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Assessment of a NOx Measurement Procedure for Periodic Technical Inspection (PTI) of Light-Duty Diesel Vehicles

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Abstract: A Periodic Technical Inspection (PTI) of vehicles promotes road safety and environmental protection. Indeed, a PTI is also used to verify the proper functioning of the vehicle's aftertreatment system (ATS) over its lifetime. While the current Directive 2014/45/EU, which covers the PTI, does not require a NOx emissions measurement, the ongoing revision of the roadworthiness package aims at including new methods for measuring exhaust NOx and particle number (PN) emissions. PTI tests are required to be simple, quick, inexpensive and effective. In this study, a new methodology for a NOx measurement during the PTIs of Diesel vehicles equipped with a selective catalytic reduction (SCR) unit is assed. Seven Euro 6 light-duty Diesel vehicles fulfilling post-Real Driving Emissions (RDE) regulations were tested. The NOx-PTI methodology consists of measuring NOx emissions from the vehicle tailpipe at engine low idle speed after properly conditioning the vehicle ATS. In such conditions, a well-functioning SCR unit reduced NOx emissions and the methodology proved to be suitable to discriminate between functioning and malfunctioning SCR systems.

Keywords: in-use vehicle emissions; NOx emissions; SCR; SCR malfunctioning; idling emissions

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1. Introduction

Air pollution is currently the largest environmental health risk in Europe, especially in urban areas [1]. Nitrogen oxides (NOx) are among the key air pollutants [2]. In 2021, the World Health Organization (WHO) published new air quality guidelines [3] (updating those from 2005) offering quantitative health-based recommendations for air quality management. The new recommended air quality guideline (AQG) levels for NO_2 are 10 µg/m^3 and 25 µg/m^3, respectively, on an annual and 24 h average base. Since the 1980s, the European Union (EU) has adopted policies on air quality. In October 2022, the European Commission (EC) proposed a revision of the Ambient Air Quality directive [4]. Additionally, in the European Green Deal's Zero Pollution Action Plan [5], EC committed to reduce the health impacts of air pollution (premature death) by more than 55%.

EEA [2] has recently reported that in the EU-27 in 2020, road transport was the main source of NOx emissions, with 37% of the share. Since the early 1990s, the EU has introduced a series of directives and regulations, known as the Euro standards (Euro 1 to Euro 6e for light-duty vehicles (LDVs) and Euro I to Euro VI-E for heavy-duty vehicles (HDVs)), focusing on reducing the concentration of air pollutants in Europe. In order to meet the NOx emission limits, Euro 6d Diesel vehicles commonly use Selective Catalytic Reduction systems (SCR) as the main deNOx technology [6,7]. An exhaustive overview of deNOx aftertreatment technologies and EU NOx emission regulations for both light- and heavy-duty vehicles is provided elsewhere [6].

In the EU, the vehicle emission compliance with relevant regulatory acts during a defined length of their lifetime is conducted via Market Surveillance (MaSu) and In-Service

Conformity (ISC). The vehicle compliance with the emissions requirements during their lifetime is the manufacturer's responsibility. In both MaSu and ISC, only a limited number of vehicles are checked. In contrast, during a Periodic Technical Inspection (PTI), the emissions of every vehicle circulating are checked for opacity (if it is a Diesel vehicle) or CO levels (in case of spark ignition engines). In the EU, all vehicles in circulation need to undergo a mandatory PTI promoting road safety and environmental protection. The compliance with PTI requirements are the responsibility of the car owner. Periodic roadworthiness requirements are defined in Directive 2014/45/EU [8]. This requires that the "Testing during the life cycle of a vehicle should be relatively simple, quick and inexpensive, while at the same time effective in achieving the objectives of this Directive".

Currently, a revision of the roadworthiness package is ongoing [9]. One of the targets is to introduce methodologies for detecting Diesel particulate filter (DPF) and selective catalytic reduction system (SCR) malfunctions in Diesel vehicles. This will require new emission test procedures and specifically NOx and particle number (PN) measurements, as they are currently not foreseen by the Directive [8]. PN-PTI has been widely discussed in recent studies [10–15]. Especially for Diesel vehicles, a PN measurement at idling proved to be an efficient methodology for detecting tampered or malfunctioning particulate filters. In March 2023, the European Commission adopted guidelines [16] to improve vehicle inspections with a focus on the particle number measurement of vehicles equipped with compression ignition engines. Some European countries (Switzerland, Netherlands, Belgium and Germany) already introduced/planned to introduce a PN measurement at PTIs.

The current Diesel fleet includes different de-NOx aftertreatment technologies [6]. Due to this variety, it becomes difficult to define a simple, quick, inexpensive and still robust "one fits all" methodology to verify the proper function of the overall ATS. Different studies have investigated possible methodologies for NOx-PTI testing. In fact, a wide variety of approaches has been proposed in the last years aimed at addressing this issue. Some examples include the work performed by Fernandez et al. [17,18] who recently proposed measuring NOx at PTIs for Diesel vehicles by exploiting the relation between the vehicle engine load (%) and NOx concentration at the vehicle tailpipe exhaust at idling. Another study [19] proposed the 'Q_{NOx} ratio' method that consists of evaluating the ratio between CO_2 and NOx emissions (g_{CO2}/g_{NOx})—normalized emission—at the tailpipe based on NOx data On-Board Diagnostic (OBD) vehicle systems. In [20], the authors proposed a 'load jump' method to properly evaluate the SCR system efficiency at PTI tests and presents the results on three Diesel Euro 6b passenger cars. The procedure requires warming-up the vehicle and performing a cool-down in idling (negative load jump), with simultaneous NOx measurements at the vehicle tailpipe. Færdselsstyrelsen (FSTYR: Danish road traffic authority) promoted a number of initiatives, some of which studied tools and methodologies to be applied at the PTIs for a NOx evaluation, including: Simplified Emission Measurement System (SEMS) [21], stationary NOx measurement [22] and OBD [23]. Ref. [22] investigated the methodology and feasibility of performing stationary NOx measurements with the goal of detecting faulty or not functioning exhaust aftertreatment systems. Ref. [23] proposes a step-by-step method to detect faulty emission systems based on On-Board Diagnostics (OBD) and its possible application at PTIs. An extended overview of the methods and technologies currently available for a NOx-PTI on buses and trucks and the status on PTIs in different European countries can be found at [24].

Herein, a new procedure for the identification of SCR unit malfunctioning in modern Diesel vehicles during PTIs is assessed. The focus is on post-RDE light-duty Diesel vehicles (Euro 6d and 6d-TEMP) where SCR units are ubiquitous. The procedure is based on the functioning principles of the SCR (details on the functioning of the SCR system can be found in [6] and references therein), and its capability to efficiently reduce NOx emissions at low idling when appropriately conditioned. The hot idling (i.e., hot engine and conditioned SCR) test appears promising for identifying a malfunctioning SCR and complies with the inspection requirements laid down in the current PTI directive [8]: testing needs to be quick, relatively simple and effective. In this context, a proper selection of the NOx measurement time span is necessary. This allows for reducing the length of the PTI test, but still granting a sufficient level of accuracy of the results and robustness of the approach.

The paper is divided into: Section 2 where the measurement equipment used, tested vehicles and the procedure are described; Section 3 where the results obtained are discussed for the procedure proposed and particular ATS configurations are presented; and Section 4 for the conclusions.

2. Materials and Methods

2.1. Vehicles and Instrumentation

Seven vehicles were tested at Vehicle Emissions Laboratories (VELA) of the Joint Research Centre (JRC) of the European Commission. All of them met post-RDE emission standards: one N1 Class III Diesel light commercial vehicle and two M1 passenger cars were type-approved as Euro 6d-TEMP-EVAP-ISC, two N1 Class III Diesel light commercial vehicles and two M1 passenger cars were type-approved as Euro 6d-ISC-FCM. Table 1 summarises the main characteristics of the vehicles tested. For vehicle #2 and vehicle #4, tests were repeated twice; hereinafter, the results will be referred to as Test 1 and Test 2. Vehicle #6 and #7 ATS included a lean NOx trap (LNT). Those two vehicles will be discussed separately in Section 3.2. Vehicle #1 was tested a second time, at a later stage, with a malfunction in the urea injector. This condition was exploited to assess a real case of SCR system malfunctioning. For this second round of testing, vehicle #1 will be referred to as vehicle #1b. The test was carried out using the same equipment described below for vehicle #1.

Table 1. Summary of vehicles tested.

#	Fuel	Displacement (cm^3)	Registration	Emission Control System	Vehicle Category	Euro Standard
1	B7	1968	2019	EGR, DOC, DPF, SCR	N1 Class III	Euro 6d-TEMP-EVAP-ISC
2	B7	1995	2021	EGR, DOC, DPF, SCR	N1 Class III	Euro 6d-ISC-FCM
3	B7	1997	2019	EGR, DOC, DPF, SCR	M1	Euro 6d-TEMP-EVAP-ISC
4	B7	2184	2021	EGR, DOC, DPF, SCR	N1 Class III	Euro 6d-ISC-FCM
5	B7	1968	2020	EGR, DOC, DPF, SCR	M1	Euro 6d-ISC-FCM
6	B7	1499	2020	EGR, DOC, DPF, LNT, pSCR	M1	Euro 6d-TEMP-EVAP-ISC
7	B7	1998	2020	EGR, DOC, DPF, LNT, SCR	M1	Euro 6d-ISC-FCM

EGR: exhaust gas recirculation, DOC: diesel oxidation catalyst, DPF: diesel particulate filter, SCR: selective catalytic reduction, LNT: lean NOx trap, pSCR: passive SCR.

A summary of the NOx measurement equipment used and their working principle is presented in Table 2. Laboratory equipment included a MEXA 7400 bench analyser and a MEXA 7100 bench analyser (HORIBA, Kyoto, Japan), both equipped with a heated sampling line and a heated pre-filter at 190 °C, a MEXA ONE bench analyser (HORIBA, Kyoto, Japan) and an AMA i60 bench (AVL, Graz, Austria). All the analysers were equipped with a chemiluminescence detector (CLD). In addition to laboratory-grade equipment, Portable Emission Measuring Systems (PEMS) were also used, including: an AVL MOVE (AVL, Graz, Austria), PEMS with a non-dispersive ultra-violet sensor (NDUV) and a HORIBA OBS ONE PEMS equipped with a CLD. Whenever two or more instruments were measuring, the reference was the laboratory-grade instrument. All the measurement systems used have been maintained and calibrated following manufacturer recommendations.

Table 2. Summary of the measurement equipment used. On-vehicle NOx sensors were used when available from the OBD port.

Vehicle #	1	2	3	4	5	6	7
Laboratory	HORIBA MEXA 7400—CLD			HORIBA MEXA ONE—CLD	HORIBA MEXA 7400—CLD	AVL AMA i60—CLD	HORIBA MEXA ONE—CLD
PEMS	AVL MOVE—NDUV	AVL MOVE—NDUV	AVL MOVE—NDUV	HORIBA OBS ONE—CLD			
NOx sensors	X	X		X			X

CLD: chemiluminescence detector, NDUV: non-dispersive ultra-violet sensor.

For those vehicles on which NOx sensors signals were available at the OBD port, engine-out and tailpipe NOx concentrations were recorded and compared to laboratory-grade or portable measurement equipment. It should be noted that the sensors need to reach the optimal working temperature for the data to be available at the OBD port. For that reason, proper warm-up conditioning was needed; see [25] for more detailed information. The data presented in the following section do not present this delay time as driving the vehicle prior to idling allowed the ATS to properly warm-up, and so the sensors.

2.2. Hot Idling Procedure

The procedure assessed in this work aims at identifying, during a PTI, modern Diesel vehicles that present a malfunctioning SCR unit and therefore excess emissions of NOx. A malfunctioning SCR system would result in undesired high NOx emissions. The test procedure used is described in the following and it is also presented schematically in Figure 1 for better understanding. The procedure consists of two main phases:

(1) A vehicle warm-up phase, in order to ensure that the SCR unit temperature is high enough to trigger NOx reduction activity;
(2) A hot idling phase, where NOx emissions are measured at tailpipe.

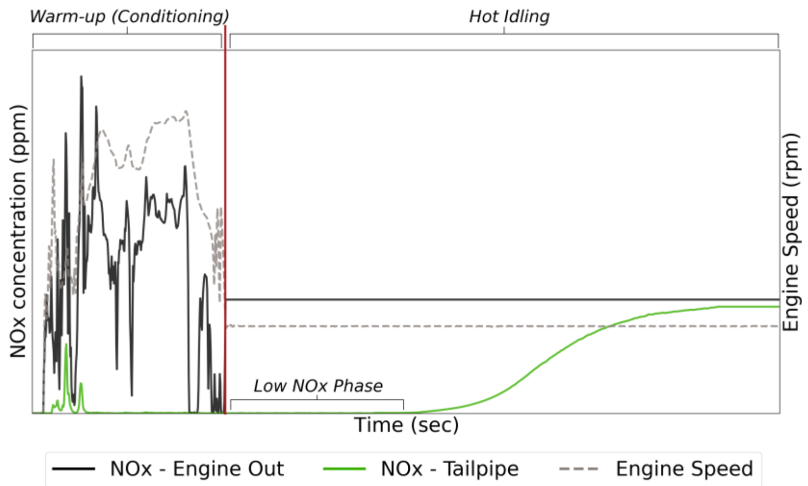

Figure 1. Simplified schematic representation of the hot idling procedure. NOx concentration and engine speed displayed are indicative.

In this work, hot start conditions were obtained by driving all the vehicles prior to testing for a period greater than 1800 s. The warm-up time could be shortened. Indeed, the RDE test procedure described in Regulation (EU) 2017/1151 [26] already defined the cold start period as the first 5 min after the test start and if the engine coolant temperature is determined, the cold start period ends once the coolant has reached 70 °C for the first time but no later than 5 min after the test start. In principle, this entails that the catalytic systems on the ATS needs to be warmed-up within that time to ensure proper emission control. Unfortunately, it was not possible to retrieve the SCR unit temperature from the OBD port for any of the vehicles. Such temperature could have been used to optimise the warm-up time, but the existing regulations do not bind vehicle manufacturers to provide catalyst temperature signals at the OBD port. Further investigation on the vehicle conditioning will follow in upcoming studies.

During the hot idling phase, unless there is an SCR unit malfunction, NOx tailpipe levels are expected to be low for a few minutes where the SCR keeps reducing the NOx emissions. This condition will be referred hereinafter as the low NOx phase. Low NOx phase duration was determined from the hot idle start-up to the time when the tailpipe NOx concentration increased above 1 ppm. During the low NOx phase, the NOx reduction takes place due to their reaction with NH_3, which is available because the urea injection continues during vehicle hot idling or because it remains stored on the catalyst during the warm-up phase [20,27,28]. Both cases would suggest an SCR that is properly functioning, allowing a malfunctioning of the system to be excluded. The amount of stored NH_3 for a specific SCR depends on several factors, including but not limited to: (i) the SCR unit volume and (ii) the operation of the vehicle right before testing. The latter, for example, impacts on the temperature reached at the SCR, whose correlation against NH_3 storage is well known [29,30]. After the low NOx phase, a gradual NOx increase at the tailpipe is expected with time since NH_3 stored previously in the SCR is progressively consumed and/or the SCR unit temperature is not sufficiently high to have a reaction even though there is still stored NH_3.

The proposed methodology does not require the measurement of other pollutants other than NOx (e.g., CO_2 could be useful to ensure that the engine of the vehicle under test is running), or information from the OBD (e.g., temperature of the aftertreatment device, NOx concentration from the internal vehicle or DEF injection information), which are not always available in Euro 6 vehicles.

3. Results and Discussion

3.1. Hot Idling Test

All the vehicles were tested following the hot idling procedure described in Section 2.2. This consisted of measuring the tailpipe NOx emission while the vehicle was in the hot idling condition. It is indicated as "hot" idling because the vehicles were preconditioned before testing to ensure that the SCR reached a sufficiently high temperature to trigger NOx reduction activity. As already stated, during the idling phase, unless there is a malfunction, the SCR unit is expected to reduce the NOx emissions for few minutes.

Figure 2 shows the NOx emission profiles of vehicles #1 and #4—Test 1 during the hot idling test. Similar plots were also obtained for vehicles #2, #3 and #5; see Figure S1 for additional details. In particular, Figure 2a shows the NOx tailpipe and engine out emission profiles of vehicle #1. The tailpipe NOx concentrations were <1 ppm during the low NOx phase (i.e., from the start of the hot idle) for 81 s (results are summarised in Table 3). At the end of the low NOx phase, the NOx concentration gradually increased reaching ~86 ppm in ~1350 s. The latter were comparable with the levels observed at the engine out steady state emission (99 ppm). Similarly to Figure 2a, Figure 2b plots the NOx emission profiles of vehicle #4—Test 1. An analogous trend to the one observed from vehicle #1 was observed, i.e., initially low NOx, <1 ppm for 496 s (see Table 3), then gradually increasing to reach ~80 ppm (again comparable to the engine out levels, 93 ppm) in ~1720 s. The NOx engine out average concentration was evaluated once the engine out NOx signal was stable; details are provided in Figure S2. For those vehicles where the engine out concentration changed during the idle, possibly due to the Exhaust Gas Recirculation (EGR) operation strategies, two values are reported in Table 3: the maximum concentration period average and in brackets, the lowest. As already presented, the observed gradual NOx increase at the tailpipe with time could be related to two different causes: (i) progressive consumption of the NH_3 stored in the SCR and/or (ii) not sufficiently high SCR unit temperature to have a reaction even though there is still stored NH_3. The decrease of the exhaust temperature, measured at the vehicle tailpipe exit, suggests that also the SCR unit temperature is gradually decreasing during the idling phase.

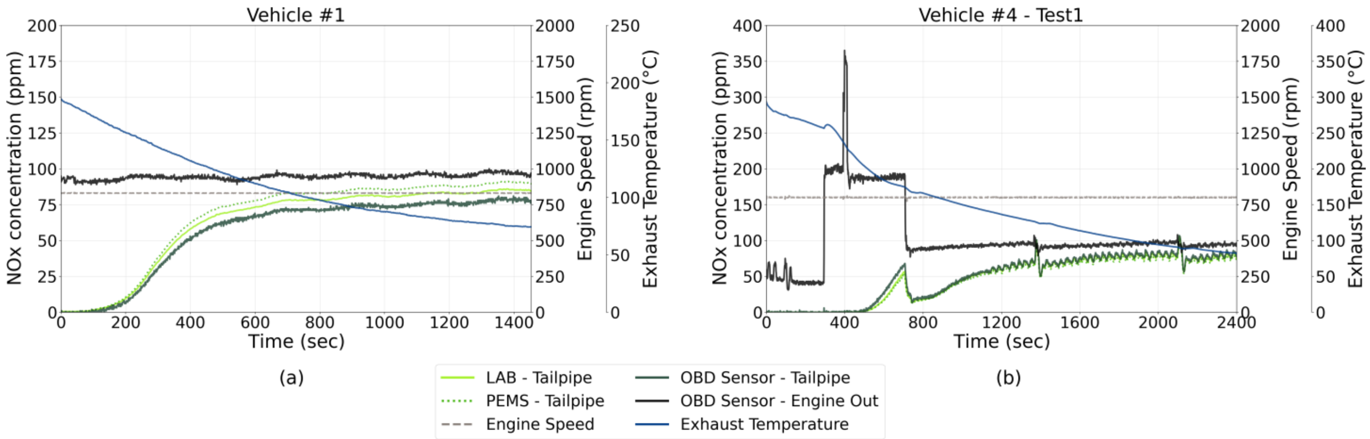

Figure 2. NOx emission profiles of vehicle #1 (**a**) and vehicle #4—Test 1 (**b**) during the hot idling test. NOx concentration measured by laboratory-grade CLD NOx analysers (solid light green line), PEMS (dotted green line) and vehicle NOx tailpipe (solid dark green line) and engine out (solid black line). Sensors are displayed together with vehicle engine speed (dashed grey line) and exhaust gas temperature (solid blue line) at the vehicle tailpipe exit. Time scale of both (**a**,**b**) starts at the end of the warm-up phase.

Table 3. Low NOx phase duration, time required for NOx tailpipe concentration to reach 10 ppm and 20 ppm (except for vehicle #3 for which the test was stopped before those concentrations were reached) and NOx engine out average concentration measured during hot idling.

Vehicle	#1	#2		#3	#4		#5
	Test 1	Test 1	Test 2	Test 1	Test 1	Test 2	Test 1
Low NOx phase < 1 ppm (s)	81	460	544	246	496	301	412
NOx < 10 ppm (s)	199	591	709	598	573	421	571
NOx < 20 ppm (s)	245	671	812		610	542	671
NOx Engine Out ave. conc. (ppm) *	99	118 (81)	135 (100)		187 (46)	224 (41)	96 (63)

* Engine out values were recorded at the OBD port for those vehicles where the NOx engine out sensor signal was available (except for vehicle #5 where NOx at engine out was measured with a laboratory analyser, see Section 2.1). For those vehicles where the engine out concentration changed during the idle two values are reported: the maximum concentration period average and in brackets the lowest, see Figure S2 for additional details. When two tests were performed on the same vehicle, the results were both reported.

From the NOx concentration profile for vehicle #4—Test 1 (Figure 2b), it is possible to observe a significant increase of the engine out NOx at ~350 s. These changes on the engine out NOx emissions coincided with the activation/deactivation of the EGR. It is worth noticing that the NOx concentration at the tailpipe was not affected by this instantaneous change upstream during the low NOx phase, possibly due to the SCR unit operation. A similar behaviour was observed for other tested vehicles (e.g., vehicle #5, see Figure S1) and it has been also reported for a heavy-duty vehicle in the literature [28]. Thus, the observed pattern suggests that the proposed hot idling procedure in PTIs allows for the identification of a properly functioning SCR unit, without being affected by the EGR strategy.

The average low NOx duration for all tests was 363 s, ranging from 81 s for vehicle #1 to 544 s for vehicle #2—Test 2. Vehicle #2 and vehicle #4 showed a fair repeatability between their two tests in terms of a low NOx phase duration and NOx engine out average concentration (both maximum and minimum values). The small deviations observed may depend among other things on the amount of ammonia stored in the SCR and/or how fast the SCR is cooling down. To provide additional insight on the NOx increase time, Table 3 also presents the time required for the NOx tailpipe concentration to reach 10 ppm and

20 ppm from an idle start. The time needed to reach 10 ppm of tailpipe NOx concentration ranged from 199 s for vehicle #1 (displaying the shortest low NOx phase) to 709 s for vehicle #2—Test 2 (displaying the longest low NOx phase) while for 20 ppm it ranged from 245 s for vehicle #1 to 812 s for vehicle #2—Test 2.

The low NOx tailpipe average concentrations measured by each instrument are reported in Table S1. The differences recorded among the measurement equipment were negligible at low NOx concentrations. Small differences were instead observed at higher NOx concentrations, e.g., vehicle #4 (see also Figure 2a) onboard NOx sensors deviates ~6 ppm from laboratory-grade equipment and ~12 ppm from the PEMS measurement.

Vehicle #1 was tested a second time (hereinafter referred as vehicle #1b). During this second test, the urea injector was not working properly: no urea solution was injected, see Section 2.1 for additional details. This second round of testing allowed for comparing a malfunctioning SCR (vehicle #1b) with the same system properly working (vehicle #1 in Figure 2). Figure 3 shows the NOx tailpipe and engine out emission profiles of vehicle #1b during the hot idling test. NOx concentrations increased by more than 45 ppm right from the test start, not following the pattern observed for the same vehicle with a properly functioning SCR, or the other vehicles tested under the same conditions, where NOx was close to zero. The same vehicle tested with a properly functioning SCR and a non-functioning urea injector displayed in the first case, low NOx (<1 ppm) during 81 s and in the second case high NOx tailpipe emissions, closer to engine out levels since the hot idling phase start.

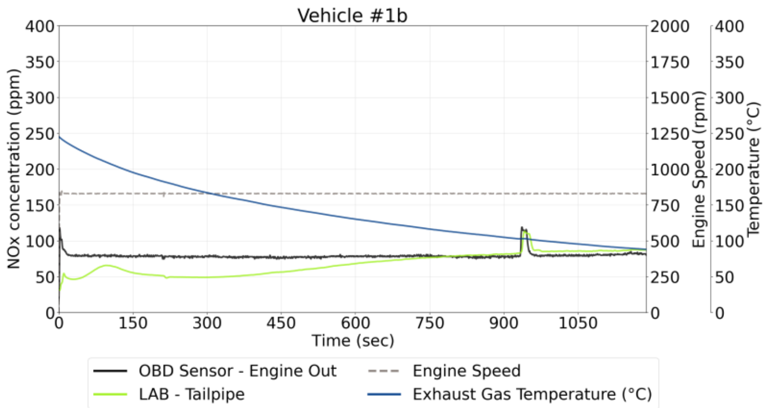

Figure 3. NOx emission profiles of vehicle #1b (Diesel Exhaust Fluid (DEF) injector not working) during the hot idling test. NOx concentrations measured by laboratory-grade CLD NOx analysers (solid light green line) and vehicle NOx engine out sensor signal (solid black line) are displayed together with vehicle engine speed (dashed grey line) and exhaust gas temperature (solid blue line) at the vehicle tailpipe exit. Time scale starts at the end of the warm-up phase.

The low NOx duration obtained from the tested vehicles (81–544 s), together with the immediate increase of NOx at the tailpipe for the malfunctioning vehicle #1b, suggest that a short measurement time span (e.g., between 15 and 45 s) would suffice to distinguish between a vehicle with a properly operating or a malfunctioning SCR. Such a short measurement time would support the PTI criteria of having a quick test.

Further investigation is still needed to assess the possibility of a re-warm-up in those cases where the operator misses the low NOx time window (e.g., due to the drop of the SCR unit temperature). Upcoming studies will address this aspect as it was not possible to check it in the presented vehicle batch.

3.2. Vehicles Equipped with LNT + SCR

Figure 4 shows the NOx emission profiles of vehicles #6 and #7 during the hot idling test. In particular, Figure 4a shows vehicle #7's NOx emission profile (measured with the CLD analyser) and engine speed, together with the NOx sensor signal at the LNT outlet (for more information on the accuracy of on-vehicle NOx sensors see [25]) and Figure 4b shows the NOx emission profile (measured with CLD analyser) and engine speed for vehicle #6 following the hot idling procedure. Vehicle #7 was an M1 Diesel car type-approved Euro 6d-ISC-FCM and its ATS included an LNT and two active SCRs. Recent studies [6] and references therein showed that in modern Diesel vehicles type-approved Euro 6d-TEMP and Euro 6d, SCR units are commonly installed (single SCR, dual SCR and SCR on filter), and some vehicles combine them with LNT.

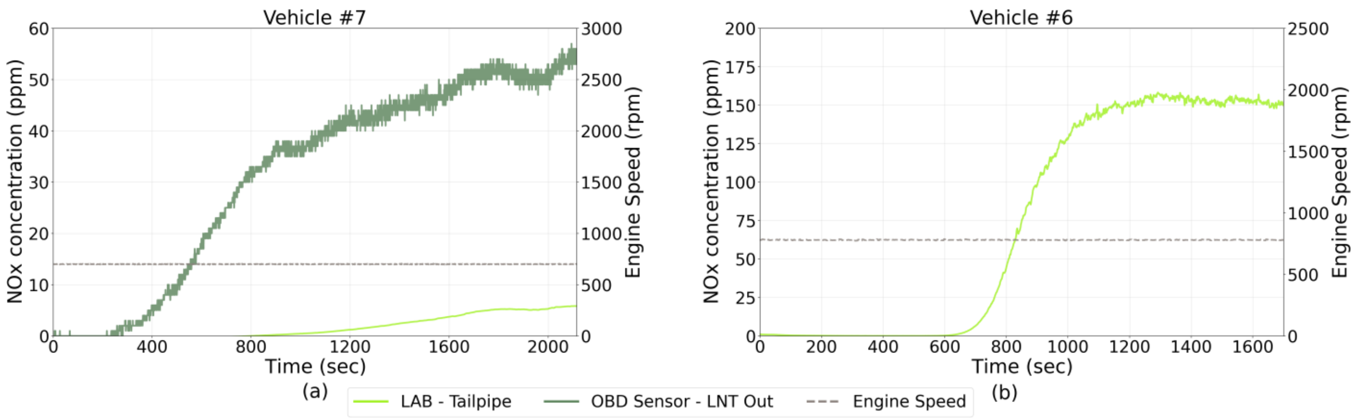

Figure 4. NOx concentration profiles at tailpipe (solid light green line) from vehicle #7 (**a**) and #6 (**b**) during hot idling test (both measured by CLD analysers). (**a**) also includes NOx sensor signal at the LNT outlet (solid dark green line), available at the OBD port. Engine speed (dashed grey line) is reported on the secondary axis. Time scale of both (**a**,**b**) starts at the end of the warm-up phase.

Vehicle #7 was equipped with three NOx sensors: (i) LNT outlet, (ii) 1st SCR unit outlet and (iii) 2nd SCR unit outlet (tailpipe). Figure 4a illustrates that this vehicle, with a more complex ATS, presents the same trend as the one described for the previous vehicles. In this case too, the tailpipe NOx was low at the hot idle start, <1 ppm for 1317 s. Then, the NOx concentration gradually, and slightly, increased up to ~6 ppm after ~1000 s.

At a first glance, the NOx concentration profile at the LNT outlet is analogous to the one discussed in Section 3.1; however, this behaviour is related to a different principle, namely NOx adsorption [31]. Looking only at the LNT outlet signal, low NOx values were observed at the hot idle start, <1 ppm for 340 s. These values are comparable with the one at the tailpipe presented in Table 3 for the other vehicles. NOx concentrations then gradually increase in ~2230 s up to ~55 ppm. Similar to what presented in Section 3.1 for EGR management, the NOx increase at the LNT outlet is damped by the operation of the two SCRs and the effect is visible on the NOx concentration at the tailpipe only delayed in time.

Vehicle #6 was an M1 Diesel vehicle type-approved Euro 6d-TEMP-EVAP-ISC equipped with an LNT and a passive SCR unit (pSCR). In this ATS configuration, the passive SCR unit relies on the NH_3 emitted by the LNT during its regeneration [32]. LNT regeneration takes place during engine rich operations, leading to a reducing exhaust gas condition. In this environment, a number of reactions occur at the LNT surface (e.g., NO/NO_2 reduction), including the formation of NH_3 and N_2O. A detailed description of the reaction mechanism can be found at [31,33,34].

The trend illustrated in Figure 4b for vehicle #6 is analogous to the one presented above in the case of an active SCR unit (with Diesel Exhaust Fluid (DEF) injection, commercially known in Europe as AdBlue), see Figure 2. In addition, the NOx values observed are consistent with the ones described in Table 3: low NOx values were observed at the hot idle start, <1 ppm for 639 s. NOx concentrations then gradually increase in ~550 s up to ~148 ppm.

The information gathered from vehicles #6 and #7 combined suggest that the presence of an LNT in the ATS could, under certain situations, limit determining whether or not the SCR unit has a DEF dosing malfunction under the hot idling procedure studied for two main reasons: (i) LNT may adsorb NOx emissions during the length of the hot idle test keeping the concentrations low; (ii) even without DEF dosing the SCR unit could be active reducing NOx using the NH_3 released by LNT. Follow-up studies investigating actual malfunctioning vehicles equipped with such an ATS configuration would allow better understating the implications that this would have during a PTI.

4. Conclusions

Seven light-duty vehicles fulfilling post-RDE Euro 6 requirements and equipped with selective catalytic reduction SCR unit/s were tested following a hot idling procedure designed for NOx Periodical Technical Inspections (PTI). The test consists of two phases: (i) a vehicle warm-up phase, ensuring that the SCR unit temperature is high enough to trigger NOx reduction activity and (ii) a hot idling phase where NOx emissions are measured at the tailpipe. The aim is to identify high NOx emitting vehicles due to a malfunctioning SCR unit.

Vehicles #1–#5 tested with the hot idling procedure displayed a consistent NOx pattern. Low tailpipe NOx was observed at the hot idle start, then gradually increased with time to values comparable to engine out levels, supporting the idea at the basis of the methodology that unless there is a malfunction, an SCR unit will continue to reduce NOx as long as the temperature is high enough and that there is ammonia in the system to reduce them. Vehicle #1b (which is vehicle #1 with a malfunction in the DEF injector) was tested following the hot idling procedure in the same conditions of vehicle #1 and resulted in high NOx tailpipe emissions, closer to engine out levels, from the idling phase start. This suggests that the hot idling procedure could be effectively used to discriminate between functioning and malfunctioning SCR systems at the PTI.

The average low NOx concentration duration (<1 ppm) for all tests was 363 s, the minimum was 81 s and the maximum 544 s. Shorter time spans (e.g., from 15 to 45 s) may also be used as a PTI measurement period. For vehicle #2 and vehicle #4, the procedure was repeated twice and the results showed good repeatability in terms of a low NOx phase duration and NOx engine out average concentration.

Future steps will focus on: the investigation of the vehicle conditioning (warm-up phase definition), the detection of actual malfunctioning vehicles equipped with ATS including an LNT in their configuration and the definition of an effective and robust pass/fail criteria.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16145520/s1, Figure S1: NOx emission profiles of vehicle #2—Test 1 (a), vehicle #3 (b) and vehicle #5 (c) during the hot idling test. NOx concentration measured by laboratory-grade NOx analysers (solid light green line), PEMS (dotted green line) and vehicle NOx tailpipe (solid dark green line) and engine out (solid black line) sensors are displayed together with vehicle engine speed (dashed grey line) and exhaust gas temperature (solid blue line) at the vehicle tailpipe exit. Additional details on the equipment used for each vehicle are provided in Table 2. Not all instruments/signals were available for each test (e.g., engine speed not available for vehicle #5). For vehicle #5, NOx at engine out was measured with a laboratory bench (c) (dashed light green line). Time scale for all vehicles starts at the end of the warm-up phase.; Figure S2: Engine-out NOx values recorded at the OBD port for those vehicles where the NOx engine out sensor signal was available (except for vehicle #5 where NOx at engine out was measured with a laboratory bench, see Section 2.1 for additional details). For those vehicles where engine out concentration changed during the idle two areas of the graph are highlighted: the maximum concentration period in red and the lowest in blue. The final average value over each area is reported in Table 3.; Table S1: NOx tailpipe average concentration (ppm) measured during static hot idling on 30 s and 60 s window since idling start using different equipment. When two tests were performed on the same vehicle, the results were both. The standard deviation (σ) for each instrument in the same time window is reported. Those values lower than 0.1 ppm have been reported as <0.1 ppm and negative ones as 0.

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