Transportation Research Part D 127 (2024) 104062

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Analysis of the Euro 7 on-board emissions monitoring concept with real-driving data

Alvin Barbier *, José Miguel Salavert, Carlos E. Palau, Carlos Guardiola

Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

ARTICLE INFO

Keywords:
Euro 7
On-board monitoring
Real-driving emissions

ABSTRACT

The Euro 7 standard is expected to intensify its focus on real-driving emissions compliance thanks to the on-board monitoring (OBM) system. OBM is designed to bridge the gap between emission limits and real-world vehicle emissions by continuously monitoring their levels using on-board sensors and models. Essentially, this system aims to verify vehicles compliance, prompt timely repairs otherwise, and provide authorities with emissions data for fleet inspection. Leveraging a large real-driving emissions database from an in-service Euro 6d-Temp vehicle, this paper reviews the current OBM proposal and discusses its possible outcomes and challenges using available sensor technology.

1. Introduction

The European road transportation sector poses significant air pollution challenges with adverse effects on public health and the environment (Krzyżanowski et al., 2005; European Environment Agency, 2023a,b). In response, the European Commission has been actively pursuing more stringent emission standards to mitigate the detrimental impacts of vehicle emissions (European Commission, 2023a). From the introduction of the Euro 1 standard in 1992, to the latest version with the Euro 6d in 2020, the pollutants considered by the regulations, as well as their magnitude, have considerably changed. Between the earliest standards and the latest version in force, nitrogen oxides and particulate matter emission limitations have been reduced for diesel vehicles by more than 85% and 95% respectively (TransportPolicy.net, 2023), showing the constant effort in promoting cleaner vehicles over the years. While these standards have played a significant role, improvements are still necessary to ensure real-world compliance with emission limits. Originally certified with the New European Driving Cycle (NEDC), discrepancies between type approval levels and real-world emissions forced the authorities to find a new testing procedure that would better reflect the levels of emissions found in on-road driving conditions (Franco et al., 2014; Degraeuwe and Weiss, 2017; Ramos et al., 2018; Gräbe and Joubert, 2022). This consideration led to the introduction of the Worldwide harmonized Light vehicles Test Procedure (WLTP) together with real-driving emissions (RDE) tests using portable emissions measurement systems (PEMS) in 2017, which have since then effectively contributed to the reduction of the emission levels in real-driving conditions (Kousoulidou et al., 2013; Valverde Morales et al., 2020; Claßen et al., 2021). As the Euro 6 standard approaches its conclusion, the focus now shifts to the upcoming Euro 7 legislation with original implementation scheduled for 2025 for light-duty vehicles (European Commission, 2022b). This new standard comes with a number of updates such as the introduction of ammonia (NH_3) emissions among the limited pollutants (European Commission, 2022a), or the implementation of an on-board monitoring (OBM) system for emissions that is expected to play a crucial role in ensuring low emissions performance from vehicles in real-world operation (Müller et al., 2022; Dimaratos et al., 2023; Franco et al., 2023).

---

* Corresponding author.
E-mail addresses: albar9@upv.es (A. Barbier), carguaga@upv.es (C. Guardiola).

https://doi.org/10.1016/j.trd.2024.104062
Received 27 September 2023; Received in revised form 12 December 2023; Accepted 4 January 2024

Nomenclature

AGVES	Advisory Group on Vehicle Emission Standards
ASC	Ammonia-slip catalyst
CAN	Controller area network
CO	Carbon monoxide
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EATS	Exhaust after-treatment systems
EEDWS	Excess emissions driver warning system
EF	Extended factor
EGR	Exhaust gas recirculation
HiFi	High fidelity sensor
HP	High-pressure
ICE	Internal combustion engine
ISC	In-service conformity
LP	Low-pressure
MaSu	Market surveillance
MiL	Malfunction indicator lamp
NEDC	New European driving cycle
NH3	Ammonia
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxides
OBD	On-board diagnostics
OBM	On-board monitoring of emissions
OTA	Over-the-air
PCM	Powertrain control module
PEMS	Portable emission measurement system
PM	Particulate matter
PN_{10}	Particle number above 10 nm
RDE	Real-driving emissions
SCR	Selective catalytic reduction
SEMS	Smart emission measurement system
THC	Total hydrocarbons
VGT	Variable geometry turbine
WLTP	Worldwide harmonized light vehicles test procedure

OBM is built upon unfulfilled aspects of the current on-board diagnostics (OBD) systems regarding the accurate and timely detection of high emitting vehicles (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2022). While on-board diagnostics systems have been effective in monitoring subsystem failures, they do not provide a comprehensive assessment of total vehicle emissions. Consequently, a fraction of vehicles on the road might emit higher levels of air pollutants than allowed, contributing therefore disproportionately to the overall emissions and air pollution. On the other hand, OBM involves the direct and continuous monitoring of vehicle emissions using physical sensors and models. Such approach has already been tested in regions such as California and China, demonstrating the potential benefits of emissions monitoring (Tan et al., 2019; Cheng et al., 2019; Zhang et al., 2020). OBM would however not replace OBD, and instead will supplement it by sharing many elements such as embedded sensors and OBD-II port, which should also ease its implementation.

In a nutshell, OBM will have two main purposes (Franco et al., 2023): the first one is about warning the driver of an excess in emissions from the vehicle. In this case, the goal is to notify the user about the need for repairs and prevent the vehicle from restart if no action was taken and high emissions are still monitored. While the first purpose targets emissions at a vehicle level, the second one aims to ensure the emissions compliance of a vehicle type, hence at a fleet level. To that end, the distance-specific emissions calculated on-board will also be sent over-the-air (OTA) and collected by the authorities to compare these levels to the limits.

The successful implementation of the OBM concept relies on two major aspects: first, it considers that current and future production emission sensors are robust and accurate enough to provide valuable information about the concentration emitted by the vehicles. In this regard, many works have already investigated the possibility of using the performance of such sensors for real-driving emissions characterization, e.g., in smart emission measurement systems (SEMS) (Vermeulen et al., 2012; Heepen and Yu, 2019). Thanks to this measurement and the information already available in modern vehicles, emission levels similar to those obtained by PEMS during RDE tests can be inferred on-board (Yu et al., 2021; Jeong et al., 2023). Secondly, OBM will also require to transmit some information over-the-air for market surveillance, and harnesses therefore the increasing vehicles connectivity and cloud analysis capabilities (Guerrero-ibanez et al., 2015; Guardiola et al., 2021). In conclusion, by continuously monitoring emissions, offering user warnings, and ensuring conformity to the emission limits, OBM promises to play a pivotal role in mitigating air pollution and advancing towards a cleaner transportation sector.

This research paper reviews and discusses some aspects of the on-board monitoring concept as presented by Franco et al. (2023) and by the Advisory Group on Vehicle Emission Standards (AGVES) (European Union, 2023). In particular, this work explores the OBM's feasibility in the context of the upcoming Euro 7 standard by applying its definition to real-driving emissions data from a vehicle with current sensor technology, hence offering insights into its potential outcomes and challenges. The results provided in this paper, which emphasize the implications of on-board emissions measurement systems, are based on a real-world database from an in-service mild-hybrid C-segment Euro 6d-Temp diesel vehicle. The ins and outs of the Euro 7 emission standard, as well as its implementation, are still under discussion with most of the methodology documents remaining at a draft stage, hence subject to changes. This paper relates therefore to the OBM-RDE definition, and their interpretation by the authors, at the time of writing.

This article is organized as follows: first, further details about the OBM concept as found in present literature and in the AGVES repository are provided. Then, the setup and the database used in this study are described, providing the reader with more information regarding the real-driving data acquisition. The fourth section outlines the steps leading to the calculation of the distance-specific emissions required by the OBM system. The results are then presented and discussed and, finally, some conclusions about the findings of this work are summarized.

2. OBM concept

This section explores in detail the expected OBM implementation. The most relevant features of the concept are reviewed and will serve as the basis for the analysis proposed in this work. The information provided below is, for the most part, based on Franco et al. (2023) (article published by the stakeholders that shaped the OBM concept), and the information found in the AGVES repository (European Union, 2023).

As stated in the Euro 7 standard proposal (European Commission, 2022b): "*'on-board monitoring system' or 'OBM' means a system on board a vehicle that is capable of detecting either emission exceedances or when a vehicle is in zero emission mode if applicable, and capable of indicating the occurrence of such exceedances by means of information stored in the vehicle, and of communicating that information via the OBD port and over the air*". This definition expresses three main aspects of the OBM concept that we discuss below.

Detecting emission exceedances. The feature at the core of the OBM concept is the effective detection of high emitting vehicles. The evaluation of emissions by the OBM system will provide two indications of tailpipe emissions: an unprocessed emission value as 'perceived' by the environment, and a processed result similar to what would be obtained during an in-service conformity (ISC) test where the extended driving divider is considered as described in the RDE regulation (European Commission, 2023b). The OBM and the definition of the RDE-ISC testing are therefore closely related. Both the *unprocessed* and *ISC-processed* distance-specific emissions will be calculated in-vehicle at the end of each trip, expressing emissions in milligrams per kilometer. The goal is to monitor the levels emitted by the vehicle and compare them to the limits summarized in Table 1. To this end, the OBM requires to monitor the total amount of pollutants emitted, and divide it by the distance traveled by the vehicle during the trip. A special treatment will be applied for trips below 10 km where the distance-specific emissions will be obtained by dividing the total emissions in [mg] by a distance of 10 km to account for the emission budget distance.[1] The manufacturer will be free to use any source of information and solution at its disposal to estimate the distance-specific emissions of a vehicle. A combination of sensors reading supported by exhaust emissions models might therefore be envisioned (Jaikumar et al., 2017; Fernandes et al., 2019; Le Cornec et al., 2020; Barbier et al., 2023). This is particularly true for cold start trips due to the present limitations of current sensors (e.g., light-off) which make measuring emissions within several seconds after a cold start event challenging (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2022; Todo et al., 2018). The OBM implementation is consequently likely to follow two phases: a short/mid-term phase, recommended for introduction with the Euro 7 regulation, focusing on monitoring NO_x, NH_3, and particulate matter (PM) emissions using current and improved sensors and models; and a long-term phase, which requires significant advancements in sensor technology to effectively monitor all pollutants. To estimate the distance-specific emissions, the vehicle must provide a continuous time-resolved (1 Hz) measurement of the pollutants to the OBM system. However, by design, most of current production PM sensors lack this capability (Kamimoto, 2017; Premnath et al., 2020; European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2022). As a result, in the first phase of the OBM system deployment, only NO_x and NH_3 distance-specific emissions will have to be calculated for each trip. During an in-service conformity test, the accuracy of the OBM system will therefore be assessed by comparing the ISC-processed emissions of NO_x and NH_3 to those obtained from the ISC test measurement systems. Nevertheless, despite not being considered for trip values, PM emissions will still have to be addressed by OBM to assess the probability of high soot emissions, whose detection will undergo the same communication and inducement procedure than NO_x and NH_3, as discussed below.

---

[1] The Euro 7 standard aims at guaranteeing that a vehicle is environmentally efficient under as many driving conditions as possible. To this end, any trip distance should be considered as valid. Given that most of the emissions are encountered at the beginning of a trip, especially in short trips with cold start conditions, a two-area limitation was proposed. First, a constant [mg] limit defines the maximum emissions allowed up to a certain distance: this is the emission *budget*. Then, the conventional [mg/km] limit applies. For a trip with a distance below 10 km, the total trip emissions should be compared to the budget limit, while they should be directly compared to the distance-specific emission limit for longer trips. This allows to account for any trip distance while still leaving some margin to very short trips, which would not be possible with a single [mg/km] limit. This concept is not further discussed here as, according to the authors' understanding, it will not be part of the OBM per se since this system will only consider [mg/km] values.

Table 1
Euro 7 exhaust emission limits for light-duty vehicles (M_1) with internal combustion engine (European Commission, 2022a).

Pollutant in mg	Emission limit per km	Pollutant in mg	Emission limit per km
NO_x	60	CO	500
NH_3	20	THC	100
PM	4.5	NMHC	68
PN_{10} (in #)	6×10^{11}		

Indicating the occurrence of such exceedances. The comparison of the distance-specific emissions calculated at the end of each trip with the emission limits by the OBM system shall activate, or not, the excess emissions driver warning system (EEDWS) through the malfunction indicator lamp (MiL). The EEDWS is designed to inform the driver about an excess of emissions from the vehicle, and induce the vehicle's repair accordingly. Ultimately, in cases where the required repairs are not carried out, the OBM system will have the capability to prevent engine restart. The status of this system can result in three different states: 'normal', 'intermediate' or 'error'. In the case where the EEDWS enters in 'error' mode, it means that the vehicle was detected as consistently emitting high levels of pollutants with required actions on the emission control systems. As a rule of thumb, the error status should be activated when the emissions evaluated by the OBM system are above 2.5 times the limit defined for the pollutant. This threshold is aligned with the current regulation, indicating that a vehicle measured with emission levels above 2.5 times the limit would be considered as an 'extreme outlier' in the ISC statistical procedure (European Commission, 2023b). However, many conditions might occasionally result in high emissions (e.g., towing), and switch the EEDWS to an error status could cause unjustified inducement and unnecessary repairs. In this regard, the EEDWS status should not be seen as an indicator of the last trip but as a general diagnostic of the vehicle's state of health regarding the control and level of emissions. This status is therefore not fixed in time and is allowed to 'self-heal'. The strategy behind the status of this system and its evolution will be in the hands of the manufacturer, with the only requirement being that high emitting vehicles are timely and effectively detected.

Communicating that information. Whether it be for verifying the faithful representation of the vehicle's emissions by the OBM system during an ISC test, or for market surveillance (MaSu) purposes to monitor the emissions distribution of a vehicle family, the emissions assessed by the OBM system require some means of communication. The former can easily be accessed through the OBD port where time-resolved data such as emissions rate should also be made available to support testing. The latter, however, requires another approach. In this case, the trips' distance-specific emissions will be randomly selected and stored inside the vehicle before being anonymously transmitted to authorities over-the-air. The goal here is to leverage the significant amount of data generated in such situation to obtain a better representation of the emissions from a specific vehicle type against the limits. The rules concerning the data transmission and ownership are not discussed here, but can be consulted in Franco et al. (2023) and European Union (2023).

Fig. 1 summarizes the aforementioned aspects of the OBM concept. Both the unprocessed and ISC-processed emissions paths are shown and their applications are illustrated as well. In particular, the ISC-processed emissions are depicted at the basis of the EEDWS status and inducement procedure. Their levels are also relevant during an ISC test in order to evaluate the correct representation of the emissions by the OBM system by comparing them to the levels obtained by PEMS during the RDE test. In such case, the ISC-processed emissions from the OBM must not underreport the levels measured by the PEMS to more than a certain threshold, so far suggested to 30%–42% depending on the situation. In any case, the EEDWS status is previously required to evaluate if a vehicle is suitable for the ISC statistical procedure, an 'error' status discarding the vehicle. Finally, market surveillance of vehicle types will be ensured by over-the-air transmission of the emission levels. Again, the reader is invited to refer to Franco et al. (2023) for a thorough description of the OBM concept.

Now that the main aspects of the OBM concept have been presented, and before describing the steps for the distance-specific emissions calculation, the next section introduces the specifications of the vehicle used in this study, the set of sensors and vehicle parameters considered to assess its emissions, and the real-driving database investigated to contextualize the results that will be provided later.

3. Setup and database

3.1. Vehicle layout

The analysis of the OBM concept in this work involves a mild-hybrid diesel vehicle manufactured and registered as Euro 6d-Temp, which specifications can be found in Table 2. The vehicle comes with a turbocharged 2.0 liter engine equipped with both low-pressure (LP) and high-pressure (HP) exhaust gas recirculation (EGR). The exhaust after-treatment systems (EATS) consist of a diesel oxidation catalyst (DOC), a selective catalytic reduction (SCR) system and a diesel particulate filter (DPF) for low tailpipe emissions. The engine also embeds many sensors aimed at controlling and monitoring its proper operation, of which the majority of the ones considered in this study are illustrated in the engine's layout representation in Fig. 2.

The proper control of the SCR is monitored thanks to two NO_x sensors placed on each side of the catalyst. The upstream sensor measures the engine-out NO_x amount, while the downstream sensor reads the tailpipe emissions after passing through the SCR where the injection of urea is used to decrease nitrogen oxides emission levels (Yuan et al., 2015; Praveena and Martin, 2018). The

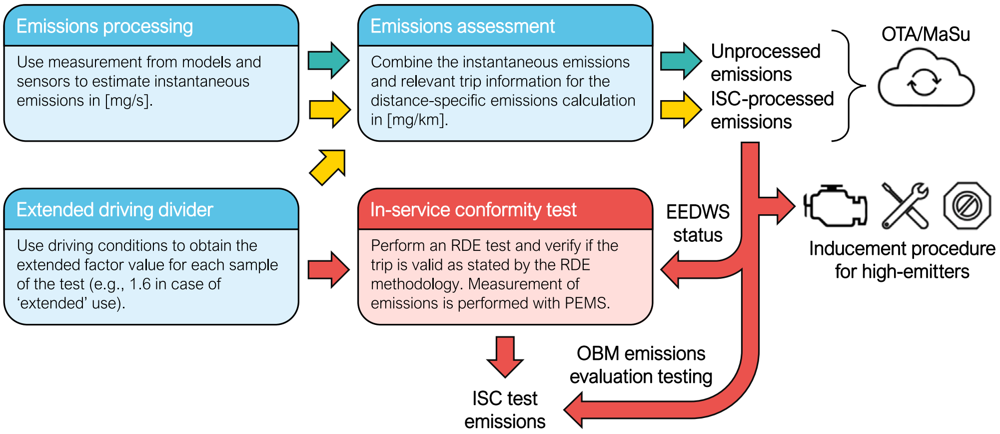

Fig. 1. Illustration of the main aspects of the OBM concept.

Table 2
Vehicle specifications.

Car segment	C-segment
Powertrain architecture	Mild-hybrid
Engine architecture	In-line 4-cylinder
Engine type	2.0 L compression ignited
Fuel	Diesel
Maximum engine power	110 kW
Vehicle mass	1680 kg
Frontal area	2.62 m^2
Drag coefficient	0.32
Tyre rolling resistance coefficient	0.0065[a]

[a] According to the European Parliament and Council (2020) for C1 tyres with fuel efficiency class A.

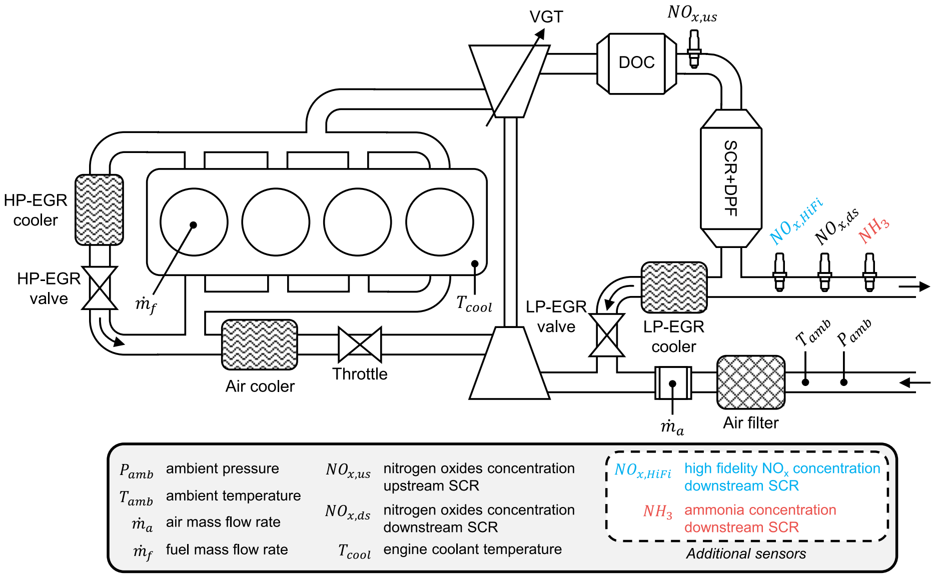

Fig. 2. Engine and exhaust after-treatment systems layout from the vehicle with original and additional sensors used in this work. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Emission sensors specifications.

	NO_x sensor	NH_3 sensor
Provider	Bosch	ECM
Model	EGS NX2	From NH3CAN Kit
Measuring range	0-3000 ppm	0-2000 ppm
Accuracy	±7 ppm at 90 ppm	±5 ppm from 0 to 200 ppm
Response time	~1.8 s	<1 s

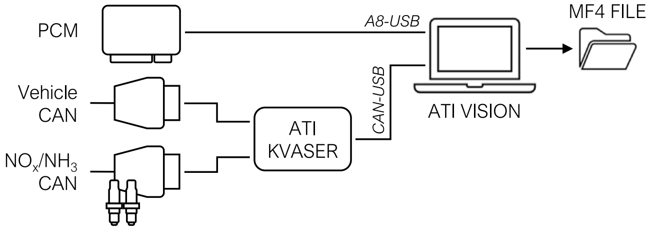

Fig. 3. Data acquisition systems communication layout for everyday trip data recording.

specifications of these sensors are provided in Table 3. One drawback from these on-board sensors is that they used to embed a conditioning strategy that makes their reading unavailable for several seconds after cold start. However, cold start emissions were also found to be the major contributor to the overall trip emissions, hence representing a significant loss of potential emissions information (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2022; Bielaczyc et al., 2020; Du et al., 2020; Chen et al., 2023). As a result, emission models are likely to substitute sensor reading during this duration and, in a later phase, future generation sensors are expected to address this issue by reducing the time until the sensor is ready to measure. In this study, an additional sensor was placed close to the original downstream NO_x sensor (indicated in blue in Fig. 2). This sensor was the same sensor than the upstream and downstream sensors with the difference that this one was powered prior to the vehicle start. Consequently, its readiness would be reached earlier and it should provide a more representative estimation of the emissions. On purpose, this sensor was chosen among the sensors identified as of high-fidelity (HiFi) by the supplier.

The Euro 7 standard proposal specifies that NH_3 should also be part of the monitored exhaust gases. Tailpipe NH_3 emissions in diesel vehicles result mainly from the SCR control (i.e., NH_3-slip), especially if the EATS do not include an ammonia-slip catalyst (ASC) (Girard et al., 2007). In this work, a NH_3 sensor (shown in red in Fig. 2) was installed downstream the SCR to measure the emission levels during the vehicle operation. More information about this sensor can also be found in Table 3.

3.2. Database

Over a series of real-world driving scenarios, data were collected and examined to gain insights into the vehicle's behavior and performance characteristics. For every trip, a file populated by data collected from the different embedded sensors was generated.

In this setup, the vehicle is equipped with an open powertrain control module (PCM) that provides access to crucial vehicle, engine and emissions variables. The data acquisition layout is composed of three main systems: the PCM, the vehicle CAN bus, and the CAN bus from the additional NO_x and NH_3 sensors. The PCM is connected to a computer through A8 serial interface and ATI Vision software is used to access the information. Finally, an ATI Kvaser is used to get access to the CAN buses via the computer, as illustrated in Fig. 3. The information from the vehicle that is collected by the PCM is recorded every 10 ms, as is the additional emission sensors reading, while the vehicle CAN bus information exhibits different sampling rates depending on the variable. All this information is gathered and stored in a file in MF4 format which is the standard file format in the automotive industry for CAN bus and sensor data reading from engine control units.[2] Among all the variables that populate these files, the ones required by the OBM concept were selected to carry out the analysis. Some of them, which are commonly monitored and already available in modern vehicles, were already presented in Fig. 2, while others such as vehicle or engine speed are standard.

The vehicle used in this study serves various investigation purposes in which the original vehicle layout might be modified. In this work, only the trips with the same layout and performed under nominal driving conditions and style were considered. The resulting database contains 574 trips distributed between February 2022 and May 2023 with around 16,500 km of various ambient and driving conditions across southern Europe. As depicted in Fig. 4, most of the database is located in the region of Valencia in Spain, and is composed for almost 60% of motorway conditions (i.e., distance share from total database with speeds above 90 km/h, urban being from 0 to 60 km/h and rural between 60 and 90 km/h).

---

[2] More information at: https://www.asam.net/standards/detail/mdf/wiki/.

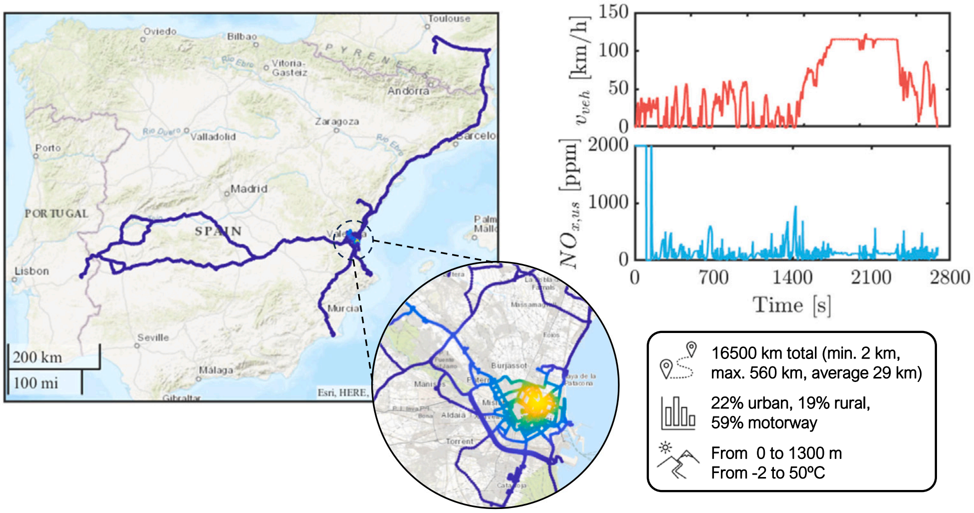

Fig. 4. Real-driving database information with geographical location of the data (left), and illustration of the signals recorded in real-time within the vehicle, here vehicle speed v_{veh} and upstream nitrogen oxides sensor signal $\mathrm{NO}_{x,us}$ (right).

Table 4
Driving conditions and emissions divider in the Euro 7 standard for light-duty vehicles (European Commission, 2022a).

Parameter	Normal driving conditions	Extended driving conditions
Extended factor	–	1.6[a]
Ambient temperature	0 °C to 35 °C	−10 °C to 0 °C or 35 °C to 45 °C
Maximum altitude	700 m	>700 m and <1800 m
Maximum speed	Up to 145 km/h	Between 145 and 160 km/h
Power metric	<20%	>20%
Minimum mileage[b]	10000 km	Between 3000 and 10000 km

[a] Emissions should be divided by this factor during the time when one of the conditions in this column applies.

[b] The vehicle mileage at the beginning of the database considered in this work was around 14000 km, hence *normal* driving conditions.

4. Distance-specific emissions assessment

This section describes the different steps followed to obtain the distance-specific emissions needed in the OBM environment (e.g., excess emissions driver warning system and market surveillance). In particular, the ISC-processed emissions will have to account for some of the aspects provided in the RDE methodology (see Fig. 1). Given that the final version was not yet available at the time of writing, features published in draft versions and assumptions based on the RDE legislation in force were combined. Before proceeding to the execution of the calculation, all the variables recorded by the vehicle were down-sampled to 1 Hz in order to respect the sampling frequency specified for time-resolved data in the OBM-RDE definition (European Union, 2023; European Commission, 2023b).

4.1. Normal and extended conditions

Extreme conditions such as very high ambient temperatures or altitudes might alter the performance of the vehicle and make the proper operation of the emission control systems challenging. These conditions, which differ from the *normal* conditions, used to be referred to as *extended* in the RDE methodology definition. During a real-driving emissions test, authorities have decided to account for the effect of these specific conditions on the vehicle's emissions by dividing the emissions during the time where extended conditions are encountered by a factor of 1.6. The same procedure must then be applied by the OBM system when computing the ISC-processed emissions. Table 4 summarizes the recommended boundaries for the upcoming Euro 7 standard, in which the ranges were updated in order to cover the most common usages and conditions found in Europe (for a definition of the boundary conditions in the current RDE package, please refer to the European Commission (2023b) document).

The application of the dividing factor, hereafter named *extended factor* (EF), is as follows: each 1 Hz measurement sample should have its corresponding factor set to 1 within normal driving conditions, and 1.6 in extended conditions. However, the extended factor can apply only once. This means that if two extended conditions are found at the same time (e.g., high temperature and high altitude), these measurement samples are considered invalid and removed from the ISC-processed calculation.

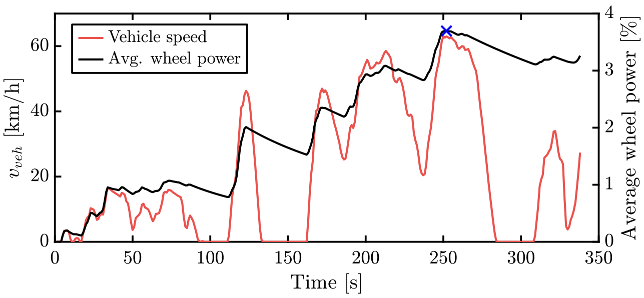

Fig. 5. Representation of the average wheel power signal used to obtain the power metric in the initial 2 km after a cold engine start. The power metric value is shown with a blue cross. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Power metric

The recognition of emissions excess during the initial 2 km of a trip after a cold start motivated the inclusion of a 'power metric'. The period directly after a cold start is particularly crucial as tailpipe pollutant emissions depend strongly on the engine-out levels. This is mostly due to the insufficiently warmed state of the engine and emission control systems, where the power output and exhaust emission mass flow might have a significant influence on the resulting tailpipe levels (Prakash and Bodisco, 2019). Under normal driving conditions, power demand is typically low (e.g., starting from a parking and driving around the city), but in extended scenarios like trailer towing or uphill acceleration, power demand can be substantially higher. To distinguish between normal and extended conditions, and therefore set appropriate emissions assessment, the power metric will be considered in the characterization of the driving conditions, as reported in Table 4. This value is based on the maximum of the average wheel power during the first 2 km of driving and is obtained as follows:

$$Power\ metric = max\left(\frac{\frac{\sum_{1}^{t_{n,max}}\left(P_{driving}\Delta_t\right)}{t_n}}{P_{rated,vehicle}}\right) \tag{1}$$

with $\Delta_t = 1$ s, $t_n = 1 : t_{n,max}$ and $t_{n,max}$ is the time elapsed to cover the 2 km distance. For each time step, the cumulative positive energy is calculated and divided by the cumulative time t_n (numerator of Eq. (1)). This value is then normalized by $P_{rated,vehicle}$ which corresponds to the maximum engine power, here considered as specified by the manufacturer. The maximum value in this average wheel power vector provides finally the power metric, which value defines if the cold start trip falls into normal or extended conditions. The instantaneous driving power $P_{driving}$ should be calculated as follows (European Union, 2023):

$$\begin{aligned} P_{driving} &= \left(F_{rolling} + F_{climbing} + F_{acceleration} + F_{air}\right)\frac{v_{veh}}{3.6} \\ &= \left(m_{veh}\cdot g\cdot f_r\cdot\cos\alpha + m_{veh}\cdot g\cdot\sin\alpha + m_{veh}\cdot a_{veh}\cdot e + c_d\cdot A_{veh}\cdot\frac{\rho_{air}}{2}\left(\frac{v_{veh}}{3.6}\right)^2\right)\frac{v_{veh}}{3.6} \end{aligned} \tag{2}$$

with $e = 1 + \frac{J}{m\cdot r^2} < 1.1$. In European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (2022), a simplified version of the instantaneous power calculation employed a value of $e = 1.07$. Given that no information about the moment of inertia J was known to the authors, the value of $e = 1.07$ was considered. The information about the vehicle mass (m_{veh}), drag coefficient (c_d), frontal area (A_{veh}), and tyre rolling resistance coefficient (f_r), were provided in Table 2. The air density ρ_{air} was obtained directly from the ambient conditions, the vehicle acceleration a_{veh} was calculated from the vehicle speed as defined in the RDE regulation, and the road grade, here represented by $\sin\alpha$, was determined from the variable $road_{grade,2}$ found in the RDE definition as well (European Commission, 2023b). This variable is a smoothed version of the road gradient based on the vehicle altitude measurement. Although not yet specified in the new regulation, the authors judged that considering this smoothed approach was consistent with the rest of the RDE methodology and should not represent a challenge for in-vehicle calculation (the reader is invited to refer to the European Commission (2023b) document for a detailed description of the road gradient calculation). This value was therefore selected and then used to obtain $\cos\alpha$ required for the rolling resistance in Eq. (2). Fig. 5 shows the average power demand during the initial 2 km where the maximum value, indicated by a blue cross, gives the *power metric* level for this trip.

The first two kilometers of a trip after a cold start for internal combustion engine vehicles should respect the following specifications (European Union, 2023):

- A cold start is defined as a trip with a coolant temperature below 70 °C at the first start of the internal combustion engine (ICE). The ICE start distance is then reached once the vehicle has run for 2 km.
- Compared to the other parameters that define the driving conditions (see Table 4), the application of the extended factor differs for the power metric: its value applies for the whole 2 km distance. As an example, in Fig. 5, since the power metric is below 20%, the initial 2 km distance falls in normal driving conditions. If this value was above 20%, then the extended factor for all the samples in these 2 km would have been 1.6.

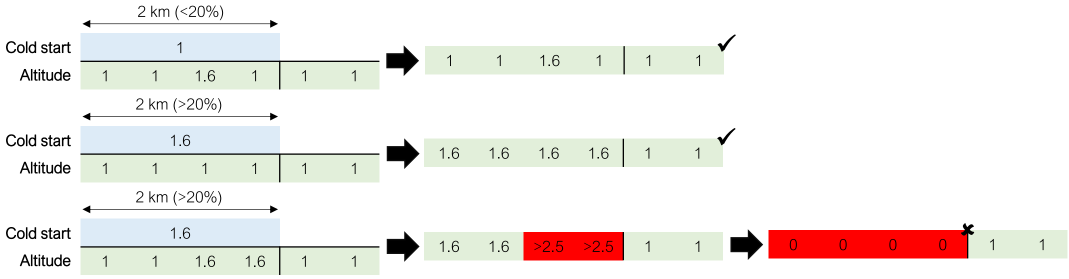

Fig. 6. Illustration of the extended factor characterization for the measurement samples according to the cold start conditions.

Fig. 6 illustrates the idea behind the power metric and driving conditions characterization. Three cases are shown: a cold start with a power metric below 20% (top), and two with a value above this threshold (middle and bottom). Here, the altitude is used for illustration purposes but the conclusions provided still apply for the other parameters that define the driving conditions. By definition, the first case (top) falls within normal conditions since the power demand was below the specified threshold. Consequently, although the altitude was detected in extended conditions, only this specific amount of time receives the 1.6 extended factor and all samples are worth considering. In the second example (middle), the power demand in the initial kilometers is too high and a factor of 1.6 should be applied to the whole 2 km distance. Given that no other extended condition was found in this interval, all the samples are again valid for the emissions calculation. The last case (bottom) exhibits the same power metric conditions than in the previous one. However, here, the altitude was also found in extended conditions during this same interval. Because of this situation, the measurement samples with more than one extended condition must be considered invalid, as it was previously mentioned. Furthermore, according to the rules specified for the initial 2 km after a cold start, any invalid point in this interval invalidates the whole distance. The 2 km are then no longer valid for emissions assessment and only the samples after this distance will contribute to estimate the emissions of the vehicle in the ISC-processed calculation.

4.3. Emissions calculation

The whole process in the emissions calculation is based on the gas concentration measurement at the exhaust. However, NO_x sensors are prone to what is known as the NH_3-cross sensitivity, which is one of the main causes of NO_x measurement deviation (Funk, 2021; Pla et al., 2021). The NH_3 resulting from the SCR control gets oxidized in the NO_x sensor, more nitrogen oxides than the actual value are measured and an offset is therefore observed (Frobert et al., 2013; Pla et al., 2022). Given that the Euro 7 standard expects to introduce NH_3 in the monitored exhaust gases, this sensitivity must be accounted for in the calculation procedure in order to properly address NO_x emissions. While more sophisticated models exist (Nakaema Aronis, 2023), a reasonable approach consists in considering the following approximation (Guardiola et al., 2020):

$$\mathrm{NO}_{x,real} = \mathrm{NO}_{x,sensor} - 0.67 \cdot \mathrm{NH}_3 \tag{3}$$

Such approach was considered in this study and every distance-specific NO_x result provided in the following refers to the corrected concentration that was obtained after removing the concentration measured by the NH_3 sensor. Furthermore, considering that the gases concentrations were measured directly at the exhaust by the dedicated sensors, the concentrations were considered to be measured on a wet basis and so no further processing was required. Finally, the concentration measured by the sensors were set to zero, as proposed by the current RDE package (European Commission, 2023b), when the engine speed was less than 50 rpm, meaning that the engine was deactivated.

In order to obtain the distance-specific emissions, it is first necessary to obtain the mass flow rate of every exhaust component, here in [mg/s]:

$$\dot{m}_{gas} = u_{gas} \cdot c_{gas} \cdot \dot{m}_{exh} \tag{4}$$

where the gas concentration c_{gas} in [ppm] and the exhaust mass flow rate $\dot{m}_{exh}$ in [kg/s] are multiplied by the ratio of the densities of the gases in the exhaust u_{gas}. In this case, $u_{\mathrm{NO}_x} = 1.593$ and $u_{\mathrm{NH}_3} = 0.5896$, and the exhaust flow rate was inferred with the method that uses the air and fuel mass flow rates:

$$\dot{m}_{exh} = \dot{m}_a + \dot{m}_f \tag{5}$$

While $\dot{m}_a$ was directly measured by the air mass flow sensor, the fuel flow rate was estimated by the PCM with internal injector models.

The distance-specific emissions in [mg/km] can finally be obtained from the gas flow rate and the vehicle speed v_{veh} in [km/h] as follows:

$$m_{gas,unprocessed} = \frac{\sum \dot{m}_{gas}}{\sum \frac{v_{veh}}{3600}} \tag{6}$$

Eq. (6) provides the *unprocessed* distance-specific emissions, as 'perceived' by the environment. In order to obtain the *ISC-processed* levels, $\dot{m}_{gas}$ needs to be divided by the extended factor EF for every corresponding sample, and only the *valid points* should be considered for all the variables constituting the equation (i.e., with an extended factor greater than 0):

$$m_{gas,ISC-processed} = \frac{\sum \frac{\dot{m}_{gas}}{EF}}{\sum \frac{v_{veh}}{3600}} \tag{7}$$

As mentioned in Section 2, any trip below 10 km will apply a distance of 10 km for ISC-processed emissions, i.e., the denominator $\sum \frac{v_{veh}}{3600}$ is replaced by 10. Note that in such case, the trip distance can be seen from two different perspectives: the 'real' one, as traveled by the vehicle, and the 'valid' one as obtained only from the valid points after driving conditions characterization (i.e., $EF > 0$). The distance to which are applied some rules, such as the one above-mentioned, still requires some clarification in the methodology definition. For example, it is not yet specified if a trip with a total distance of 11 km, but, with 2 km of invalid points, should be considered as a trip of 11 km, or 9 km and therefore require its distance-specific emissions to be obtained by applying a distance of 10 km. From the authors' point of view, it was believed that considering the distance obtained after removing the datapoints with invalid conditions was the most consistent approach. In this specific example, the trip would be considered as 9 km long and would apply a reference distance of 10 km for the emissions calculation. Note, however, that this applies only for ISC-processed levels since the trip distance is directly applied for the unprocessed value calculation (all samples are considered in the unprocessed assessment).

4.4. Regeneration events

The Euro 7 standard proposes to address the distance-specific emissions from trips with regeneration events by a weighted average approach (European Union, 2023):

$$m_{gas,trip} = \frac{m_{gas,regen}\overline{d_{regen}} + m_{gas,\neg regen}\overline{\Delta_{regen}}}{\overline{d_{regen}} + \overline{\Delta_{regen}}} \tag{8}$$

where $m_{gas,regen}$ and $m_{gas,\neg regen}$ are respectively the distance-specific emissions of the exhaust gas component *during* and *outside* of the regeneration event for the trip in [mg/km], and $\overline{d_{regen}}$ and $\overline{\Delta_{regen}}$ represent the average *distance* and *interval between two events* of the last 10 regenerations in [km]. This supposes therefore that the vehicle will save the information from at least the last 10 regeneration events over the lifetime of the vehicle.

The characterization of the average distance and interval between two regeneration events requires that the vehicle provides a regeneration flag. Such variable is commonly found in recent vehicles to indicate in which mode the engine is, e.g., fast catalyst light-off or regeneration. The distance between regeneration events Δ_{regen} is considered as the distance between the end of one regeneration event and the start of the next one.

Some of the requirements to be considered in the processing of trips with regeneration events are provided and discussed below:

- The extended factor still applies during the regeneration event. Consequently, any time interval found in extended conditions has to be divided by the extended factor before performing the final calculation. Similarly, if the conditions are invalid, the data during this interval will not be considered in the calculation.
- In the current methodology draft, $m_{gas,\neg regen}$ must exclude the 2 km after first engine start. At this stage, no details were mentioned regarding specific vehicle's starting conditions for this requirement, such as cold or hot start. Consequently, in this work, the first 2 km were always removed from the calculation for trips with a regeneration event. Of course, this assumes that the regeneration event does not start during this starting distance, which is very likely to be expected in normal driving conditions exempted from regenerating system failure.
- The trip distance must be greater than 10 km. At this time, no information was provided whether this distance corresponds only to valid points as mentioned earlier, or if it is related to the trip distance itself before any processing is applied. In order to be consistent with the previous assumptions, in this work, this distance was considered to be the sum of valid points in the trip (i.e., $EF > 0$) where it was considered that the lower limit of 10 km was required to be representative of a trip with a regeneration event.
- The regeneration distance must be shorter than the non-regeneration distance, otherwise "*the emissions for the non-regeneration period shall be determined by a separate test*" (European Union, 2023). Given that this condition was expressed for the RDE test in ISC conditions, in this work, it was decided to exclude any trip where such situation would occur. Indeed, in real-driving conditions, the driver is not following a procedure and such situation might be encountered. Considering that, so far, no details were provided for the OBM calculations in this specific case, removing such trips from the emissions analysis was considered a more appropriate approach.

As mentioned in Section 3, the vehicle at hand was used in different investigation studies, which resulted in some modifications of its layout over the research activities. Similarly, some trips might have not been registered and the continuous monitoring of the kilometers traveled by the vehicle is therefore not always ensured. For all these reasons, the authors have decided to use all the consecutive regeneration events available in the database to characterize $\overline{d_{regen}}$ and $\overline{\Delta_{regen}}$. This approach means that a single value for each of these variables will be obtained from the mean of the database and then be used throughout the analysis instead of being updated from the last 10 regeneration events as originally required. Fig. 7 shows the distance and interval levels from all

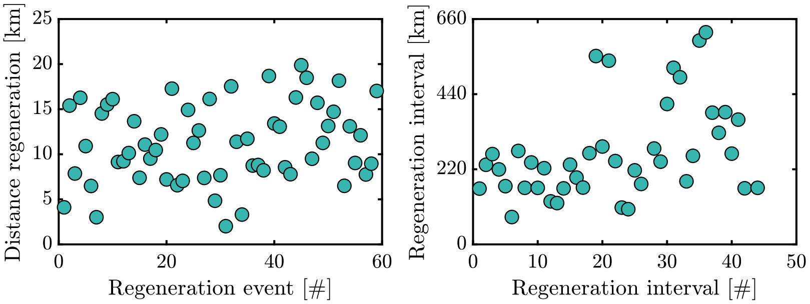

Fig. 7. Analysis of the regeneration events from the database: distance of regeneration (left) and interval between two consecutive regeneration events (right).

Table 5
Regeneration events characterization results.

	Quantity	Mean	Standard deviation
Regeneration distance [km]	59	11.2	4.35
Regeneration interval [km]	46	270.5	140

the regeneration events found in the database. A total of 59 regeneration events (left plot) and 46 intervals (right plot) were found, with a maximum of 9 consecutive events before a modification in the vehicle layout or a break in the vehicle mileage continuity occurred and therefore forced the reset of the interval counter. Note that in this characterization, the distances provided correspond to the actual values measured no matter if the driving conditions were normal, extended, or invalid. The results are summarized in Table 5, in which the mean values of 11.2 km and 270.5 km will later be used respectively as $\overline{d_{regen}}$ and $\overline{\Delta_{regen}}$ in Eq. (8). The high standard deviation in the regeneration interval levels was justified by the different conditions encountered when a regeneration occurred. If the vehicle was mainly used in urban and rural conditions, regeneration events used to be more frequent (around every 220 km in this case). However, if a regeneration event occurred at the beginning of a very long highway trip (> 500 km), the vehicle might not require to regenerate the DPF system for more than 600 km because of better vehicle emissions performance in these conditions.

5. Results and discussion

The aforementioned aspects and calculation method of the OBM concept were applied to the database described in Section 3, and the results are analyzed below. Note that the levels of pollutants provided in this section result from the processing of the concentration measured by the exhaust sensors. These results are therefore not representative to, nor compared to, PEMS standard. Here, the goal is to evaluate what would be measured by the OBM system in an in-vehicle situation. Also, it is important to remind that the results reflect the outcomes of a vehicle that was not developed for the Euro 7 standard and should therefore be considered with care when comparing with the emission limits. Similarly, as described in Section 3, most of the database is located in the region of Valencia in Spain. The emissions of the vehicle are consequently representative of the driving conditions in this area, and would likely differ if encountered in another part of the world.

5.1. Database against Euro 7 definition

Fig. 8 shows the effect of the new driving conditions definition in the Euro 7 standard compared to the current RDE package on the real-driving database from this study. The left plot shows the distribution of the power metric value obtained in trips with a cold start where the vertical dashed line indicates the transition between normal and extended driving conditions. It can be observed that none of the 454 cold start trips contained in the database has run with a maximum average wheel power more than 20% within the initial 2 km. The right plot shows the distribution of the driving conditions found in the database depending on the RDE definition. The modification in the boundaries resulted in an increase of trips fully consisting of normal conditions, which is explained by the wider range of altitude and temperature, hence justifying the decrease observed in trips containing extended and invalid points. Note that in this figure, *invalid* means any trip that exhibits samples whether outside of the specified boundaries, or made up of two extended conditions at the same time.

5.2. No_x sensor light-off effect

As mentioned in Section 2, one of the current challenges in cold start trips is the accurate measurement of initial emissions due to long light-off delays in emission sensors. This duration can last for several seconds in NO_x sensors and a significant loss of information is therefore expected. As a result, solutions such as emission models are foreseen in the OBM system to substitute the sensor reading during this critical time. In this work, an additional NO_x sensor, that was actuated in such a way that it would reach

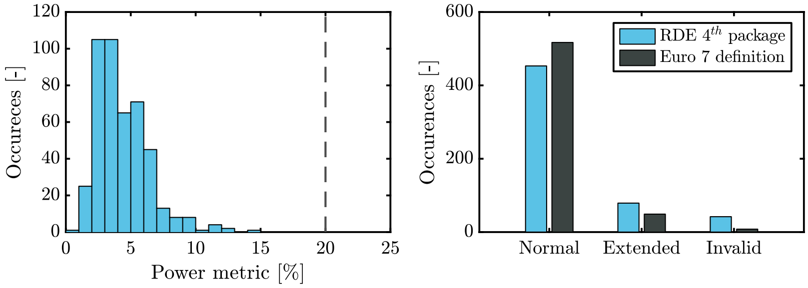

Fig. 8. Effect of the modification in the definition of the driving conditions boundaries on the characterization of trips: power metric of every cold start trip (left), and distribution of the driving conditions found in the database (right).

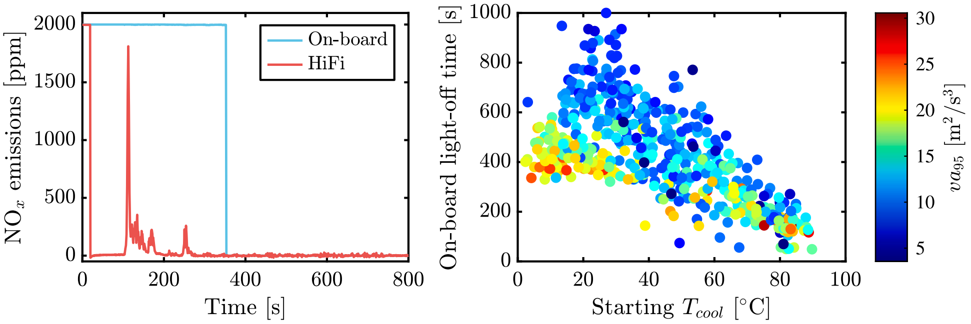

Fig. 9. NO$_x$ sensor light-off effect analysis: comparison of on-board and HiFi sensors signal in a typical trip (left), and light-off time as a function of starting coolant temperature and va_{95} (right).

its operating conditions early on, was placed on the exhaust line (more information in Section 3). The goal with this sensor was to recover as much emission concentration information as possible. Fig. 9 presents the effect of the light-off time on the measurement carried out by these sensors in the present layout. The left plot shows an example where the strategy embedded in the on-board sensor makes its measurement unavailable for a significant amount of time (around 350 s at a default level of 2000 ppm in this trip). The signal from the HiFi sensor, which exhibits a faster activation time, illustrates concretely the emissions information that would be lost if relying only on the on-board sensor. The right plot of this figure gathers the light-off time needed for the on-board sensor to measure NO$_x$ emissions as a function of the starting coolant temperature. The filling of every marker is based on the 95th percentile of the product of the actual vehicle speed per positive acceleration during the light-off time period (va_{95}). This parameter is defined in the RDE methodology to characterize the driving dynamics of a trip (European Commission, 2023b). In other words, the higher the value of va_{95}, the more aggressive is the driving. This plot shows that, in general, for similar operating conditions at the start of the vehicle, the driving style during the initial kilometers plays a significant role in getting an operational emission measurement. With a more aggressive driving style, more fuel is injected in the engine, more energy is released, and a faster increase of the exhaust temperature is expected. As a result, the sensor can reach its operational temperature faster.

As presented in left plot of Fig. 9, the long light-off time for the sensor to be ready to measure emissions can be responsible of a significant loss of information. Fig. 10 quantifies this aspect. The left side of this figure compares the distance of measurement from both sensors to the total trip distance, once they have reached their complete measurement capacity. It can be observed that the HiFi sensor outperforms the on-board sensor in recovering the driving distance (represented by the red dots over the black line). This is especially true for trips below 30 km due to the higher proportion that the light-off delay represents in these conditions. On the other hand, the right side addresses the proportion of NO$_x$ that was measured by the HiFi sensor during the on-board sensor light-off time for every trip compared to the overall quantity (obtained by integrating the NO$_x$ mass flow rate described in Eq. (4)). This value expresses therefore the proportion of NO$_x$ that has been “lost” by the on-board measurement and which would need to be replaced by models in future vehicle applications if the light-off time is not reduced. In particular, this plot shows the values from trips without a DPF regeneration to better appreciate this quantity, as a regenerative trip would naturally increase the total quantity and proportionally reduce the contribution of the light-off interval. In general, no matter the distance of the trip, the sensor light-off time in cold start conditions results in more than 60% loss of the total NO$_x$ information, which aligns with the observations made regarding the contribution of cold start emissions to the overall quantity (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2022; Bielaczyc et al., 2020; Du et al., 2020; Chen et al., 2023). Therefore, long trips and hot start conditions constitute the only conditions in which the information loss could be less significant. Nonetheless, hot start conditions might still result in an important loss of information, especially for very short trips which represent one trip after another with a short amount of stopped time in between in which the NO$_x$ sensor might have cooled down faster than the engine coolant.

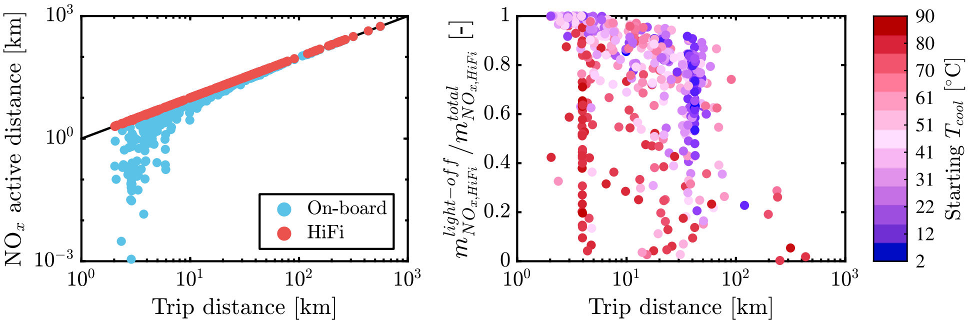

Fig. 10. Active measurement distance comparison from both downstream NO$_x$ sensors (left), and proportion of NO$_x$ emitted during the light-off interval $m^{light-off}_{NO_{x,HiFi}}$ compared to the total trip quantity measured by the HiFi sensor $m^{total}_{NO_{x,HiFi}}$ for trips without DPF regeneration (right).

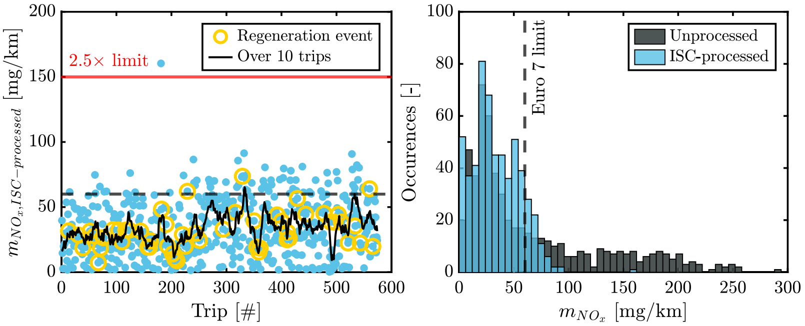

Fig. 11. Distance-specific emissions of NO$_x$ from the trips found in the database: ISC-processed emissions with standard and upper limit (left), and distribution of both unprocessed and ISC-processed emissions (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

According to these findings, the HiFi sensor was the signal considered to obtain the distance-specific emissions of NO$_x$ presented below. As regards to the NH$_3$ emissions, the NH$_3$ sensor had a similar operating strategy than the HiFi NO$_x$ sensor, allowing its measurement to be available approximately at the same time.

5.3. Emissions results

The emissions processing and calculation described in Section 4 were applied to the trips found in the database to obtain the distance-specific emissions of NO$_x$ and NH$_3$. Fig. 11 presents the results for NO$_x$ emissions. The left plot shows the trip-by-trip ISC-processed emissions as it would be obtained by the OBM system. This value is compared to the Euro 7 limit (dashed line), and also to the maximum of 2.5 times the limit which is represented by a red line. The trips with a regeneration event are highlighted with a yellow circle. The majority of the trips are below the 60 mg/km limit and only one trip was detected above the 2.5 criteria (trip 181). This specific case demonstrates some of the limitations of the NH$_3$ cross-sensitivity assessment. Fig. 12 shows the signals of the different emission sensors in this trip. The upstream and downstream NO$_x$ sensor signals from the left plot (NO$_{x,us}$ and NO$_{x,HiFi}$ respectively) illustrate that a significant emission peak is observed after 500 s in the downstream signal. However, these emissions do not seem to result from the upstream levels which remain relatively constant and below the peak observed. However, looking at the NH$_3$ signal in the right plot allows to appreciate that this increase in emissions results from an NH$_3$-slip where NH$_3$ got oxidized in the downstream sensor and ended being detected as NO$_x$ (i.e., cross-sensitivity). Nevertheless, as illustrated by the NO$_{x,real}$ signal (see Eq. (3)), the processes taking place in the SCR control are complex and the simple approach considered here resulted in an estimation of NO$_x$ that remained above the upstream levels. Properly separating the different exhaust components represents one of the main challenges in the emissions processing, and this aspect should receive a particular attention for the first implementation phase of the OBM system.

Finally, for illustration purposes, a moving average over 10 trips is also shown in a solid black line in left plot of Fig. 11. This line shows why it was mentioned that the EEDWS should not be considered as an indicator of the last trip emissions. In this case, even though a value was detected above the highest limit criteria, the performance of the vehicle over time stays relatively constant without exceeding significantly the standard limit, hence leaving some margin before reaching a critical situation.

The right plot of Fig. 11 summarizes what kind of distribution authorities could receive from over-the-air emissions transmission. In this case, both unprocessed and ISC-processed emissions are considered and compared to the limit. As expected, many trips exhibit

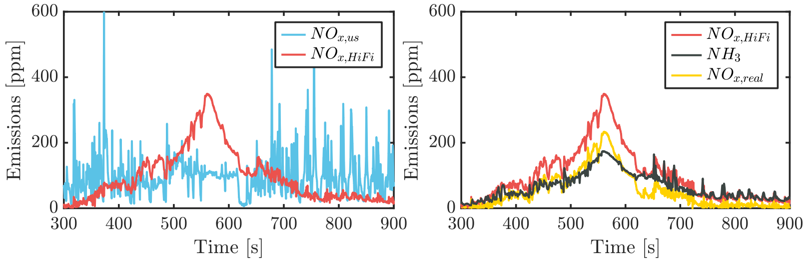

Fig. 12. Analysis of the emission sensors signals from the trip with the highest distance-specific emissions value in Fig. 11 (trip 181): NO_x signals from upstream ($NO_{x,us}$) and downstream ($NO_{x,HiFi}$) sensors (left), and NH_3 and estimated real NO_x emissions ($NO_{x,real}$) after accounting for the NH_3 cross-sensitivity (right).

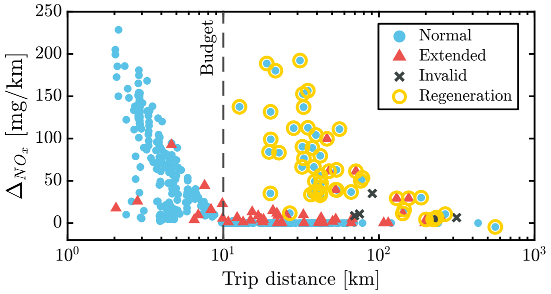

Fig. 13. Difference between unprocessed and ISC-processed NO_x emissions as a function of trip distance. Δ_{NO_x} is obtained by subtracting $m_{NO_{x,ISC-processed}}$ to $m_{NO_{x,unprocessed}}$.

unprocessed emission levels above the limit as compared to the ISC-processed values. Two main reasons explain this observation: first, trips with regeneration events will undeniably emit higher pollutant concentrations. While this effect is mitigated in the ISC-processed value by the weighted average (see Section 4 for more details), the unprocessed level represents the amount of emissions as 'perceived' by the environment, hence without any kind of post-processing. Secondly, the ISC-processed procedure considers that if a trip distance was below the budget distance (i.e., 10 km in this case), then the total emissions should be divided by this budget distance. However, the unprocessed value considers the actual trip distance to obtain the distance-specific emissions, and this will therefore undoubtedly penalize its level. These effects can clearly be observed in Fig. 13 where Δ_{NO_x}, which is obtained by subtracting $m_{NO_{x,ISC-processed}}$ to $m_{NO_{x,unprocessed}}$, exhibits a significant increase below the budget distance of 10 km, and when a regeneration event occurred during the trip. The rest of the deviations are justified by extended or invalid driving conditions found during the trip which modified the extended factor applied to the emissions concentration. Note that in some conditions, the unprocessed value might be more favorable than the ISC-processed one (see for instance the case in the lower right corner of Fig. 13 in which the value of Δ_{NO_x} is negative). Such situation is justified by the use of the weighted average calculation for the ISC-processed value (see Eq. (8)). This specific trip consisted in a long highway operation for more than 500 km in which the vehicle did not require any regeneration (the last regeneration event occurring at the very beginning of this same trip). Consequently, the denominator of Eq. (8), considering the average values, was actually lower than the actual levels, hence resulting in an increase of the distance-specific emissions ($m_{NO_{x,ISC-processed}}$ is about 4 mg/km higher than $m_{NO_{x,unprocessed}}$).

Fig. 14 provides the same analysis than in Fig. 11 but for NH_3 emissions. Similar conclusions than with NO_x were reached with respect to global emissions performance and eventual EEDWS strategy. The trip with a value above the 2.5 times the limit in the left plot corresponds to the same trip than previously mentioned in Figs. 11 and 12. Overall, the trips with higher levels correspond to situations in which a NH_3-slip occurred due to inefficient SCR operation, e.g., variations of SCR storage capacity and exhaust temperature such as during a regeneration event. Here, unlike what was observed for NO_x in Fig. 11, the distribution of unprocessed and ISC-processed emissions are quite similar with the majority of the trips below the limit.

As a summary, it is important to highlight that the levels obtained by the OBM system will result from the concentrations measured by sensors, or estimated by models, which come with their own accuracy, sensitivity and aging. As an example, in European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (2022) it was mentioned that concerns were raised regarding the durability of NH_3 sensors. Similarly, due to the low limit for this pollutant, the measurement deviation from the true value by the sensor could accumulate and constitute a significant share of the final measured distance-specific emission level. If the installation of an ammonia-slip catalyst becomes common practice, the emission levels could be reduced to very low levels and this effect might be reduced. Nevertheless, it is appropriate to note that some assumptions considered in the calculation, as for the NH_3 cross-sensitivity algorithm and the exhaust flow estimation from the embedded sensors, might also induce some deviations. In the end, all these aspects will have to be evaluated and considered by the manufacturers when comparing the emissions measured

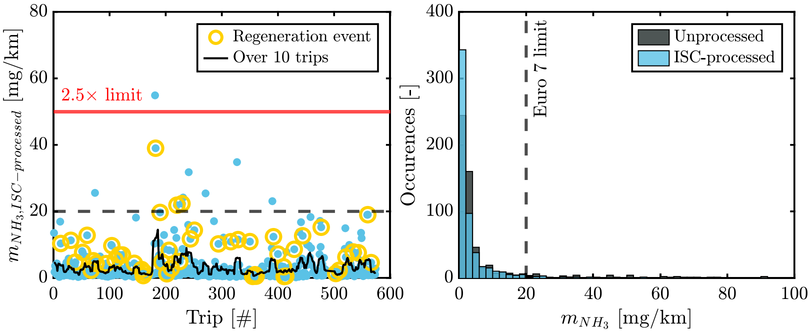

Fig. 14. Distance-specific emissions of NH_3 from the trips found in the database: ISC-processed emissions with standard and upper limit (left), and distribution of both unprocessed and ISC-processed emissions (right).

by the OBM system to the limits, which might represent a challenging situation to avoid repetitive and unjustified EEDWS error alerts.

6. Conclusions

This article has reviewed some aspects of the current proposal for the OBM concept, which implementation is expected to take place with the upcoming Euro 7 emission standard. This system aims to bring closer on-road vehicle emissions to the limits defined by the authorities by continuously monitoring and evaluating their levels in the vehicle. Ultimately, the system should verify vehicles compliance and induce a repair procedure by warning the driver if the vehicle is exceeding the limits. To this end, the OBM system will estimate on-board the distance-specific emissions at the end of each trip by combining sensor readings and exhaust emission models. On top of the in-vehicle assessment, the vehicle will also have to transmit data over-the-air for market surveillance where emissions compliance of an entire vehicle family will be examined by authorities.

Although the final definition of this concept is subject to changes in the near future, the building blocks already provided allow to analyze what are the expected outcomes of this system with available vehicles technology. In this work, the analysis of the OBM concept was carried out with a database of real-world everyday trips from a mild-hybrid Euro 6d-Temp diesel vehicle. NO_x and NH_3 emissions were measured thanks to emission sensors installed in the vehicle's exhaust and these signals were used to infer the distance-specific emissions of every trip. Overall, it was observed that, whereas some aspects still need to be clarified (e.g., definition of distances in the calculations before or after removing invalid points), the vehicle was able to stay under the upper limit defined by the proposal. Nevertheless, it is worth mentioning that these results are representative of the conditions encountered in this database and that the conclusions might differ if the vehicle was tested in another part of the world, especially given that this vehicle was not developed for Euro 7 limits.

The findings of this work have highlighted two main aspects of the current OBM concept definition that might represent a challenge for its upcoming application. The first one concerns the light-off delay of the emission sensors. A significant part of the emissions are found during the cold start interval of the trip. However, this section tends to also cover the activation time of the sensor, hence resulting in an important loss of information. Although future sensors are expected to counteract such effect, models will probably be required as a first step to substitute sensor reading during this period. Correct model development, calibration, and fidelity will therefore all play a significant role in the proper estimation of the emissions. The second aspect deals with the measurement of NH_3 emissions. In particular, NO_x sensors are sensitive to the release of ammonia in the exhaust which creates a deviation of the NO_x measurement. Given that the new standard proposes to regulate both pollutants separately instead of limiting the value of NO_x+NH_3 as currently provided by NO_x sensors, the correct separation of both components must be ensured, whether it be through the use of sensors, models, or a combination of both. Nonetheless, such requirement is not a trivial task, and some concerns exist regarding the durability of NH_3 sensors to properly estimate the ammonia levels over the lifetime of the vehicle. The implications of these aspects are considerable and must be tackled by manufacturers and policymakers, as they will affect the accurate estimation of emissions, and might lead into a potential risk for vehicles eligibility.

CRediT authorship contribution statement

Alvin Barbier: Data curation, Investigation, Writing – original draft. **José Miguel Salavert:** Investigation, Writing – review & editing. **Carlos E. Palau:** Investigation, Writing – review & editing. **Carlos Guardiola:** Funding acquisition, Investigation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by grant PID2019-108031RB-C21 financed by MCIN/AEI/10.13039/501100011033. Funding for open access charge: CRUE-Universitat Politècnica de València.

References

Barbier, A., Salavert, J.M., Palau, C.E., Guardiola, C., 2023. Predicting instantaneous engine-out NOx emissions in a real-driving vehicle data scenario. Int. J. Engine Res. 24 (8), 3626–3641. http://dx.doi.org/10.1177/14680874231163912.

Bielaczyc, P., Merkisz, J., Pielecha, J., Woodburn, J., 2020. RDE-compliant PEMS testing of a gasoline Euro 6d-TEMP passenger car at two ambient temperatures with a focus on the cold start effect. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2020-01-0379.

Chen, J., Sato, S., Eang, C., Tanaka, K., Tange, T., 2023. Real-world cold start emissions evaluation for direct-injection gasoline vehicle with PEMS and SEMS. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2023-01-0379.

Cheng, Y., He, L., He, W., Zhao, P., Wang, P., Zhao, J., Zhang, K., Zhang, S., 2019. Evaluating on-board sensing-based nitrogen oxides (NOx) emissions from a heavy-duty diesel truck in China. Atmos. Environ. 216, http://dx.doi.org/10.1016/j.atmosenv.2019.116908.

Claßen, J., Krysmon, S., Dorscheidt, F., Sterlepper, S., Pischinger, S., 2021. Real driving emission calibration - Review of current validation methods against the background of future emission legislation. Appl. Sci. 11, http://dx.doi.org/10.3390/app11125429.

Degraeuwe, B., Weiss, M., 2017. Does the new European driving cycle (NEDC) really fail to capture the NOx emissions of diesel cars in Europe? Environ. Pollut. 222, 234–241. http://dx.doi.org/10.1016/j.envpol.2016.12.050.

Dimaratos, A., Kontses, D., Doulgeris, S., Zacharof, N., Keramidas, A., Stamos, G., Papageorgiou-Koutoulas, A., Samaras, Z., 2023. The potential of on-board data monitoring for the characterization of real-world vehicle fuel and energy consumption and emissions. In: SAE Technical Paper. SAE International, http://dx.doi.org/10.4271/2023-24-0113.

Du, B., Zhang, L., Geng, Y., Zhang, Y., Xu, H., Xiang, G., 2020. Testing and evaluation of cold-start emissions in a real driving emissions test. Transp. Res. D 86, http://dx.doi.org/10.1016/j.trd.2020.102447.

European Commission, 2022a. COM/2022/586 final. Annexes to the Proposal for a Regulation of the European Parliament and of the Council on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7) and repealing Regulations (EC) No 715/2007 and (EC) No 595/2009. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022PC0586.

European Commission, 2022b. COM/2022/586 final. Proposal for a Regulation of the European Parliament and of the Council on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7) and repealing Regulations (EC) No 715/2007 and (EC) No 595/2009. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022PC0586.

European Commission, 2023a. Environmental aspects of the automotive industry, URL: https://single-market-economy.ec.europa.eu/sectors/automotive-industry/environmental-protection_en.

European Commission, 2023b. 01/09/2023 version of: Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008. URL: https://eur-lex.europa.eu/eli/reg/2017/1151/2023-09-01.

European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2022. Technical Studies for the Development of Euro 7 – Testing, Pollutants and Emission Limits. Technical Report, Publications Office of the European Union, URL: https://data.europa.eu/doi/10.2873/97170.

European Environment Agency, 2023a. Europe's air quality status 2023. URL: https://www.eea.europa.eu/publications/europes-air-quality-status-2023.

European Environment Agency, 2023b. Road transport. URL: https://www.eea.europa.eu/en/topics/in-depth/road-transport.

European Parliament and Council, 2020. Regulation (EU) 2020/740 of the European Parliament and of the Council of 25 May 2020 on the labelling of tyres with respect to fuel efficiency and other parameters, amending Regulation (EU) 2017/1369 and repealing Regulation (EC) No 1222/2009. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02020R0740-20200605.

European Union, 2023. CIRCABC online document repository for the advisory group on vehicle emission standards, URL: https://circabc.europa.eu/ui/group/f57c2059-ef63-4baf-b793-015e46f70421.

Fernandes, P., Macedo, E., Bahmankhah, B., Tomas, R., Bandeira, J., Coelho, M., 2019. Are internally observable vehicle data good predictors of vehicle emissions? Transp. Res. D 77, 252–270. http://dx.doi.org/10.1016/j.trd.2019.11.004.

Franco, V., Dilara, P., Hennig, N., Manara, D., Forloni, F., Short, I., Ligterink, N., Ehrly, M., Kontses, D., Samaras, Z., 2023. On-board monitoring of emissions in the future Euro 7 standard. In: SAE Technical Paper. http://dx.doi.org/10.4271/2023-24-0111.

Franco, V., Posada Sánchez, F., German, J., Mock, P., 2014. Real-World Exhaust Emissions from Modern Diesel Cars. Technical Report, The International Council on Clean Transportation.

Frobert, A., Raux, S., Creff, Y., Jeudy, E., 2013. About cross-sensitivities of NOx sensors in SCR operation. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2013-01-1512.

Funk, S., 2021. Real world NOx sensor accuracy assessment and implications for REAL NOx tracking. SAE Int. J. Adv. Curr. Pract. Mobil. 3 (6), http://dx.doi.org/10.4271/2021-01-0593.

Girard, J.W., Cavataio, G., Lambert, C.K., 2007. The influence of ammonia slip catalysts on ammonia, N2O and NOx emissions for diesel engines. In: SAE Technical Paper Series. http://dx.doi.org/10.4271/2007-01-1572.

Gräbe, R.J., Joubert, J.W., 2022. Are we getting vehicle emissions estimation right? Transp. Res. D 112, http://dx.doi.org/10.1016/j.trd.2022.103477.

Guardiola, C., Pla, B., Bares, P., Mora, J., 2020. Model-based ammonia slip observation for SCR control and diagnosis. IEEE/ASME Trans. Mechatronics 25 (3), 1346–1353. http://dx.doi.org/10.1109/TMECH.2020.2974341.

Guardiola, C., Vigild, C., de Smet, F., Schusteritz, K., 2021. From OBD to connected diagnostics: A game changer at fleet, vehicle and component level. IFAC-PapersOnLine 54 (10), 558–563. http://dx.doi.org/10.1016/j.ifacol.2021.10.221.

Guerrero-ibanez, J.A., Zeadally, S., Contreras-Castillo, J., 2015. Integration challenges of intelligent transportation systems with connected vehicle, cloud computing, and internet of things technologies. IEEE Wirel. Commun. 22 (6), 122–128. http://dx.doi.org/10.1109/MWC.2015.7368833.

Heepen, F., Yu, W., 2019. SEMS for individual trip reports and long-time measurement. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2019-01-0752.

Jaikumar, R., Shiva Nagendra, S., Sivanandan, R., 2017. Modeling of real time exhaust emissions of passenger cars under heterogeneous traffic conditions. Atmospheric Pollut. Res. 8, 80–88. http://dx.doi.org/10.1016/j.apr.2016.07.011.

Jeong, J.W., Cha, J., Chon, M.S., Lee, K., 2023. Suitability of SEMS equipment for monitoring RDE tests. Int. J. Automot. Technol. 24 (3), 749–758. http://dx.doi.org/10.1007/s12239-023-0062-1.

Kamimoto, T., 2017. A review of soot sensors considered for on-board diagnostics application. Int. J. Engine Res. 18 (5–6), 631–641. http://dx.doi.org/10.1177/1468087416678499.

Kousoulidou, M., Fontaras, G., Ntziachristos, L., Bonnel, P., Samaras, Z., Dilara, P., 2013. Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors. Atmos. Environ. 64, 329–338. http://dx.doi.org/10.1016/j.atmosenv.2012.09.062.

Krzyżanowski, M., Kuna-Dibbert, B., Schneider, J., 2005. Health Effects of Transport-Related Air Pollution. World Health Organization, Regional Office for Europe.

Le Cornec, C.M., Molden, N., van Reeuwijk, M., Stettler, M.E., 2020. Modelling of instantaneous emissions from diesel vehicles with a special focus on NOx: Insights from machine learning techniques. Sci. Total Environ. 737, 139625. http://dx.doi.org/10.1016/j.scitotenv.2020.139625.

Müller, V., Pieta, H., Schaub, J., Ehrly, M., Körfer, T., 2022. On-board monitoring to meet upcoming EU-7 emission standards – Squaring the circle between effectiveness and robust realization. Transp. Eng. 10, http://dx.doi.org/10.1016/j.treng.2022.100138.

Nakaema Aronis, A., 2023. Control and Diagnosis of a SCR-ASC After-Treatment System for NOx and NH3 Emission Reduction Under Real Driving Conditions and Potential System Failures (Ph.D. thesis). Universitat Politècnica de València.

Pla, B., Piqueras, P., Bares, P., Aronis, A., 2021. NOx sensor cross sensitivity model and simultaneous prediction of NOx and NH3 slip from automotive catalytic converters under real driving conditions. Int. J. Engine Res. 22 (10), 3209–3218. http://dx.doi.org/10.1177/1468087420966406.

Pla, B., Piqueras, P., Bares, P., Aronis, A., 2022. Simultaneous NOx and NH3 slip prediction in a SCR catalyst under real driving conditions including potential urea injection failures. Int. J. Engine Res. 23 (7), 1213–1225. http://dx.doi.org/10.1177/14680874211007646.

Prakash, S., Bodisco, T.A., 2019. An investigation into the effect of road gradient and driving style on NOx emissions from a diesel vehicle driven on urban roads. Transp. Res. D 72, 220–231. http://dx.doi.org/10.1016/j.trd.2019.05.002.

Praveena, V., Martin, M.L.J., 2018. A review on various after treatment techniques to reduce NOx emissions in a CI engine. J. Energy Inst. 91 (5), 704–720. http://dx.doi.org/10.1016/j.joei.2017.05.010.

Premnath, V., Khalek, I., Thompson, P., Woo, L., 2020. Evaluation of an on-board, real-time electronic particulate matter sensor using heavy-duty on-highway diesel engine platform. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2020-01-0385.

Ramos, A., Muñoz, J., Andrés, F., Armas, O., 2018. NOx emissions from diesel light duty vehicle tested under NEDC and real-word driving conditions. Transp. Res. D 63, 37–48. http://dx.doi.org/10.1016/j.trd.2018.04.018.

Tan, Y., Henderick, P., Yoon, S., Herner, J., Montes, T., Boriboonsomsin, K., Johnson, K., Scora, G., Sandez, D., Durbin, T.D., 2019. On-board sensor-based NOx emissions from heavy-duty diesel vehicles. Environ. Sci. Technol. 53 (9), 5504–5511. http://dx.doi.org/10.1021/acs.est.8b07048.

Todo, Y., Ichikawa, H., Yotou, H., Aoki, K., Kawai, M., 2018. Development of high accuracy and quick light-off NOx sensor. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2018-01-0334.

TransportPolicy.net, 2023. EU: Light-duty: Emissions, URL: https://www.transportpolicy.net/standard/eu-light-duty-emissions/.

Valverde Morales, V., Clairotte, M., Pavlovic, J., Giechaskiel, B., Bonnel, P., 2020. On-road emissions of euro 6d-TEMP vehicles: Consequences of the entry into force of the RDE regulation in Europe. In: SAE Technical Papers. SAE International, http://dx.doi.org/10.4271/2020-01-2219.

Vermeulen, R., Ligterink, N., Vonk, W., Baarbé, H., 2012. A smart and robust NOx emission evaluation tool for the environmental screening of heavy-duty vehicles. In: Proceedings of the 19th International Transport and Air Pollution (TAP) Conference.

Yu, Y.S., Jeong, J.W., Chon, M.S., Cha, J., 2021. NOx emission of a correlation between the PEMS and SEMS over different test modes and real driving emission. Energies 14 (21), 7250. http://dx.doi.org/10.3390/en14217250.

Yuan, X., Liu, H., Gao, Y., 2015. Diesel engine SCR control: Current development and future challenges. Emiss. Control Sci. Technol. 1 (2), 121–133. http://dx.doi.org/10.1007/s40825-015-0013-z.

Zhang, S., Zhao, P., He, L., Yang, Y., Liu, B., He, W., Cheng, Y., Liu, Y., Liu, S., Hu, Q., Huang, C., Wu, Y., 2020. On-board monitoring (OBM) for heavy-duty vehicle emissions in China: Regulations, early-stage evaluation and policy recommendations. Sci. Total Environ. 731, 139045. http://dx.doi.org/10.1016/j.scitotenv.2020.139045.