins: Urban (>50 km/h), Rural (50-75 km/h), and motorway (>75 km/h). The highest emissions seen are from the Euro VI A vehicle that operates 75% of the time inside the urban environment.

The Euro VI C, an N3 vehicle, is used for national distribution. The vehicle operates 37% of the time in an urban environment where the highest emissions are identified at about 2800 mg/kWh. Under motorway operation, this vehicle performs reasonably well.

FIGURE 4 (a) Euro VI D vehicle's NOx emissions averaged data over the indicated speed bin. The dark blue bar considers all data without exclusions; the other two light blue bars consider the data left after applying all Euro VI D or E prescribed exclusions. (b) MAWs integrated emissions frequency distribution.



Euro VI D vehicles show very similar emissions under rural and motorway operations, but they still show high emissions under urban operations. The first Euro VI D, an N2 vehicle (EU VI D1), belongs to a laundry company. The vehicle's daily mission is collecting and distributing laundry, and the distance the vehicle was monitored covering 187 hours and about 8600 km. The vehicle operated 37% of the time and 20% of the distance inside the urban environment. The vehicle ran 9% of the time with a cold engine. The second Euro VI D vehicle (EU VI D2) is an N3 tractor tanker semi-trailer used for the distribution of chemicals. As can be seen, the urban emissions of this vehicle are almost twice those of the vehicle EU VI D1. This vehicle operated 15% of the time inside an urban environment and 13% of the time in idle. The high emissions shown on the urban operation reflect how, sometimes, long-haul trucks are optimized for motorway operation.

Finally, the last Euro VI D vehicle (EU VI D3) is an N3 tractor semi-trailer vehicle used for the distribution of goods. This vehicle shows similar emissions as the EU VI D2 vehicle. This highlights the spread of urban emissions performance on N3 trucks.

FIGURE 5 Examples of NOx emissions over different speed ranges for a Euro VI Step A N3 tipper, a Step C N3 tractor, an N2 Step D rigid distribution truck (D1), a Step D N3 tractor tanker semi-trailer (D2), and an N3 tractor semi-trailer (D3).

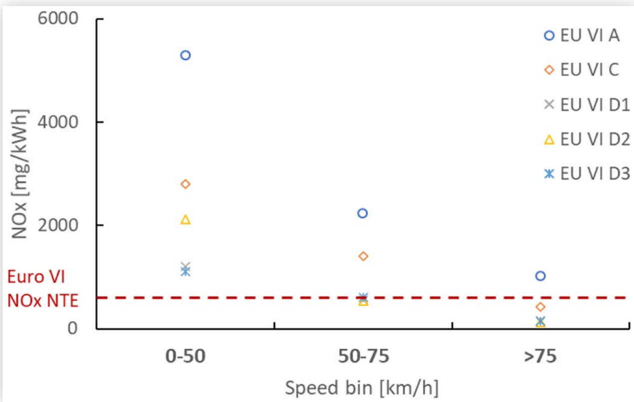
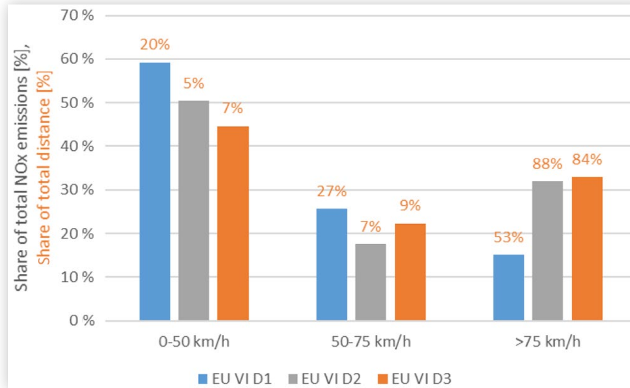


FIGURE 7 Share of NOx emissions of three typical speed intervals in the total NOx emissions of three HDVs with a Step D-certified engine tested in daily real-world operation. The graph also shows the share of each speed interval in the total driving distance.



Beyond the analysis of the urban operation emissions from these vehicles, it is important to understand the impact of the cold start, and this is shown in the figure below. Figure 6 below shows the cold-start emissions of the Euro VI D vehicles. As can be seen, the cold start still represents a big challenge for heavy-duty applications.

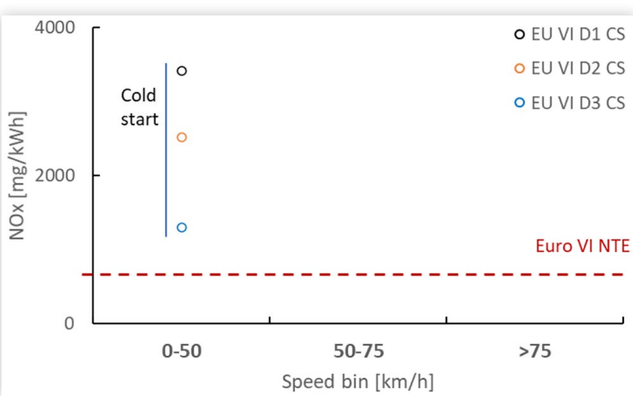
When all NOx emissions are binned in speed ranges, it becomes apparent that for three vehicles with Euro VI Step D-certified engines in real-world operation, the most NOx is emitted at low-speed driving speeds, such as that occurring in an urban environment. For the tested vehicles, driving at low speeds contributes about 45% to 60% of the total NOx emissions for distance shares between 7% and 20%, as can be seen in Figure 7.

Conclusions

The results shown in this study relate to the day-to-day operation of heavy-duty vehicles. Most of these vehicles, particularly the Euro VI D vehicles being tested over the official PEMS test on the public road or under comparable conditions, would show no exceedance of the applicable limit value. In the regular daily operation, it can be seen that there are operating conditions where the average emissions increase significantly.

The highest NOx emissions are observed at low speeds and in cold-start conditions for Euro VI D vehicles. The results show that during the urban operation, these vehicles produce the highest absolute grams of NOx emissions despite the low share of driving distance. The vehicles studied operated a reasonable amount of time within the urban operation, this is linked to their mission, and thus, the high emissions results are of concern. The same vehicles show low average emissions values when driven in rural and motorway conditions. As has been seen, the compliance values reported for the vehicles in many cases do not consider these high emissions due to the rules for data exclusion. The length of the trips and the structure of the trip have an influence on the result, as well as how the vehicle is driven. The current shares of operation prescribed in the ISC test are not representative of the usage of some vehicles, and thus, cases like the vocational vehicles that are used mainly in the urban environment, and demonstrate to be compliant with the emissions limits, emit high emissions during their day-to-day operation.

FIGURE 6 Average of cold-start emissions.



Outlook

Effective legislation must ensure that the remaining emission peaks are properly controlled. This can be achieved by considering all emissions data of a test under normal operations. As seen from day-to-day driving data, these tests contain long idling periods, short trips, and semi-warm starts, events that are common for HDV operations. A consequence would be that the data analyses and limit setting would need to be adapted to tailor for these specific events where temporarily high emissions may occur. A separate evaluation for specific driving conditions (especially urban) on top of the total test average can help in finding these critical emissions events, as well as defining an evaluation period or distance that reflects the vehicle's mission or a part of it.

Challenging conditions should not be overcompensated or averaged out by the rest of the test. However, evaluation of the emissions data may be needed for short trips, long idling, and cold-start phase.

Step E, already applicable for new vehicle types from January 2021 (and applicable for all vehicles from January 2022), already includes the cold-start emissions at a fixed share of 14%. The highest absolute grams of NOx emissions are produced during the cold start of the vehicle, as seen from the results, and thus Step E solution is a step forward in looking more closely towards the cold-start operation; this may also help in controlling urban operations to a certain extent.

Currently, the development of the post Euro VI emission standards for cars, vans, lorries, and buses is under discussion. It is clear from the results shown in this study that the new emissions standards should prioritize implementing a testing procedure that is able to tackle the remaining emission events on top of achieving low average emissions.

The next emission standards should apply to all of the normal driving operations these vehicles can find while being used in Europe. This means that boundary conditions linked to temperature, altitude, or shares of operation should be comprehensive enough to cover the missions where these vehicles are being used.

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Contact Information

Dr Pablo Mendoza Villafuerte
AECC
Boulevard Auguste Reyers 80, B-1030 Brussels, Belgium
www.aecc.eu
pablo.mendoza-villafuerte@aecc.eu

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Appendix 1: Vehicle Categories and Mission

Mission	Homologation	Nomenclature in figure	Vehicle category
Bus	EU VI A	1	M3
	EU VI A	2	M3
	EU VI A	3	M3
	EU VI A	4	M3
	EU VI A	5	M3
Regional	EU VI A	6	N2
	EU VI A	7	N2
	EU VI A	8	N3
	EU VI A	9	N3
National/long haul	EU VI A	10	N2
	EU VI A	11	N3
	EU VI A	12	N3
	EU VI C	a	N3
	EU VI C	b	N3
	EU VI C	c	N3
	EU VI C	d	N3
	EU VI C	e	N3
Refuse	EU VI A	13	N3
	EU VI A	14	N3
	EU VI A	15	N3
	EU VI A	16	N3
	EU VI A	17	N3
Vocational	EU VI A	18	N3
	EU VI A	19	N3
	EU VI A	20	N3

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