Exploratory research into a NOx test for the periodic inspection of diesel vehicles

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Samenvatting

Moderne dieselvoertuigen zijn uitgerust met emissiereductiesystemen om de schadelijke stikstofoxide-emissies te verlagen die door de dieselmotoren worden geproduceerd. Zowel in de EU als in Nederland is er momenteel in de periodieke keuring geen test om te controleren of deze NO_X-reductiesystemen naar behoren functioneren. Hierdoor vallen eventuele defecten of geknoei aan deze systemen niet op tijdens de periodieke keuring. Als reparaties of onderhoud uitblijven, is het gevolg daarvan dat deze voertuigen buitensporige hoeveelheden NO_X uitstoten, vergelijkbaar met oudere dieselvoertuigen van tientallen jaren geleden.

Om periodiek de goede werking van NO_X-reductiesystemen met AdBlue te controleren, onderzoekt DG-JRC (Joint Research Centre - Europese Commissie) in samenwerking met CITA (Internationale Commissie voor Voertuiginspectie) de haalbaarheid van een 'NO_X hot idle test', een stationaire uitlaatgastest voor dieselvoertuigen. Deze test omvat de meting van de NO_X-concentratie in de uitlaat tijdens stationair draaien van de dieselmotor, terwijl het NO_X-reductiesysteem op werktemperatuur is. Voorafgaand aan de test moet het NO_X-reductiesysteem worden opgewarmd. Een gemeten NO_X-concentratie boven een bepaalde drempelwaarde zou duiden op een defect systeem wat leidt tot overmatige NO_X-uitstoot tijdens rijden op de weg.

De test zou periodiek moeten worden uitgevoerd tijdens de APK (Periodieke Technische Keuring). Voor de APK is het vereist dat de test kort en praktisch is, vergelijkbaar met de nieuwe test voor dieselroetfilters. De test zou zich moeten richten op Euro-6dtemp personenauto's en bestelauto's die rond 2019 op de markt kwamen, en op Euro-VID vrachtauto's, die vanaf 2012 op de markt kwamen, omdat bij deze dieselvoertuigen NO_X-reductiesystemen met AdBlue gebruikelijk zijn. In Nederland zou de test betrekking hebben op ongeveer 250.000 personenauto's en bestelwagens, waarvan het merendeel bestelwagens, en ongeveer 143.000 zware bedrijfsvoertuigen.

Het Ministerie van Infrastructuur en Waterstaat heeft besloten bij te dragen aan het EU-onderzoek en heeft TNO gevraagd een verkennend onderzoek uit te voeren om ervaring op te doen met de praktische uitvoering en de effectiviteit van de 'NO_X hot idle test'. Hiervoor werd het concept van de testprocedure van de 'NO_X hot idle test' toegepast op vier dieselbestelwagens en twee vrachtwagens. De tests werden uitgevoerd met goed werkende NO_X-reductiesystemen, maar ook met opzettelijk uitgeschakelde systemen.

Op basis van het verkennende testprogramma met vier bestelwagens en twee vrachtwagens concluderen we het volgende:

- Met de 'NO_X hot idle test' kan worden vastgesteld dat een NO_X-reductiesysteem helemaal niet meer werkt. Het is niet duidelijk of met de test is vast te stellen dat een NO_X-reductiesysteem een minder goede werking heeft, zoals bijvoorbeeld bij bepaalde kleinere defecten en veroudering van het systeem. Deze beperking aan de test zou kunnen komen doordat 'stationair draaien' een relatief makkelijke testconditie is. De test zou daarom tot een lage NO_X-uitstoot kunnen leiden, zelfs als het NO_X-reductiesysteem onder normale rijomstandigheden slecht presteert. Het aanscherpen van de drempelwaarde kan de kans op foutieve testresultaten (onterechte afkeuring) verhogen.

- Het testprogramma heeft aangetoond dat alleen stationair draaien onvoldoende is om het NO_X-reductiesysteem op bedrijfstemperatuur te brengen. Daarom vereist de 'NO_X hot idle test' een rit op de weg voorafgaand aan de test om het systeem op te warmen: 2-10 minuten rijden voor auto's/bestelwagens, 10-15 minuten voor zware bedrijfswagens. Voor trekkers kan het systeem tijdens de terugrit afkoelen, waardoor een geldige test in bepaalde gevallen onmogelijk is.
- Zonder een duidelijke indicatie om te controleren of het NO_X-reductiesysteem voldoende is opgewarmd, kan de test mogelijk leiden tot foutieve testresultaten (onterechte afkeuring). Een mogelijkheid om foutieve test resultaten te voorkomen, is om een extra opwarmrit toe te staan, gevolgd door een tweede test.
- De uitvoering van de test zelf lijkt binnen de huidige Nederlandse APK (Algemene Periodieke Keuring) te passen, omdat het een snelle test is met een meetsonde in de uitlaat, vergelijkbaar met de recent ingevoerde roetfiltertest. De huidige EU-richtlijn voor periodieke keuring schrijft echter geen opwarmrit op de openbare weg voor. Zo'n nieuwe vereiste zou de doorlooptijd verhogen en de complexiteit van de gehele testprocedure vergroten. Daarom moet worden geëvalueerd of dit werkbaar is voor APK-werkplaatsen en of dit acceptabel is voor voertuigbezitters.
- Voor het opsporen van gemanipuleerde NO_X-reductiesystemen is de test mogelijk minder effectief, omdat sjoemelkastjes voorafgaand aan de test kunnen worden uitgeschakeld. Deze extra moeite kan sommige eigenaren mogelijk wel ontmoedigen om te manipuleren.
- De 'NO_X hot idle test' lijkt meer geschikt voor auto's en bestelwagens dan voor vrachtwagens. Voor vrachtwagens en met name trekkers zonder oplegger is het namelijk moeilijker om de SCR-katalysator met een testrit op te warmen en deze op temperatuur te houden tot en met de stationaire uitlaatgastest.
- Voor de test is een instrument nodig om de NO_X-concentratie in de uitlaat te meten, wat nieuw is voor de APK. De eisen voor dit instrument moeten worden gespecificeerd door metrologische instituten. APK-werkplaatsen zouden moeten investeren in dit nieuwe testinstrument.

Aanbevelingen

Op basis van de bevindingen van dit onderzoek doen we de volgende aanbevelingen:

- Aanvullende tests op auto's, bestelwagens en vrachtwagens uitvoeren om:
  - de effectiviteit van de test te beoordelen voor het vaststellen van een niet correcte werking van het NO_X-reductiesysteem wanneer er sprake is van typische defecten of veroudering die tot een afname van de goede werking van het systeem kunnen leiden,
  - het risico op foutieve testresultaten (foutieve afkeuringen en goedkeuringen) te onderzoeken en – te bepalen of de optie voor een tweede test na een initiële afkeur een effectieve manier is om foutieve testresultaten te vermijden.
- Te onderzoeken of de vereiste opwarmrit op de weg haalbaar is binnen het kader van de Nederlandse APK.
- Te onderzoeken of de test geschikt is om manipulatie van vrachtwagens op te sporen bij weginspecties nabij een snelweg. Vooral voor trekkers kan de test betrouwbaarder zijn dan tijdens een APK-test, omdat de motor en het NO_X-reductiesysteem waarschijnlijk volledig opgewarmd zijn wanneer een voertuig een oplegger heeft en direct na het verlaten van de snelweg wordt getest. Om de effectiviteit van weginspecties te vergroten, zou een voertuig met een op afstand werkend meetsysteem (plume chase vehicle) kunnen worden ingezet om voertuigen op de snelweg te screenen en voertuigen met een hoge uitstoot te selecteren voor een 'NO_X hot idle test' tijdens een technische inspectie langs de weg. Ook kan onderzocht worden of het herinvoeren van (delen van) de OBD (On-Board Diagnostics) test een effectief middel is om slecht functionerende NO_X-reductiesystemen vast te stellen.

- Hoewel algemeen bekend is dat NO_X-reductiesystemen zonder AdBlue kunnen functioneren, kunnen verouderen, defect kunnen raken en kunnen worden gemanipuleerd, zijn er weinig goede gegevens beschikbaar waarmee de omvang van het probleem is te bepalen. We raden daarom aan om de benodigde statistische gegevens te verzamelen en metingen uit te voeren.
- We bevelen tevens aan om de ontwikkelingen ten aanzien van de test procedure in de EU te volgen.

Summary

Modern diesel vehicles are equipped with NO_X control systems to reduce harmful nitrogen oxide emissions produced by their engines. In both the EU and the Netherlands, there is currently no periodic inspection to verify the proper functioning of these NO_X control systems. As a result, if these systems are not repaired if needed, or if they are tampered with, these vehicles could emit excessive levels of NO_X, similar to older diesel vehicles from decades ago.

To check the roadworthiness with regard to the proper functioning of NO_X control systems using AdBlue, DG-JRC (Joint Research Centre - European Commission), in collaboration with CITA (International Motor vehicle Inspection Committee), is investigating the feasibility of a 'NO_X hot idle test' for diesel vehicles. This test would encompass the measurement of the NO_X concentration in the tailpipe while idling the diesel engine. An important requirement is that the NO_X control system is at working temperature during the test. The test must therefore be preceded by a procedure to warm up the NO_X control system. A measured NO_X concentration above a certain threshold value would need to indicate a defective system, leading to excessive NO_X emissions when driving on the road.

The test would have to be conducted during PTI (Periodic Technical Inspection). For PTI it is required that the test is short and practical, analogue to the new diesel particle filter test. The test would target vehicles Euro 6dtemp passenger cars and vans which entered the market around 2019 and Euro-VI trucks which entered the market in 2012. For these vehicles NO_X control systems using AdBlue are common. The test would encompass in the Netherlands roughly 250.000 passenger cars and vans, of which vans are the majority and roughly 143.000 heavy-commercial vehicles.

The Ministry of Infrastructure and Water management decided to contribute to the EU research and asked TNO to conduct an exploratory investigation to gain experience with the practical execution and the effectiveness of this 'NO_X hot idle test'. To do so, the draft test procedure of this test was applied to four diesel vans and two diesel heavy-duty vehicles. The tests were performed with good working NO_X control systems, but also with completely deactivated NO_X control systems.

Conclusions
Based on the exploratory test program conducted on four vans and two trucks, we conclude the following:

- The 'NO_X hot idle test' can detect a NO_X control system which doesn't work at all, but it is not clear if the test is suitable for identifying a NO_X control system which has certain smaller failures or are degraded, leading to a reduced efficiency. This limitation of the test may arise because 'idling' is a relatively easy test condition and may show low NO_X emissions even if the NO_X control system performs poorly under normal driving. Tightening the test threshold to improve the accuracy may increase the likelihood of false failures.
- The test program showed that idling alone is insufficient to bring the SCR catalyst to its operating temperature.

- Therefore the 'NO$_X$ hot idle test' requires a pre-test drive to warm the SCR catalyst: 2 - 10 minutes for cars/vans, 10 - 15 minutes for heavy-duty vehicles. For heavy-duty tractors, the system may cool down on the return trip without payload, making a valid test impossible in certain cases.
- Without a clear indication to check if the catalytic NO$_X$ control system is warmed up sufficiently, the test can potentially lead to false fails. An option to avoid false fails is to allow another warmup drive followed by a second test.
- The execution of the test itself seems to fit within the current Dutch PTI (APK: (Algemene Periodieke Keuring) because it is a quick test with a measuring probe in the tail-pipe, similar to the recently introduced particle filter test. However, currently EU guidelines for periodic inspections do not prescribe a pre-test drive on public roads. Such a requirement would add to the lead time and complexity of the overall test procedure, so it must be evaluated to determine if it is practical for PTI workshops and acceptable to the vehicle owners.
- For detection of tampered NO$_X$ control systems, the test might be less effective because tampering devices can be switched off prior to the test. However, this extra effort may prevent some owners to tamper.
- The NO$_X$ hot idle test is more suitable for cars and vans than for trucks. For trucks and especially tractors without semi-trailer, it is more difficult to heat up the SCR catalysts with a pre-test drive and to maintain this temperature during the idle test.
- The test would require an instrument to measure the tailpipe NO$_X$ concentration which is new for PTI. Requirements for this instrument would need to be specified by metrological institutes and PTI workshops would have to invest in the new test instrument.

Recommendations
Based on the findings of this investigation we make the following recommendations:
- Additional tests on cars, vans and heavy commercial vehicles would be needed to:
  - assess the effectiveness of the test to confirm not proper functioning in the case of typical defects that can lead to a reduced performance of a NO$_X$ control system,
  - to investigate the risk for false test fails and passes and - to determine if the option for a second test after an initial test fail is an effective way to avoid false test results.
- It needs to be investigated if the required pre-test drive on the road is feasible in the framework of the Dutch APK.
- The test might be suitable for indicating tampering of heavy-duty vehicles at road-side inspection near a motorway. Especially for tractors, the test may be more reliable than during a PTI test, since the engine and NO$_X$ control system are likely to be fully warm when a vehicle has a normal cargo load and is tested just after it leaves the motorway. We recommend to investigate the feasibility of this option. To increase the effectiveness of road-side inspection, a remote sensing vehicle (plume chase vehicle) could be deployed to screen vehicles on the motorway and select suspected NO$_X$ high emitters for a NO$_X$ hot idle test and a more thorough technical inspection at the road-side.
  It could also be considered to investigate the re-introduction of (parts of) the OBD (On-Board Diagnostics) test for newer vehicles.
- Although it is widely known that NO$_X$ control systems can run without AdBlue, degrade, can fail and can be tampered with, there are few good statistics available which show the magnitude of the problem. We therefore recommend to collect the required statistical data and to conduct measurements.
- We recommend to follow the development of the diesel NO$_X$ hot idle test for PTI in the EU.

Contents

Abbreviations

Abbreviation	Meaning
APK	Algemene Periodieke Keuring (Periodic Inspection)
DTC	Diagnostic Trouble Code
ECT	Engine Coolant Temperature
ECU	Engine Control Unit
EFM	Exhaust Flow Meter
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
(N)PTI	(New) Periodic Technical Inspection
OBD	On-Board Diagnostics
PEMS	Portable Emissions Measurement System
ppm	parts per million
SCR	Selective Catalytic Reduction

1 Introduction

1.1 Background

There is currently no check of the proper functioning of NO_X reduction systems on the latest generations of diesel vehicles in the Netherlands and the EU. This can lead to increased NO_X emissions to levels of old vehicles if vehicles are not repaired, properly maintained or tampered with. Information on the occurrence of malfunctions and tampering and thus the impact on the emissions of the fleet is very limited and not easy to obtain. The EU Horizon 2020 project DIAS investigated the problem of tampering by vehicle owners and concluded that there is a significant market for tampering services and products such as AdBlue emulators [2020a, van den Meiracker et al.], [2020b, van den Meiracker et al.].

A simple test, to be conducted during (N)PTI ((New) Periodic Technical Inspection), might determine whether or not a system is working properly. JRC, in collaboration with CITA, is investigating the feasibility of a simple NO_X idle test for diesel passenger cars and NL (The Ministry of Infrastructure and Water management) decided to contribute to that research.

1.2 Objectives

The overall objective is to investigate the feasibility of the provisional NO_X hot idle test for use during periodic inspection of the latest generation of cars, vans and heavy-commercial vehicles (as of Euro 6dtemp or Euro VI-D). In general a test shall be practical, effective in detecting the proper functioning of the NO_X reduction systems (SCR catalyst and EGR valve) with no false fails and false passes and require little extra time and resources.

There are several project goals based on ongoing research by JRC and CITA. The intention is that the relatively limited research discussed in this document will contribute to achieving those goals and provide as much information and experience as possible within a limited program on the following points:

- Gain experience with the test.
  - Practical actions to conduct the test,
  - Test time to conduct the test and to bring a vehicle in test condition. Special attention is needed for the latter because an SCR system needs to be hot to work, (a possibly test criterion is an engine coolant temperature >70 °C)
- There shall be no or a very low chance of a false test fail or false test pass. A second, confirmatory test could be considered.
- Pass-fail criteria. An effective threshold value is necessary. What value is a safe threshold value to effectively detect a malfunctioning NO_X reduction systemwithout unjustified approval or disapproval.
- Instrumentation: investigate the suitability of current measurement principles such as used for PEMS, NO_X sensor, 5-gas tester and handheld testers.
- Costs: low costs (and lead time) are an important criterion.
  - For facilities such as measuring instrument and other facilities.
  - For the time to perform the test and administration of the test result.

- Feasibility
  - Complexity: a person with a technical level PTI inspector must be able to perform the test.
  - Can the test be carried out in an PTI inspection station or workshop. The test must be able to be carried out in and, or near a workshop or inspection station.

If a short simple NO_X test for diesel cars with an effective SCR catalytic converter seems feasible, an extensive follow-up study can be carried out into broad feasibility.
Such a follow-up study should determine instrument specifications, threshold values and test conditions and the selectivity with regard to correct operation of NO_X control system without unjustified approval or disapproval.

1.3 Approach

For the Dutch PTI (APK), only a short, simple and cheap test is suitable. The project therefore specifically investigated the proposed short test with a hot idling engine, in which the concentration of NO_X in exhaust gas, measured in the tail-pipe, must be below a certain threshold value. To investigate the feasibility of the hot idle NO_X test, it was applied to a number of M1, N1 and N3 vehicles with compression ignition engines (minimal Euro 6dtemp or Euro VI-D, E). For a part of the vehicles the test was repeated with deactivated NO_X control systems to check the effectiveness of the test, if the test can distinguish or detect fully non-functional NO_X control systems. Various trips were driven in advance of the test to determine what effort is needed to bring a vehicle in test condition. A number of instruments were selected to conduct the actual NO_X concentration measurement (PEMS, 5-gas tester, handheld NO_X tester). An additional data exercise was conducted to determine the effectiveness of an idle test for heavy-duty trucks.

2 Periodic inspection

Current PTI test does not check NO_X control systems

Diesel internal combustion engines naturally produce nitrogen oxides (NO_X) and particulate matter. Modern vehicles (and also a group of mobile equipment and tractors) have emission control systems to significantly reduce NO_X and particulate emissions from the engine. This is regulated in the European type-approval framework by setting requirements, such as maximum emissions of NO_X and particulate matter under specified test conditions.

Malfunctions, aging or manipulation of an emission control system can lead to a large increase in NO_X and particulate emissions, up to the level of an old diesel vehicle. To a limited extend, the necessary repair and maintenance is stimulated by means of OBD. In case of a severe malfunction or no refill, inducement (reduced power and speed) can force an owner to perform the required repair or refill the AdBlue tank. On-board diagnostics has thresholds built in to prevent false positives and built in lead time for owners to respond to the driver warning messages. Less severe OBD warnings can be ignored, OBD can be erased and manipulated.

The current Directive 2014/45/EU, which covers the PTI, does not require a NO_X emissions measurement and contains limited measures for the periodic inspection of diesel vehicles by means of visual inspection of exhaust emission control equipment. The only tailpipe test is a check of harmful smoke emissions by measuring the so-called opacity of the exhaust gas. Alternatively, Member States may use an OBD test instead of the smoke opacity test. In some members states amongst which the Netherlands it was concluded that the smoke opacity test as well as the OBD check can't be used to determine whether a diesel particulate filter is functioning properly.

The opacity test is outdated and not suitable for checking diesel cars with a particulate filter. In the Netherlands, an improved particulate filter test was therefore introduced in the Dutch PTI (called APK) on 1 January 2023. This is a test in which the number concentration of soot particles in the exhaust is measured with a particle counter when a vehicle is idling. At the introduction of this new particle counter test, the European OBD on-board diagnostic system is no longer read during the periodic inspection for diesel cars with a particulate filter. This means that aside from the visible inspection, there is no inspection if the NO_X control system is working as it should. Even if an OBD test would be done, in case of no completed readiness test or even p-codes indicating malfunctions with the SCR system, only the opacity test or as of January 2023, the particle counter test has to be done and remains decisive. EU regulation stipulates that a malfunction indicator (often called engine light) needs to be lit in the case of certain malfunctions of the emissions control system. In some cases this leads to inducement, the reduction of power and speed which should force an owner to have the malfunction repaired. In the Netherlands there is no control or enforcement to ensure that vehicles in between PTI's are maintained and repaired properly.

This means that for NO_X control systems on diesel vehicles there is hardly any control, and no supervision and enforcement to ensure correct functioning of the NO_X control systems, with the result that vehicles with malfunctions, need maintenance such as an AdBlue refill, or that have been manipulated can drive on public roads with increased NO_X emissions.

Short, practical test needed

The ongoing revision of the roadworthiness package of the EU aims at including new methods for measuring exhaust NO_X and particle number (PN) emissions. In the EU, several options for a NO_X test for PTI were already investigated [2019, Pascal Buekenhoudt et al.] and investigation is still ongoing. The main issue for a test, is that the engine and SCR need to be at working temperature and preferable be tested with the engine under load such that the diesel engine produces NO_X which a well-functioning NO_X control system should reduce to below a certain threshold value. Early studies summarized in a CITA position paper [2022, CITA] propose predefined drive cycles to be conducted while sampling NO_X from the tail-pipe while driving, the use of a burdensome chassis-dyno or applying a series of free accelerations, optionally helped by switching on auxiliary loads. These tests are burdensome and do not meet the requirements of a short, simple and cheap test for the Dutch PTI situation. JRC proposes a short practical test ('NO_X hot idle test') which requires a warm engine coolant (>=70 °C) and the measurement of the NO_X concentration in the tailpipe, see paragraph 3.1.

Given the limited number of Euro-6d diesel cars in the Dutch fleet and relatively many APK stations in the Netherlands that would need a new measuring instrument if a new test is introduced, only a short, simple and cheap test is suitable. The project therefore specifically investigated the short test with an idling engine, in which the NO_X concentration must be brought below a certain threshold value. It was investigated whether the SCR catalytic converter can be brought to working temperature by means of a short warmup ride, if vehicles with excessive NO_X emissions can be detected and whether or not tests could lead to false fails or false passes. The first is important so as to not falsely render a vehicle not roadworthy and prejudice the owner. The latter is important for the test to be effective for detecting vehicles with excessive NO_X emissions.

Which vehicles could be considered?

Passenger cars and light commercial vehicles of environmental (Euro) class 6d-temp or higher, heavy commercial vehicles of environmental (Euro) class VI or higher, with a combustion engine with a compression ignition (diesel engine) and which have a NO_X control system that can effectively reduce NO_X emissions produced in the diesel engine of which the effectiveness relies on maintenance and a properly working system without malfunctions.

In the Netherlands sales of diesel light-duty passenger cars (M1) has dropped over the last years. Light-duty vans (N1) and small and heavy-trucks with diesel engines still represent a large share of the sales for these categories. Therefore, the test sample and recruitment of test vehicles targeted N1 vans and trucks of recent Euro classes.

To indicate the extend of the target fleet of *light-duty* vehicles (N1, M1, passenger cars and small vans) for a diesel NO_X hot idle test, fleet data is gathered. September 2023 approximately 47 thousand out of about the 9 million passenger cars are new M1 diesels (0.5%) and 222 thousand out of a million are new N1 diesels (22%). New diesels here means an admission date later than the first of September 2019.

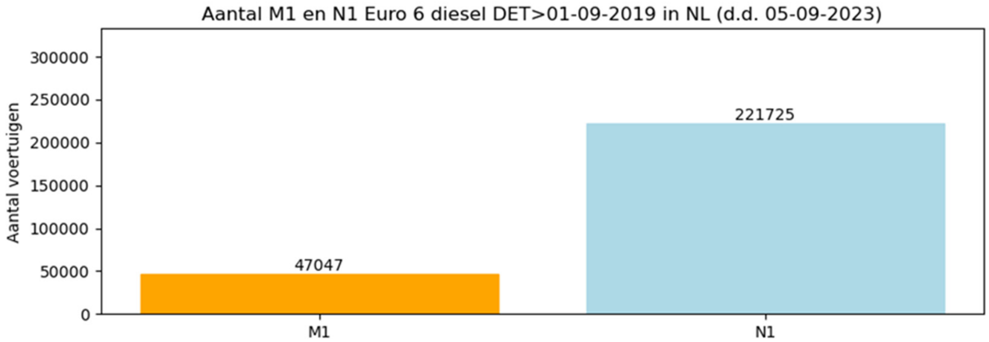

Figure 2.1: Number of diesel M1 and N1 vehicles on 5-September 2023 which are registered with a date of first admission (NL: datum eerste toelating (DET)) later than 1 September 2019. Most newly registered diesel vehicles in the Netherlands are N1. (Source open RDW database[1])

Perioden	Totaal motorvoertuigen	Personenauto	Motorfiets	Totaal bedrijfsmotorvoertuigen	Bestelauto	Speciaal voertuig	Bus
	x 1 000						
2023	10 808,9	8 917,1	690,7	1 201,1	989,8	56,0	8,8

Bron: CBS

Figure 2.2: Extraction of CBS statline[2] of registered numbers of motor vehicles in 2023 per category.

For *heavy-duty vehicles* most of the new admissions would still be diesel (compared to e.g. gas-fueled and electric) for these and coming years and the share will be large and increasing. Local zero emission zones will enter into force in 2027 forcing on the uptake of BET Battery Electric Trucks). To indicate the extend of the target fleet of heavy-duty vehicles (M2/3 (buses) and N2/N3 (commercial vehicles) for a diesel NO_X idle test, fleet data is gathered. In October 2024 in the Netherlands 70,000 registered vehicles are step D and E.

Table 2.1: Number of diesel M2/3 and N2/3 vehicles on 4 October 2024 of Euro class VI. (Source open RDW database[3]).

RDW Opendata base dd. 04-10-2024, Counts of vehicle registrations of stage VI	European vehicle category					
Stage and step, TA all vehicles	M2	M3	N2	N3	Total	
EURO VI A, 01.2014	46	1139	2262	20511	23958	17%
EURO VI B, 01.2014	0	234	844	7737	8815	6%
EURO VI C, 01.2017	48	1280	3212	36211	40751	28%
EURO VI D, 09.2019	17	373	4534	20956	25880	18%
EURO VI E, 01.2022	20	471	4611	38737	43839	31%
Total	131	3497	15463	124152	143243	
	0%	2%	11%	87%		100%

[1] https://opendata.rdw.nl/browse
[2] https://opendata.cbs.nl/statline/#/CBS/nl/
[3] https://opendata.rdw.nl/browse

If the test would have mainly have Euro 6/VI and SCR equipped vehicles in scope, the test would target ~250.000 passenger cars and vans, of which vans are the majority, and ~143.000 heavy-commercial vehicles.

3 Method

The test program aimed to gain rapid insight into the practical feasibility and effectivity of the ‘NO_X hot idling test’ where the tailpipe NO_X concentration shall be below a provisional threshold of 15 ppm and whether the test can detect an improperly functioning NO_X reduction system, for instance a car with a deliberately deactivated SCR NO_X control system.

For this goal, four light and two heavy-duty vehicles were subjected to various tests where the vehicles were idled and driven on the public road to bring the NO_X control and engine at working temperature. Several parameters were obtained by an OBD Scan tool and by exhaust gas measurement instruments which can measure NO_X concentration exhaust gas while stationary or driving on the road.

Tests were conducted with well-functioning NO_X control systems and with deactivated systems. Deactivation was achieved by simply electrically disconnecting the EGR control and AdBlue pump plugs or fuses. After deactivating AdBlue dosage, the vehicle was driven to empty the ammonia stored in the SCR. The deactivations lead to diagnostic trouble codes, but the vehicles could be driven and tested with both or either one of both simulated malfunctions.

For heavy-duty vehicles initially a data analyses with on-road NO_X sensor data was conducted to determine if a warm SCR at idling indeed always leads to low NO_X concentrations.

3.1 Provisional PTI Diesel hot idle NO_X test

An outline for a test is provided by JRC which describes that the NO_X concentration in the tailpipe needs to be measured during idling of the engine when the vehicle is stationary. Figure 3.1 shows an example of the NO_X emissions during the warmup drive and afterwards, during the test.
Figure 3.2 shows the provisional test execution and decision logic.
The rationale for the test is that a properly functioning SCR system would lead to a low NO_X concentration in the tailpipe which can be measured with an exhaust gas analyzer. A provisional threshold for the measured tailpipe NO_X concentration is provided of 15 ppm. A properly working SCR system only achieves a low NO_X concentration when it is at working temperature, which is generally higher than 150 °C and when sufficient AdBlue was dosed which is necessary for the chemical reduction of NO_X in the hot catalyst.
The engine coolant temperature would indicate if engine and NO_X control system are at working temperature. The engine coolant temperature therefore has to be observed prior to the test and determines whether or not a 5 minute drive prior to the test is necessary to warm up the vehicle.

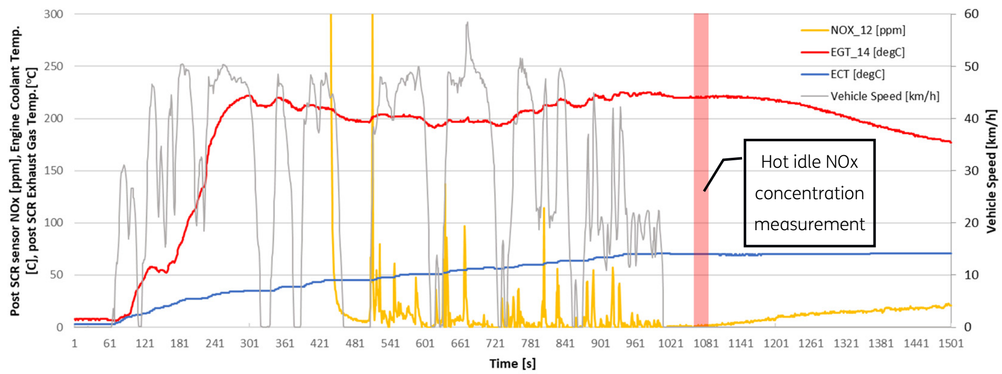

Figure 3.1: Example of NO_x emissions during the warmup drive and afterwards, during the hot idle NO_x test.

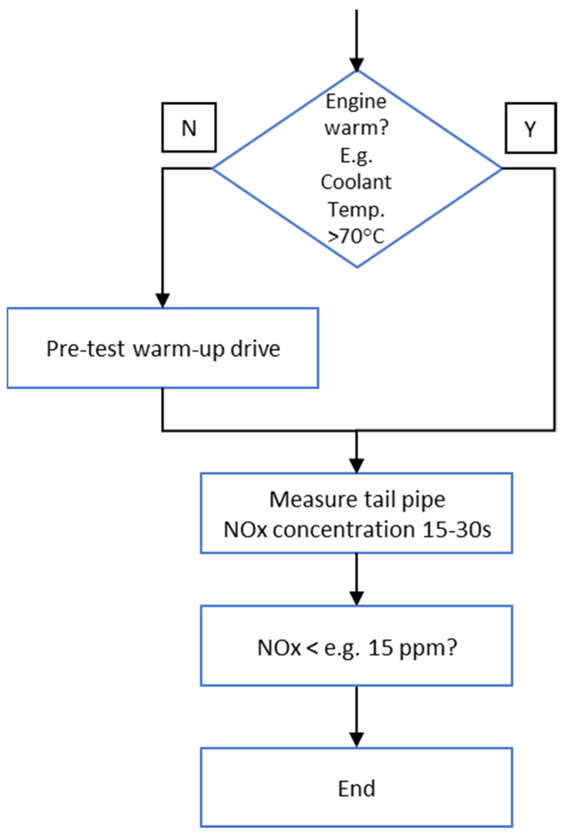

Figure 3.2: Provisional example of the procedure of the NO_x hot idle test with provisional decision criteria and threshold.

3.2 Test program

The program aimed to gain first insights applying the concept of hot idle test as currently being discussed and suggested by JRC. Since preconditioning, the warming up of the test vehicle (NO_x control and engine/engine coolant) is a known prerequisite, several different warmup scenarios were applied to get an indication of what is a minimal required warmup scenario and to understand warmup behavior and indicators; idle warmup, high idle warmup, short drive, or in case no sufficient warmup is achieved, a trip necessary to bring SCR system in working condition. Several instruments were used to measure tailpipe concentrations of mainly NO_X, CO_2 and O_2 (PEMS, Testo 350, TEN 5-gas tester, tailpipe and engine out exhaust gas concentrations of NO_X and O_2 from the present NO_X sensors and parameters and variables from the vehicle and engine by means of SEMS. In addition, a work-shop diagnostic tool was used to check the status of the vehicle prior to testing to ensure a correct functioning of the systems, during the test program to check OBD response to applied failures.

3.2.1 Test vehicles

Given the numbers of registrations, a NO_X hot idle test in the Netherlands would mainly target light commercial vehicles (vans) and heavy commercial vehicles (trucks) with diesel engines. The hot idle test was therefore conducted with a number of Euro 6/VI vehicles of recent Euro classes dtemp(X) and higher for N1 and step D for heavy-duty (N3) vehicles. See Table 3.1 for the recruited test vehicles

Table 3.1: List of test vehicles subjected to provisional hot idle tests.

Brand, type	EU category	EU standard
VW Caddy	N1	Euro 6 X
VW Transporter	N1	Euro 6 AR
Peugeot Expert	N1	Euro 6 AQ
Renault Master 3.5t	N2->N1	Euro 6 AR or VI-D/E?
DAF XF, tractor	N3	Euro VI C
Mercedes Actros, 19t rigid	N3	Euro VI D

3.2.2 Measurement equipment

Table 3.2 shows an overview of the exhaust gas analysers and instruments used.
The measurement set-up consists of a PEMS and exhaust flow meter connected to the tailpipe. The sample probes of a workshop instrument (TEN- 5gas), a portable gas tester (Testo 350) and a workshop PN counter (TEN AEM) were inserted in the exhaust flow meter as if this was the end of the tailpipe. The exhaust flow meter (EFM) was attached to the tailpipe prior to each test when a short drive with the vehicle was conducted. Each vehicle was prepared to easily connect the EFM to the tailpipe so that it takes 15-30s additional time to perform these actions. However, normally the probe of a workshop instrument would have to be inserted in the tailpipe.

This would take an almost comparable amount of time in both cases and is not critical considering the gradual decrease of temperature of the warmed up NO_x control system. In addition an OBD tester was used to scan OBD messages, diagnostic trouble codes such as emission related trouble codes (p-codes) and readiness.

Table 3.2: Overview of the exhaust gas analysers and instruments used.

Equipment	Emissions, signals		TNO TUI nr.*
PEMS (Portable Emissions Measurement System)-gaseous+ Exhaust Mass Flow Meter	NO, NO_2, CO, CO_2, THC [ppm, %] EMF [kg/h]	Formal lab grade on-road testing instrument in a stationary set-up in the workshop	60150508 EMF bl = 94010342 EMF bcl = 94010343 EMF G = 23003415
SEMS (Smart Emissions Measurement System)	NO_x sensors, Exhaust gas temperatures, Adblue dosing Engine Coolant Temp	Sensor and CAN-data based autonomous data-acquisition	94017843
Testo 350	NO_x, O_2, NH_3, CO, CO_2 [ppm, %], Lambda [-]	Handheld tester	21004732
TEN 5-gas tester	CO, CO_2, HC, O_2, NO_x [ppm, %], Lambda [-]	Workshop equipment extended with NO_x measurement	94023592
TEN AEM particle counter	PN concentration [#/cm^3]	Workshop equipment	21005257
PEMS-PN	PN [#/cm^3]	Formal lab grade on-road testing instrument	23001007
OBD tester	dtc, p-codes	Workshop equipment	94023593 for passenger cars and light-duty vehicles. 94028917 for trucks.

*Refers to TNO registration of instrument and it’s status, including calibration status.

4 Results

In this chapter the results and observations of all tested vehicles are provided and discussed.

4.1 VW Caddy, N1 small van

The first test vehicle is the TNO-owned VW Caddy certified Euro 6dtemp, N1 diesel with 55kW engine and 1466 kg registered mass in running order. The vehicle has EGR, DPF and SCR.

In about 8 minutes driving at low speeds, the post SCR temperature could be brought up to 180 ⁰C. It takes considerably longer drives at higher speeds to bring post SCR above 200 ⁰C.

When the NO_X control systems were working well, test results showed low NO_X concentrations during the idling test, even after a warmup idling and also just after a warmup drive in the range of 3 to 13 ppm. When both EGR and SCR are deactivated NO_X concentrations are clearly higher, from 140 to 200 ppm. When either the SCR or the EGR was deactivated, NO_X concentrations ranged from 35 to about 50 ppm. Warming up of ECT to from 40 to 70 °C takes 5 minutes and from 20 to 70 °C it takes 8 minutes.

Table 4.1: NO_X idle tests, with different conditioning, conducted with a small Euro 6b N1 class I van equipped with SCR and EGR. Complete deactivation/malfunction/removal of EGR and, or SCR was simulated by disconnecting the wire to respectively the EGR valve and the reagent dosing unit.

Testnr.	NO_X control working Y/N		Conditioning	Driving time	OBD DTC's	Exhaust gas temperature post SCR / Engine coolant temp. [°C]	NO_X concentration	Test pass/fail
	EGR	SCR			Yes/No	[⁰C]	[ppm]	
Test 1	Yes	Yes	Idle warmup	0	No	94 / 58	13	False test (ECT<70)
Test 2	Yes	Yes	PTI test short trip 30 km/h max starting semi warm engine at 40° ECT	8 (~5 minutes needed for ECT >70)_	No	180 / 79	3	Pass
Test 3	Yes	Yes	PTI test short trip 70 km/h max, warm start	11	No	189 / 87	3	Pass
Test 4	No	No	SEMS data missing	-	-	-	-	-
Test 5	No	No	PTI test short trip 100 km/h max	40	Yes	192 / 86	140	Fail
Test 6	No	No	Idle warmup and high RPM	0	Yes	145 / 73	170-200	Fail – false positive
Test 7	No	No	SEMS data missing	-	-	-	-	-
Test 8	Yes	No	PTI test short trip 100 km/h max	13	Yes	212 / 82	35-38	Fail
Test 9	No	No	SEMS data missing	-	-	-	-	-
Test 10	No	Yes	PTI test short trip 100 km/h max (ECT 20-70 in 8 minutes)	24	Yes	170 / 83	39-51	Fail

4.2 VW Transporter, N1 van

The test vehicle is the TNO-owned VW Transporter certified Euro 6 AR, N1 diesel, 81kW engine, 1879 kg registered mass in running order. The vehicle has EGR, DOC, DPF, SCR and ASC.

An engine coolant temperature of 70 °C is achieved 15 to 17 minutes after a cold start when driving a short trip with a max. speed of 50 km/h. The post SCR temp is than 220 °C and sufficiently high for a hot idle test. The SCR heats up fast to 200 °C in about 200 s with a trip up to a maximum of 50 km/h.

Idling or high idling can bring coolant at the required minimum >70 °C but isn't sufficient to warm up the SCR. If coolant alone was the test criterion, the test would lead to a false positive result. The high idling test performed later is conducted with a warm engine (ECT>70 °C) and also leads to a fail because of the sufficiently high ECT no drive is necessary hence SCR is not warmed up. With correct working NO_X control systems the measured tailpipe NO_X concentration is 1 to 2 ppm and substantially higher when SCR is manipulated (24- 57 ppm).

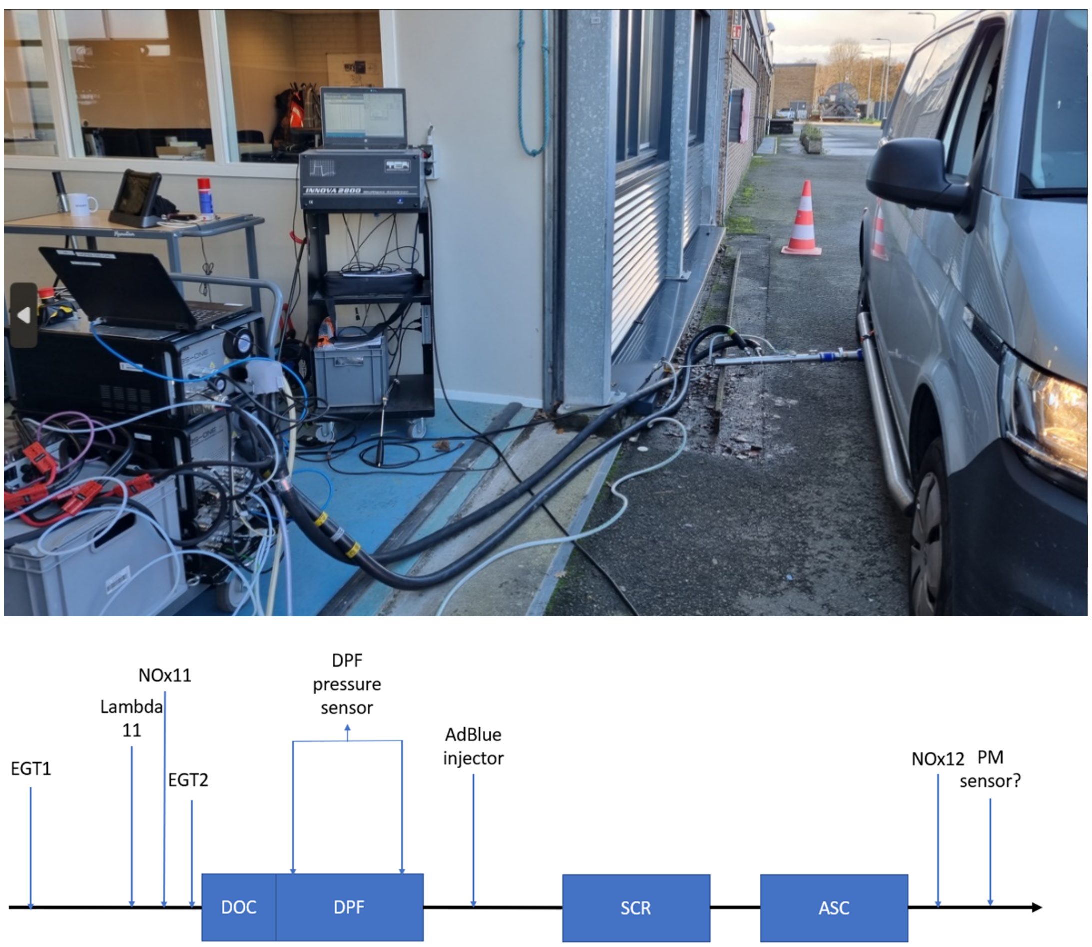

Figure 4.1: Exhaust configuration of the VW transporter with sensors and catalysts/filters.

Table 4.2: NO_x idle tests, with different conditioning, conducted with a van equipped with SCR and EGR. Complete deactivation/malfunction/removal of SCR was simulated by disconnecting reagent dosing unit.

Test #	Test description	Condition	Additional conditions	Exhaust gas temperature post SCR [°C] / Engine coolant temp. [°C]	30s average NO_x [ppm]	Test pass/fail
1 (27-11)	Test drive	Trip max 70 km/h	No malfunctions	245	1	Pass
2 (28-11)	PTI test short trip, minimum drive time until ECT 70C	Trip max 50 km/h, ~15 min	No malfunctions	220 / 70	1	Pass
3 (28-11)	PTI test short trip after repeat with warm engine	Trip max 50 km/h max ~15 min	No malfunctions	214 / 85	2	Pass
4 (29-11)	Idle from cold after cold start	Overnight soak ~-2C cold start, idle until stable (1.5h)	No malfunctions	160 / 70	100	Fail - false positive
5 (29-11)	High idle with warm engine	After test 4, 2500 rpm	No malfunctions	240 / 82	24	Fail - False positive
6 (29-11)	PTI test long trip SCR dosing failure/tampering	Trip max 80 km/h	SCR dosing unplugged	202 / 87	50	Fail
7 (30-11)	PTI test short trip SCR dosing failure/tampering	Trip max 50 km/h (ECT 3 - 70 in 17 min)	SCR dosing unplugged	197 / 70	42	Fail
8 (30-11)	PTI test short trip SCR dosing failure/tampering	Trip motorway max 100 km/h	SCR dosing unplugged	204	57	Fail
9 (4-12)	PTI test short trip SCR dosing failure/tampering	Cold start, trip max 50 km/h,	SCR dosing unplugged	201 / 76	52	Fail
10 (4-12)	PTI test short trip	Warm start, max 50 km/h, 15 min	No malfunctions	213 / 83	2	Pass

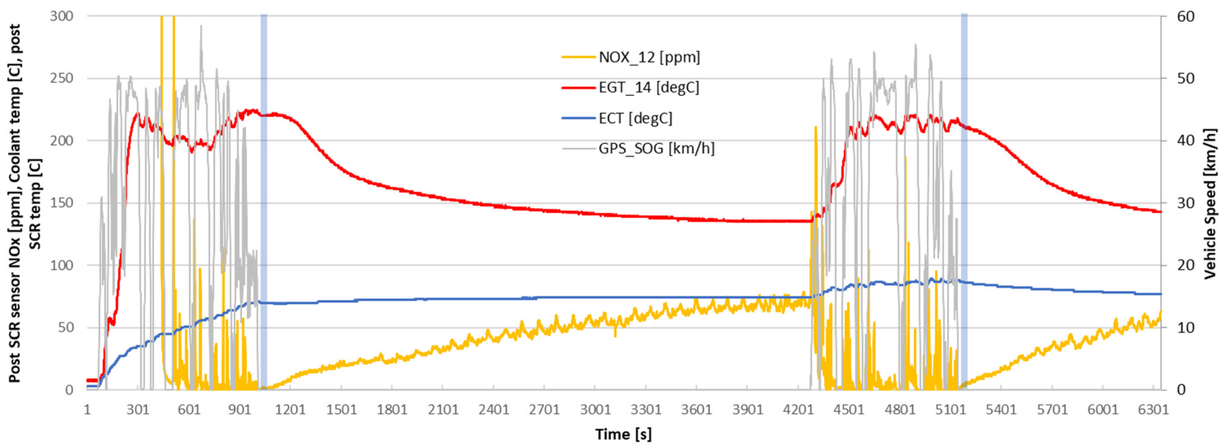

Figure 4.2: Test 2 and 3 NO_X idle tests (indicated by blue sections) after a 50 km/h drive of about 15 minutes. Tests have to be conducted immediately after return from the trip as NO_X concentration rises rapidly.

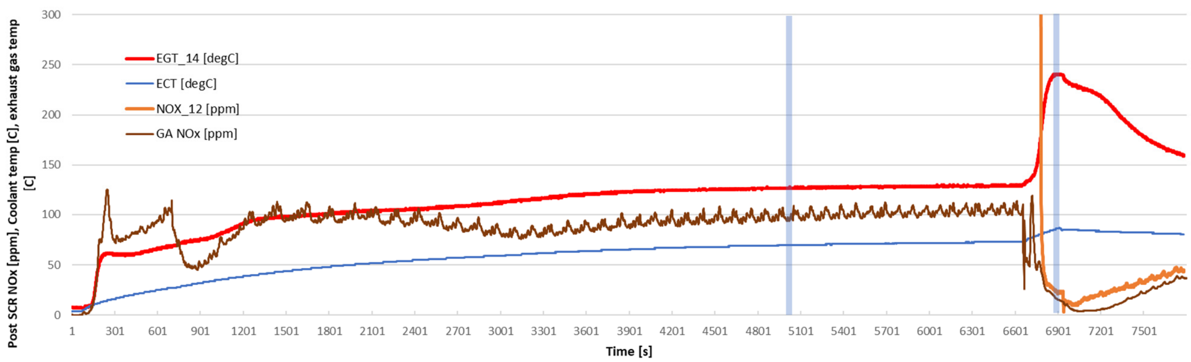

Figure 4.3: Test 4 and 5. NO_X idle tests (indicated by blue sections) after idle warmup and at high idle. Engine Coolant Temperature reached 70 °C after 5000 s.

4.3 Peugeot Expert, N1 van

The Peugeot Expert is a Euro 6 AQ certified N1 class van.

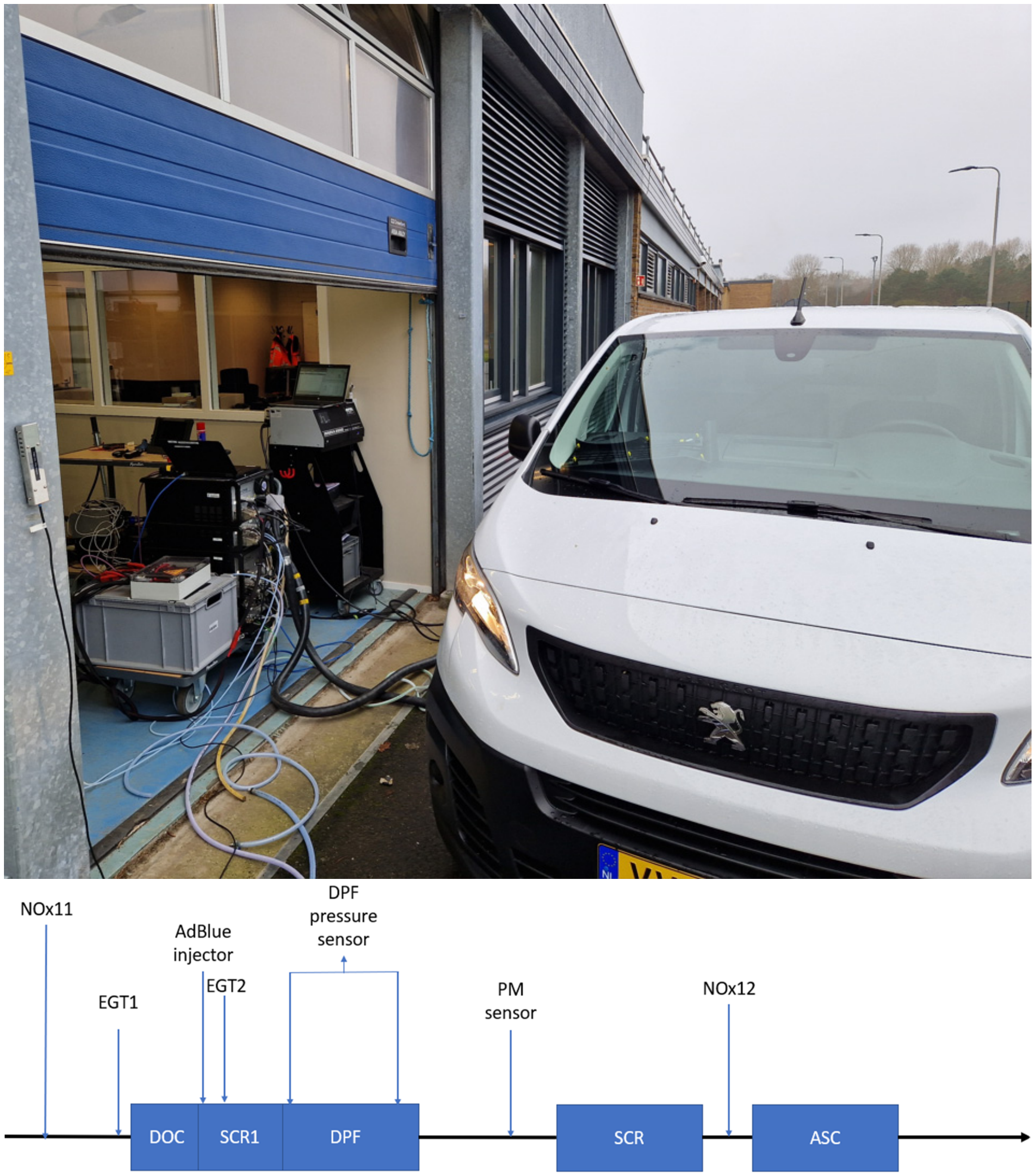

Figure 4.4: Exhaust configuration of the Peugeot Expert with sensors and catalysts/filters.

From a cold start it takes approximately 13 minutes to reach an ECT of 70 °C. The first SCR (SCR1) in the exhaust reaches light-off temperature of about 180 °C in about a minute. A high idle test when ECT>70 °C leads to a false positive (false fail) because the SCR is still below working temperature. When the SCR is warm, NO_X concentrations are 0 to 3 ppm, well below 15 ppm.

The SCR can be at operating temperature while ECT is still well below 70 °C. With SCR deactivated the tailpipe NO_X concentration was about 50 ppm but it took a long drive for the SCR to use the remaining ammonia before the test results in a fail (NO_X<15ppm). When also EGR was manipulated the NO_X concentration increased to 184 ppm.

Table 4.3: NO_x idle tests, with different conditioning, conducted with a van equipped with SCR and EGR. Complete deactivation/malfunction/removal of EGR and, or SCR was simulated by disconnecting respectively the EGR valve and the reagent dosing unit.

Test #	Test description	Condition drive	Additional conditions	Exhaust gas temperature post SCR [°C] / Engine coolant temp. [°C]	30s average NO_x [ppm]	Test pass/fail
1 (5-12)	PTI test short trip	Cold start, max 50 km/h, ~15 min	No malfunctions	190 / 75	0.8	Pass
2 (6-12)	PTI test after long idle	Long idle	No malfunctions	123 / 72	111	Fail – false positive
3 (6-12)	PTI high idle test 2500 rpm	Test 2	No malfunctions	163 / 90	74	Fail - false positive
4 (6-12)	PTI test short trip driving until NO_x 12 becomes active > test	Warm start, trip max 70 km/h	No malfunctions	250 / 88	0	Pass
5 (6-12)	PTI long idle test	Long idle after warm trip	No malfunctions	135 / 91	108	Fail - false positive
6 (7-12)	PTI test short trip, driving to ECT=70C, then return.	Cold start 1C, trip 50 km/h max (~15 min.), ECT=70 at 13 min.	No malfunctions	193 / 74	1	Pass
7 (7-12)	PTI test short trip, minimum drive time until SCR 'on'	Drive until SCR 'on' (55-180C in 60s) ECT= 55C	No malfunctions	200 / 55	3	False test (ECT<70) (Pass)
8 (8-12)	PTI test short trip, minimum drive time until SCR 'on'	Drive (210s) until SCR 'on' (3-180C in 65s) (ECT=34°C)	No malfunctions	205 / 34	0	False test (ECT<70) (Pass)
8b (8-12)	Empty SCR	Drive to 'empty' SCR	SCR dosing unplugged (connector on reagent tank)			
9 (11-12)	Empty SCR	Drive until SCR 'empty'	SCR dosing unplugged	235 / 90	48	Fail
9b (11-12)	Try to empty SCR PTI test long trip	1h trip 100 km/h max	SCR dosing unplugged	240 / 90	50	Fail
10 (12-12)	PTI test short trip, EGR and SCR deactivated		EGR unplugged, SCR dosing unplugged	240 / 80	184	Fail

DTC (2)

Engine ECU -- CMM_MD1CS003_EURO6_4 (2 DTCs)

DTC	Description	Status
U040F:81	Emissions control CAN network (Downstream NOx sensor) -- Data received invalid	Permanent
P2047:13	AdBlue/DEF injector control -- Open circuit	Permanent

Figure 4.5: DTC's on 8-12 after disconnecting plug on reagent tank.

DTC (6)

Engine ECU -- CMM_MD1CS003_EURO6_4 (6 DTCs)

DTC	Description	Status
U010E:87	Emissions control CAN network (AdBlue/DEF pump - gauge module) -- Lost information	Permanent
U02A5:87	DeNOx system (CAN) -- Lost information	Permanent
P2047:13	AdBlue/DEF injector control -- Circuit open	Permanent
P0406:12	Exhaust Gas Recirculation (EGR) valve position signal -- Short circuit to positive	Permanent
P0403:13	Exhaust Gas Recirculation (EGR) valve control -- Circuit open	Permanent
P1461:27	Programming of Exhaust Gas Recirculation (EGR) valve stops -- Inconsistent signal change	Permanent

Figure 4.6: DTC's on 12-12 after also disconnecting EGR plug.

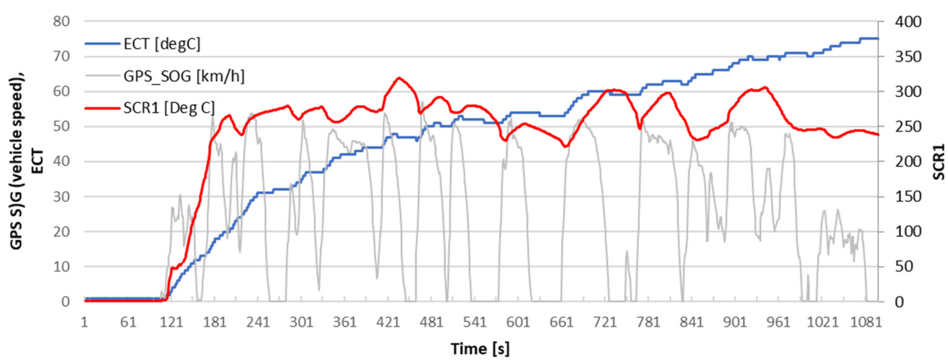

Figure 4.7: The warmup behaviour during test 6, starting with an engine coolant temperature (ECT) of 1 °C. It takes approximately 13 minutes to reach an ECT of 70 °C. The first SCR (SCR1) in the exhaust reaches light-off temperature of about 180 °C in about a minute.

4.4 Renault Master, N1 box van

The vehicle is probably an N2 recertified N1 chassis cabin with a box superstructure with a registered maximum technically permissible laden mass of 3.5t. It is certified either Euro 6 AR or VI-E.

It takes 10 minutes to reach 70 °C from a cold start with a short trip driving 50 km/h maximum. The post SCR temperature is then 254 °C and sufficiently high for a hot idle test. In principle the test could be conducted after a shorter trip when the SCR is sufficiently warm (higher than ~180 to 200 °C for most types) which is after 4 to 5 minutes of driving. For the high idle test (5) the vehicle fails because coolant temperature is higher than the required minimum of 70 °C but SCR isn't warmed up sufficiently. For the test with manipulated SCR the vehicle just fails because of the measured NO_X concentrations of 18-20 ppm. It was not sure if the SCR was fully empty, without any ammonia stored. But with the trip to empty the SCR lasting 47 minutes, also driving speeds of 80 km/h, one would expect the catalyst to be at least almost empty. This means that with a threshold of 15 ppm the vehicle with completely deactivated SCR only fails by a small margin of 3-5 ppm when possibly some ammonia is still stored. During one of the tests with manipulated SCR also NO_X values of 10 ppm were measured meaning that the test could lead to a false negative result.

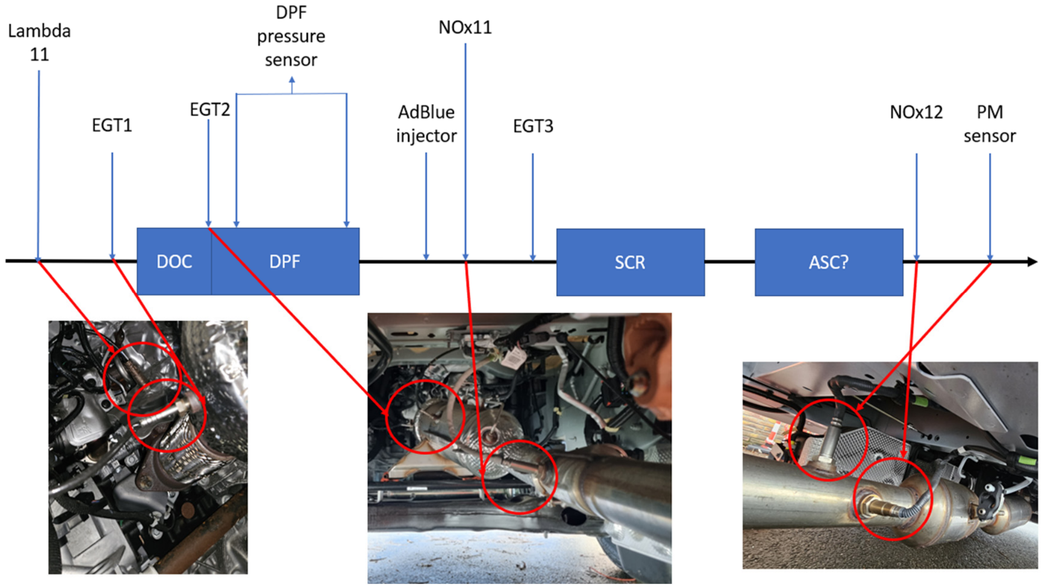

Figure 4.8: Exhaust configuration of the Renault Master with sensors and catalysts/filters.

Table 4.4: NO_x idle tests, with different conditioning, conducted with a van equipped with SCR and EGR. Complete deactivation/malfunction/removal SCR was simulated by disconnecting the reagent dosing unit.

Test #	Test description	Conditioning before drive	Condition drive	Additional conditions	Exhaust gas temperature pre SCR (EGT3) [°C] / Engine coolant temp. [°C]	30s average NO_x [ppm]	Test pass/fail
1 (3-1)	PTI test short trip	Soaked multiple weeks	Cold start, drive to 50 km/h max ECT 71 after 600s Post SCR temp 254C	No malfunctions	240 / 78	1	Pass
2 (4-1)	PTI test after cold engine long idle	Overnight soak	Cold start, long idle	No malfunctions	100 after 1h	going from 115 to 30 in 1h	
3 (4-1)	PTI test short trip	1 hour soak	Short trip, half warm engine halfwarm start, up to 50km/h driving until SCR on > Test	No malfunctions	178	0	Pass
4 (8-1)	PTI test very short trip	weekend soak	Cold start, drive until first roundabout and back ("minimum trip") > Test. + high rpm test	No malfunctions	180 / 40	4	False test (ECT<70) (pass)

5 (8-1)	PTI test high idle		Previous test	No malfunctions	145 / 79	45	Fail - false positive
6 (9-1)	PTI test long trip to empty catalyst	overnight soak	SCR tampering, longer trip to empty catalyst	SCR dosing unplugged 1 DTC	199 / 77	18 Able to reduce idle NO_x when hot (ammonia still present)	Fail
7 (10-1)	PTI test short trip	2 hour soak	SCR tampering, short trip with warm startup to 50 km/h driving until ECT 70C->test	SCR dosing unplugged 1 DTC	190 / 74	20 Able to reduce idle NO_x when hot (ammonia still present)	Fail
8 (15-1)	PTI test short trip, minimum drive time until SCR 'on'	Weekend soak	SCR tampering, short trip with cold start, up to 50 km/h driving to ECT 70C->test	SCR dosing unplugged 1 DTC	211 / 71	19 Able to reduce idle NO_x when hot (ammonia still present)	Fail

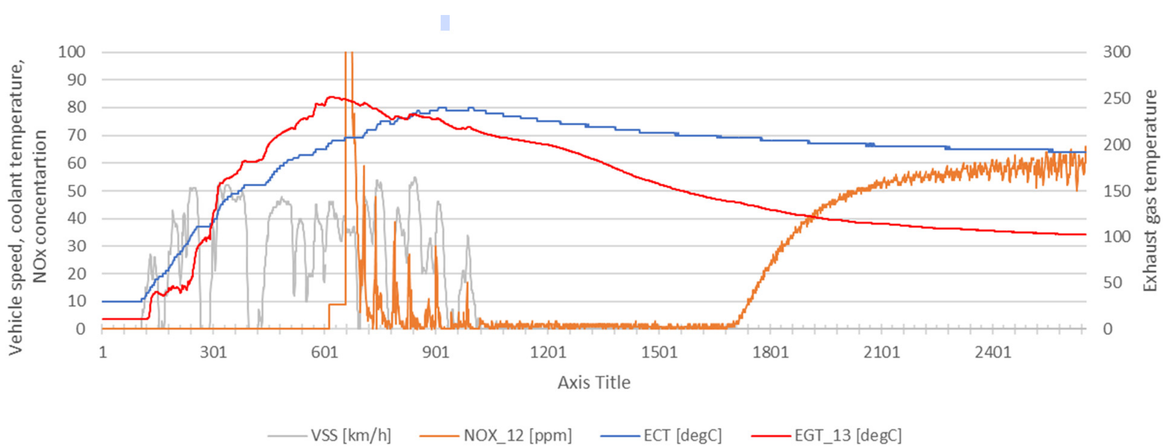

Figure 4.9: NO_x hot idle test1, with a preconditioning drive of about 15 minutes. The bleu bar indicates the test period. ECT 70 °C criterion is reached after about 10 minutes. ECT and pre SCR temp are sufficiently high for the test.

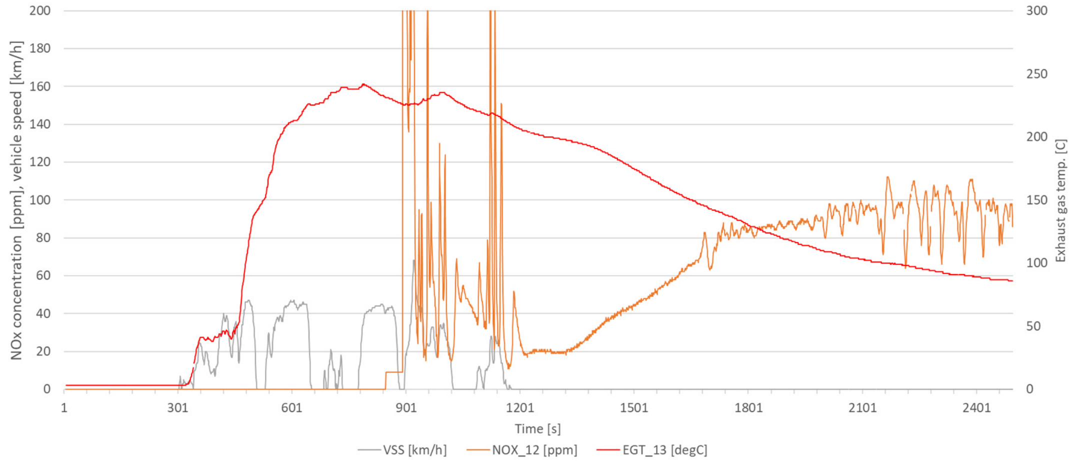

Figure 4.10: NOx hot idle test 8. When the SCR is deactivated and after an hour of driving (test 6 and 7) NOx concentration reaches is 19 ppm during the idle test and also during driving NOx peaks are not very high despite the deactivated SCR. Supposedly the NOx control system still reduces NOx but works only partially. The threshold of 15 ppm would only just lead to a fail.

DTC (1)

Urea dosing control module (1 DTC)

DTC	Description	Status
DTC202E13	AdBlue/DEF injector Open circuit	Active

Figure 4.11: DTC on 9-1 after disconnecting the plug of the AdBlue injector.

4.5 DAF XF, N3 heavy-duty tractor

It is common that tractors are brought to a workshop for periodic inspection without semi-trailer. Therefore, an N3 4x2 tractor was used for the testing. This represents a normal but difficult vehicle for a test because driving without trailer and payload will lead to a slow warmup of the catalysts of the emission control system.

The test vehicle was a rented DAF XF certified Euro VI-C, N3 diesel, 4x2 tractor, with 330 kW engine and 8.2t registered mass in running order. The vehicle was driven without a semi-trailer. The vehicle has EGR, DPF and SCR.

Figure 4.12: Heavy-duty N3, Euro VI-C tractor as used for the tests.

With idling, short drives and even with longer drives at the motorway with the tractor, post SCR temperatures could not be brought up to a targeted minimum working temperature of 180 °C at test start. The post SCR temperature did reach more than 200 °C during rural and motorway driving but when exiting rural and motorway roads driving to the test location the post SCR temperature starts to cool down and drops below 180 °C.

Nevertheless, measurements were performed after the drives with an idling engine. When the NO_X control systems were working well, test results showed a NO_X concentrations of °about 25 ppm (test 1), the post SCR temperature was however about 152 °C and ECT>=70 C was not met, resulting in a false test. Within 15 minutes of driving after a cold start, coolant temperature reaches about 52 °C and thus does not reach 70 °C yet.

When both NO_X control systems were deactivated (test 3 and 4) the NO_X concentration were 190 and 210 ppm and with only a deactivated EGR 180-200 ppm for one test and 210-230 ppm for another. For the case where only the SCR was deactivated (test 7), the NO_X concentration was 125 ppm. However, when both systems are activated after a long drive (test 6) still a somewhat elevated NO_X concentration was measured of about 60-70 ppm. This would result in a false positive. With each malfunction, a test would correctly lead to a fail.

For the tractor it was not possible to test with a warm SCR (post SCR temperature of approximately >160 °C). Especially the last part of the trip contains some slow driving, for the test vehicle without payload it means that the SCR cools down quickly on the way back to the test location.

Table 4.5: NO_X idle tests, with different conditioning, conducted with an N3 tractor equipped with SCR and EGR. Complete deactivation/malfunction/removal of EGR and, or SCR was simulated by disconnecting respectively the EGR valve and the reagent dosing unit.

Testnr.	NO_X control working Y N (manipulated, unplugged)		Conditioning	Driving time	OBD DTC's	Exhaust gas temperature post SCR at test start / / Engine coolant temp. [°C]	30s average NO_X [ppm]	Pass/fail
	EGR	SCR		Minutes		[^{0}C]	[ppm]	
Test 1	Yes	Yes	70 km/h, short drive	15	No	150 / 52	25-30	False test (ECT<70)
Test 2	No	Yes	70 km/h, short drive	14	Yes	137 / 57	180-200	False test (ECT<70)
Test 3	No	No	70 km/h, short drive	14	Yes	137 / 75	190	Fail
Test 4	No	No	85 km/h, long drive	30	Yes	143 / 84	210	Fail
Test 5	No	Yes	85 km/h, long drive	22	Yes	137 / 82	210-230	Fail
Test 6	Yes	Yes	85 km/h, long drive	30	No	150 / 84	60-70	False positive
Test 7	Yes	No	85 km/h, long drive	34	Yes	159 / 84	125	Fail

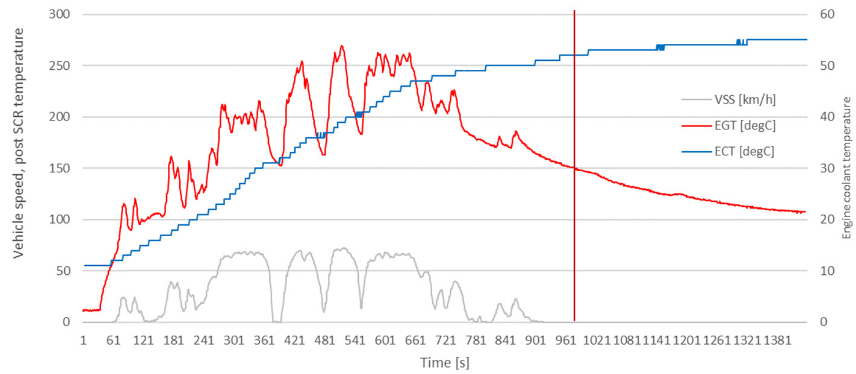

Figure 4.13: (Test 1) when driving the post SCR temperature increases to working temperature but cools down when driving back from highway to the test location. After parking the vehicle, placing wheel chocks and inserting the test probe in the tailpipe after the drive approximately 1 minute), the post SCR temperature has reached approximately 150 °C. The trip was started with a cold engine.

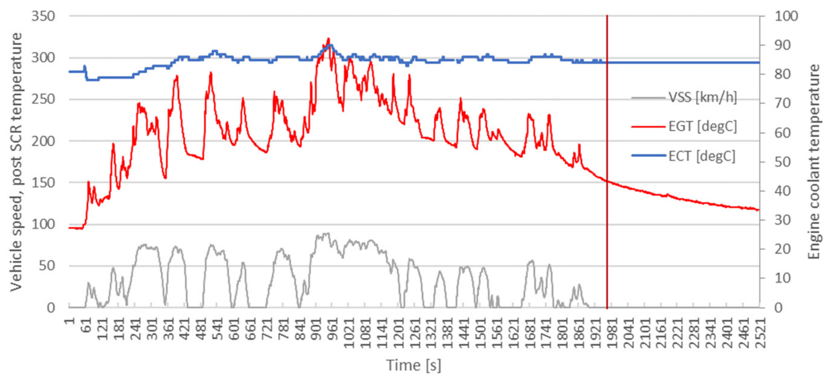

Figure 4.14: (Test 6) when driving the post SCR temperature increases to working temperature but cools down when driving back from highway to the test location. After parking the vehicle, placing wheel chocks and inserting the test probe in the tailpipe after the drive (test 6, approximately 1 minute), the post SCR temperature has reached approximately 150 °C. The trip was started with a warm engine.

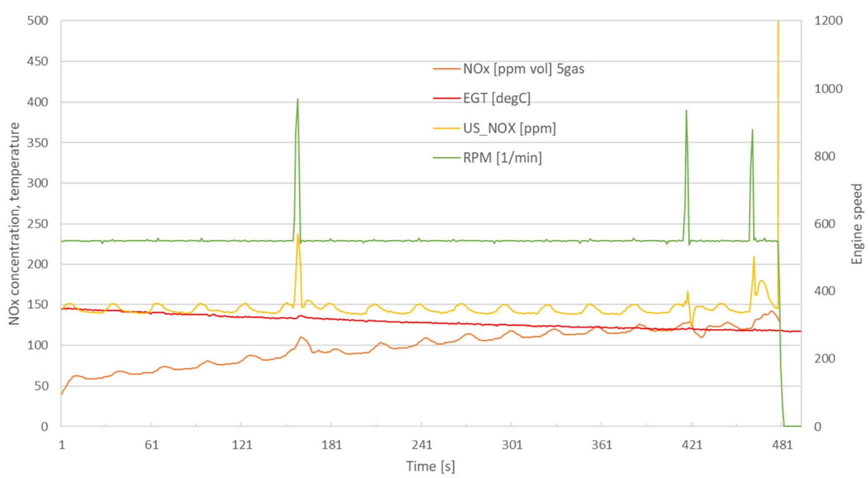

Figure 4.15: After a long drive (test 6) the tailpipe NO_X concentration is about 60-70 ppm.

4.6 Mercedes Actros, N3 heavy-duty rigid truck

The test vehicle was a rented Mercedes Actros, Euro VI-D, N3 diesel, 4x2 tractor, with 7.7 l 175 kW engine and 9.7 t registered mass in running order. No additional payload was added. The vehicle has EGR, DPF and SCR.

Figure 4.16: Rigid truck with PEMS EMF tube with PEMS gas heated line, Testo 350 and TEN 5 gas probes (top, middle) and the TEN AEM particle counter probe directly inserted in the under body tailpipe (below).

When at working temperature, the NO_X measured tail concentration is about 0 ppm. With shorter warmup drives the SCR temperature becomes more critical. In two cases the SCR was critically low or didn't reach light off (test 4 and 5), while engine coolant was higher than the minimum required value of 70 C. NO_X concentration for these tests was higher (8 and 25 ppm) than when fully warmed up (0 and 1 ppm) and still lower than with a manipulated SCR (71-77 ppm).

Table 4.6: NO_X idle tests, with different conditioning, conducted with an N3 tractor equipped with SCR and EGR. Complete deactivation/malfunction/removal of EGR and, or SCR was simulated by disconnecting respectively the EGR valve and the reagent dosing unit.

Test #	Test description	Conditioning before drive	Condition drive	Additional conditions	Exhaust gas temperature post SCR [°C] / Engine coolant temp. [°C]	30s average NO_X [ppm]	Test pass/fail
1 (22-1)	PTI test trip	weekend soak	Cold start, drive 50 km/h max 24 min	No malfunctions	189	1	Pass
2 (22-1)	PTI test trip	2h soak	Semi warm start, drive 50 km/h max ECT 79 26 min	No malfunctions	EGT_14: 196 EFM: 176 ECT: 79	0	Pass
3 (23-1)	PTI test minimal	overnight soak	Cold start, drive 50 km/h max Minimal trip 11 min	No malfunctions	EGT_14: 162 EFM: 157	13	
4 (23-1)	PTI test minimal trip	2h soak	Semi warm start, minimal trip ECT 74	No malfunctions	170 / 74	8	Pass
5 (23-1)	PTI test minimal trip	1h soak	Semi warm start, minimal trip round about ECT 72C	No malfunctions	135 / 72	25	False positive (SCR cooled down while ECT>72)
6 (24-1)	PTI test minimal trip	Overnight soak	start, Minimal trip round about ECT 52C	No malfunctions	165 / 52	24	False test (ECT<70C)

7 (24-1)	PTI test long trip to empty catalyst	1h soak	Long trip to ‘empty SCR catalyst	SCR manipulation (injector unplugged)	205 / 82	77	Fail
8 (24-1)	PTI test short trip	1h soak	Semi warm start, drive 50 km/h max	SCR manipulation (injector unplugged)	175 / 76	76	Fail
9 (25-1)	PTI test trip	Overnight soak	Cold start, drive 50 km/h ma	SCR manipulation (injector unplugged)	173 / 79	71	Fail
10 (25-1)	PTI test long idle	Overnight soak	Long (1h) idle	No malfunctions	60-100	77	False test, a drive was necessary

Nabehandelingssysteem Conti Temic - (ACM) Nabehandeling uitlaatgas - -	P	JA
• 210D05 - AdBlue-doseerklep - Onderbroken	ATT	-
• EE1004 - AdBlue-druksensor - Kortsluiting naar massa	ATT	-
• 011105 - Verstuiververwarming - Onderbroken	ATT	-

Figure 4.17: DTC on 24-1 after disconnecting the plug of the AdBlue injector.

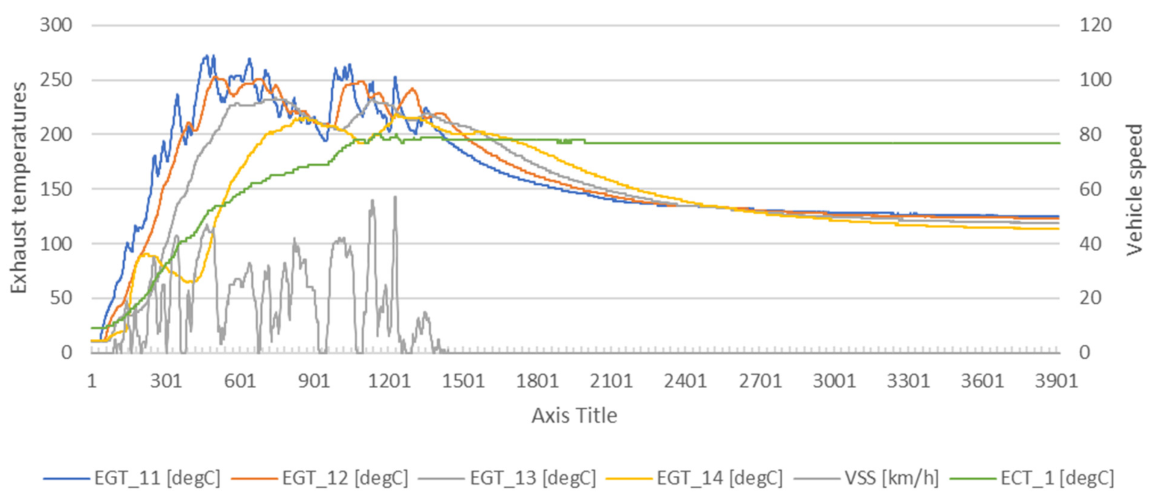

Figure 4.18: Test 2: SCR temperature reaches approximate working temperature between 5-10 minutes of driving whereas engine coolant temperature takes approximately 15 minutes to reach 70 °C. On the way back to the test location and when parked for testing post SCR temperature (EGT_14) remains at working temperature sufficiently long to conduct a PTI test.

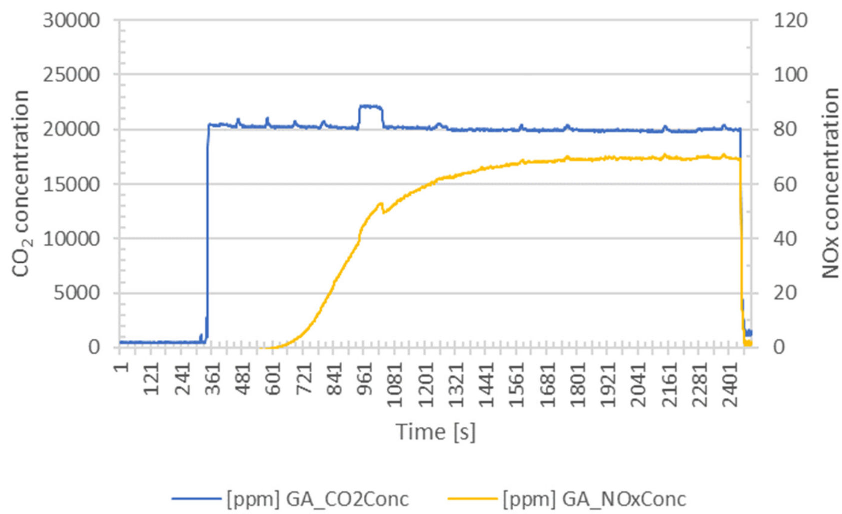

Figure 4.19: Test 2: PEMS data showing NO_x concentration and CO_2 concentration after connecting the exhaust meter to the tailpipe. NO_x concentration starts rising after 5 minutes from 0 to 70 ppm due to cooling down of the SCR.

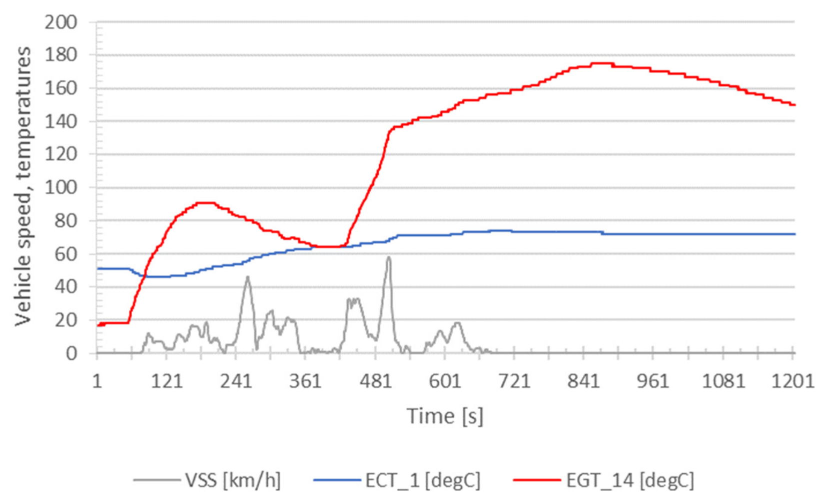

Figure 4.20: Test 4: SEMS (vehicle) data showing vehicle speed and temperatures of the engine coolant and exhaust gas in the tailpipe. While after a warmup drive the engine has a coolant temperature higher than 70 C (72), which should indicate test readiness, the exhaust gas temperature has merely reached light off temperature of the SCR catalyst. The

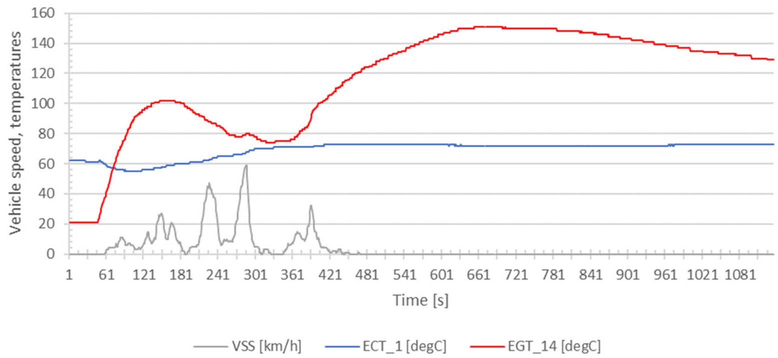

Figure 4.21: Test 5: SEMS (vehicle) data showing vehicle speed and temperatures of the engine coolant and exhaust gas in the tailpipe. While after a warmup drive the engine has a coolant temperature higher than 70 °C, which should indicate test readiness, the exhaust gas temperature has merely reached light off temperature of the SCR catalyst.

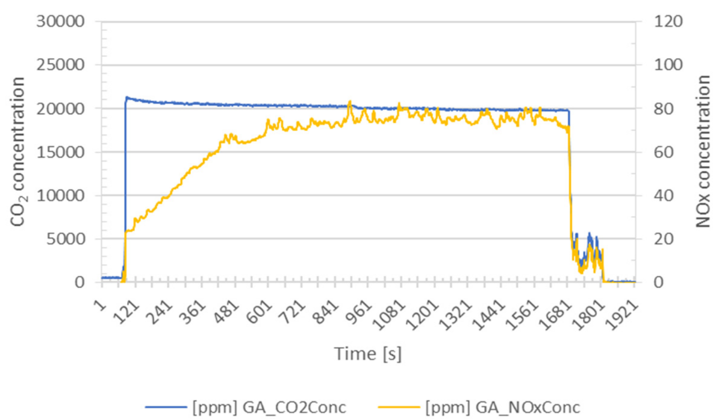

Figure 4.22: Test 5. PEMS data showing the measured tailpipe CO_2 and NO_x concentration after arrival at the workshop. The NO_x concentration is rising due to the low SCR temperature.

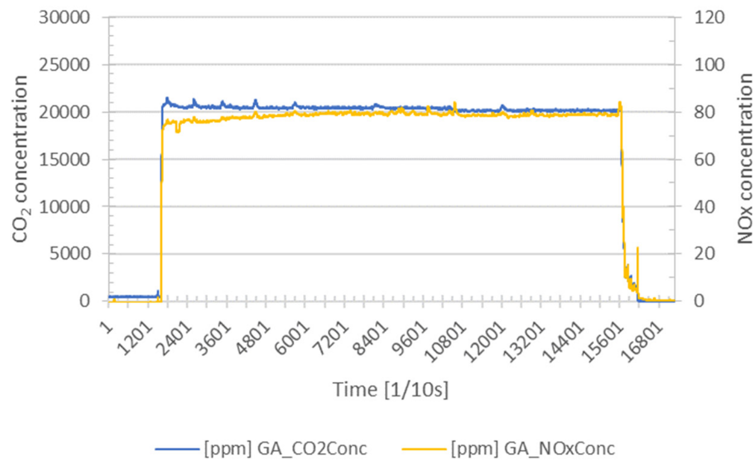

Figure 4.23: Test 6: the measured tailpipe CO_2 and NO_X concentration after arrival at the workshop. The NO_X concentration is almost stable around 72-80 ppm due to the SCR manipulation (lack of ammonia stored in the catalyst to reduce NO_X).

5 Data-exercise heavy-duty

At TNO measurement data is available from earlier measurement campaigns from trucks that had failures and were deliberately manipulated to the NO_X control system and of trucks that were in good running order. These data were analysed to get a first impression if a stationary test, where NO_X concentration is measured in the tail-pipe, can detect if a system is malfunctioning or does not lead to false positives of false negatives.

Vehicles, trips, data and 'hot idling' selection

The dataset used is from TNO's emission monitoring program in which vehicles are instrumented for a prolonged period (months up to years) with TNO's Smart Emission Monitoring System (SEMS), which routinely acquires real world vehicle trip data consisting of GPS tracks, tailpipe emission signals (e.g. CO_2 and NO_X) and various vehicle signals via the vehicle's CAN bus.

Table 5.1: Overview of tested vehicles used for the analyses.

Vehicle Information				
TNO vehicle ID	Type	EU class	Body type	Particularities NO_X reduction
DA_LF_87BNZ7	LF 210 FA	EURO VI-D	Truck	functional, no particularities
DA_XF_99BBS2	FT XF	EURO VI-A	Tractor trailer	With & without SCR malfunctions due to a faltering NO_X sensor and dosing unit
MA_TX_49BFG1	TGX	EURO VI-B	Tractor trailer	With & without SCR malfunctions due to a faltering ambient temperature sensor
MB_CI_34BDH1	CITARO G	EURO VI A	Single deck, articulated	Functional, no particularities
VO_FH_26BNR1	FH	EURO VI-D	Tractor trailer	Functional, no particularities

Processing method

The first processing step was selecting stationary moments from the selected data according to the following criteria.

1. The engine must be on and hot:
2. a. running at more than 500 RPM, with an engine torque of 15 % at maximum;
   b. with a minimum exhaust gas temperature (EGT) of 200 degrees Celsius or, when EGT is not present, a minimum engine coolant temperature of 70 degrees Celsius.
3. The vehicle must have a speed lower than 0.5 km/h.

Next, from the NO_X concentration signal in ppm, during the selected stationary moments, non-overlapping 15 second NO_X concentration mean values were calculated. Finally, these 15 second NO_X mean values were plotted, tabulated and comparatively analyzed to find out whether (or not) and how (at what threshold levels) a reliable distinction between poorly and properly functioning NO_X reduction systems can be made. Thresholds were chosen at 50 ppm, 100 ppm and 300 ppm.

Results

The main results from the analysis of the obtained 15-s-mean NO_X tailpipe concentrations during engine idling, for five heavy-duty vehicles, are given in Table 5.2. Three vehicles are selected because they perform well in real-world operation and reduce engine out NO_X with high efficiency when SCR working conditions are met. Two of these vehicles show that more than 98% of the tests are passed if a 50 ppm NO_X threshold would be used. The pass rate increases when the threshold is increased to 100 ppm. For the third vehicle this rate is lower but the cause is unknown. A possible explanation is that the Adblue tank needed a refill. The results can't be regarded for further analyses as it is not known when the possible issues occurred. For two other vehicles, for the trips when there were no malfunctions detected by OBD, the 50 ppm pass rate is 93.5 to 95.5% and 96.7 and 98.2% respectively. The pass rate increases when the threshold is increased to 100 ppm. For these two vehicles it is known that they had malfunctions for a given time; one had a broken ambient temperature sensor and one had an active Malfunction Indication, after which two NO_X sensors and Adblue dosing unit were replaced. For the vehicle with the broken temperature sensor, the pass rate is clearly lower for both the 50 ppm and 100 ppm threshold, ranging from about 1 to 9.8%. For the other vehicle with the Malfunction Indication the 50 ppm pass rates are 81 to 89%. For all the vehicles almost all tests have NO_X concentrations below 300 ppm.

Four vehicles with correct functioning SCR fail up to 6.5% of the tests (false positives) using a 50 ppm threshold which reduces to 2.3% when a threshold of 100 ppm is used. In the case of a large malfunction with complete deactivation of SCR for one vehicle, 0.9 to 9.8% of the test would have been passed (false negative) using the 50 ppm threshold and 1.5 to 10.2% if a 100 ppm threshold was used.

For this vehicle the lower threshold of 50 ppm does not lead to a large decrease of false negatives, while for the other vehicles with correct working SCR the false positives are reduced going from 50 to 100ppm.

For the vehicle with only a degradation in SCR control, the malfunction was detected by OBD, but would pass 81.4 to 88.6 % of the tests (false negatives) using the 50 ppm threshold. Supposedly, the NO_X control system still managed to reduce NO_X to a sufficiently low level when idling.

OBD may detect most of the malfunctions of components that could lead to increased NO_X emissions. For one vehicle this hasn't worked, as the broken ambient sensor was not detected by OBD, but still resulted in a deactivation of AdBlue dosage. This problem is to be solved by EU Regulation and OEMs as faulty sensors that can deactivate an SCR control should be detected by OBD.

The results are obtained from vehicles driving and idling on the road. For vehicles with correct working SCR the driving history might still have caused a temporal increase of the NO_X tailpipe concentration during idling, even when the SCR was warm. These individual cases haven't been investigated in detail.

Dedicated testing, bringing vehicles in stable test condition, might reveal if there is potential to improve the simple idle test to reduce the occurrence false positives. An approach to reduce the chance of a false positive could be that if a positive test result is found, a consecutive second test with extended conditioning could be conducted to make the final pass-fail decision.

Table 5.2: Overview showing pass rates for the '15 seconds hot NO_x idle test' for three chosen thresholds of 50 ppm, 100 ppm and 300 ppm respectively.

15-s-mean NO_x concentration values during stationary moments (speed=0 km/h, idling, exhaust gas temp>200 °C)					
Vehicle ID	Trip periods MM-YYYY	% of test results < 50 ppm	% of test results < 100 ppm	% of test results < 300 ppm	Remarks on NO_x reduction performance based on the observed 15-s mean NO_x concentration values
DA_LF_#	04- to 06-2020	100.0	100.0	100.0	Works fine
DA_XF_#	2019	95.5	98.4	100.0	
	03- to 04-2019	93.5	97.7	100.0	Works fine, 15-s NO_x concentration mean
	04- to 06-2019	95.4	98.3	100.0	most of the time < 50 ppm
	06- to 08-2019	97.6	98.8	100.0	
	08- to 11-2019	81.4	93.5	99.8	Malfunction Indication 'Adblue' followed by repair (replacement of two NO_x sensors and dosing unit)
	11-2019 to 02-2020	88.6	96.0	99.7	
	02- to 04-2020	91.7	97.3	99.9	Improvement but NO_x not as low as before
	04- to 05-2020	83.9	92.6	99.8	Again problems? MI during ISC test.
MA_TX_#	09- to 11-2018	0.9	1.5	99.2	Broken ambient temperature sensor
	11-2018 to 02-2019	9.8	10.2	99.3	Broken ambient temperature sensor
	02- to 11-2019	61.2	66.9	99.8	Sensor replaced 05-2019
	11-2019 to 02-2020	96.7	99.8	100.0	Works fine after replacement of the ambient temperature sensor.
	02- to 05-2020	98.2	99.9	100.0	Works fine
MB_CI_#	04- to 05-2017	92.9	96.5	100.0	Works fine, except on 6 days, AdBlue low?
VO_FH_#	02- to 04-2020	98.4	99.1	100.0	Works fine

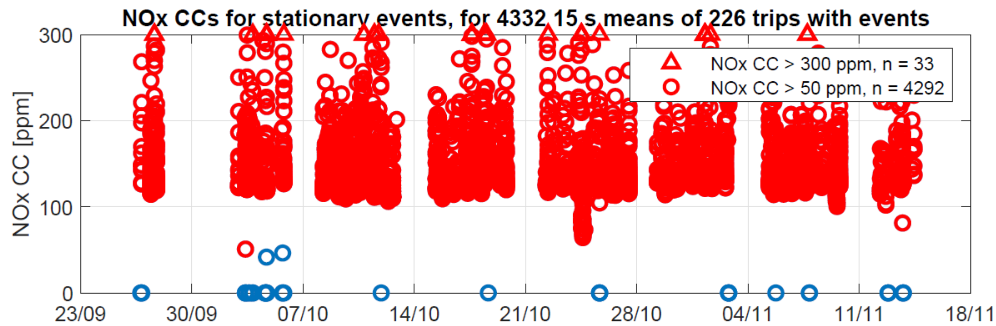

Figure 5.1: MA_TX_#, 09- to 11-2018, high 15-s-mean NO_x concentration values due to faltering ambient temperature sensor.

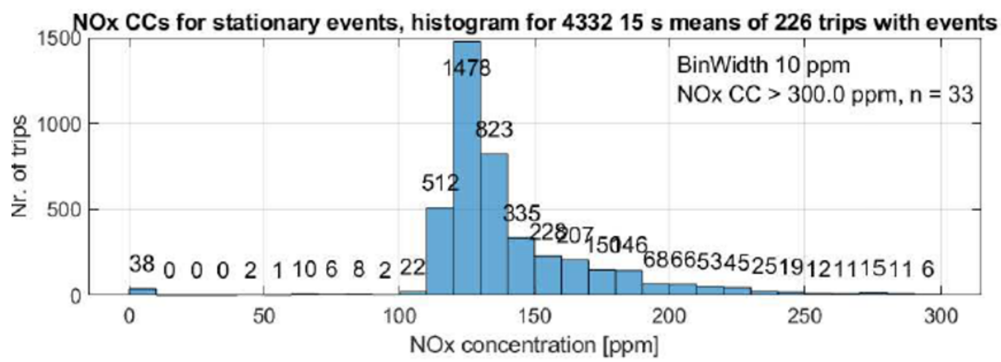

Figure 5.2: Frequency distribution MA_TX_#, 09- to 11-2018, 15-s-mean NO_x concentration values with broken ambient temperature sensor.

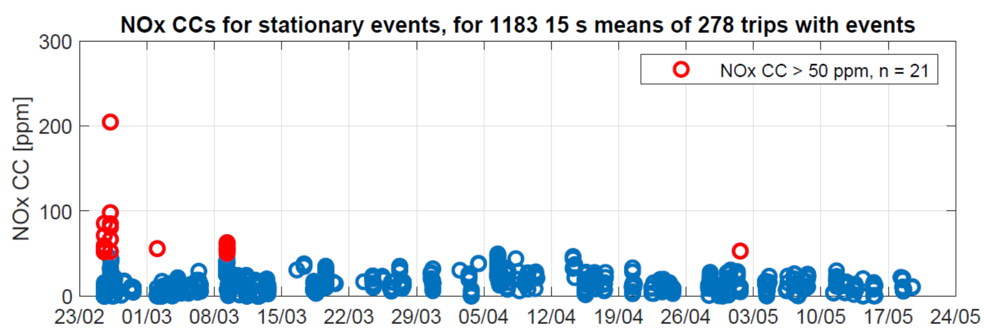

Figure 5.3: MA_TX_#, 02- to 05-2020, properly low 15-s-mean NO_x concentration values after replacement of the broken ambient temperature sensor.

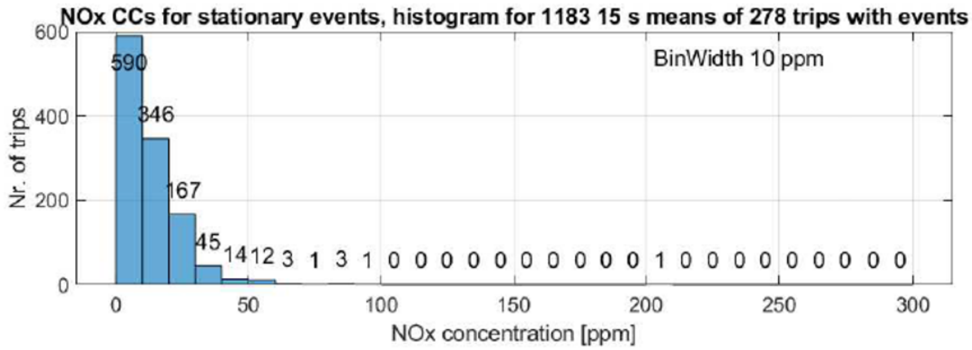

Figure 5.4: MA_TX_#, 02- to 05-2020, properly low 15-s-mean NO_X concentration values after replacement of the broken ambient temperature sensor.

Conclusions

Data-analyses indicated that a hot idle test (15 seconds, Exhaust Gas Temperature >200 ºC) for vehicles with correct functioning NO_X control system could lead to a fraction of false fail test results up to 6.5% at 50 ppm threshold which decreases to 2.3% at a 100 ppm threshold. Vice versa, for a vehicle with a completely deactivated SCR, the test could lead to a fraction of false pass test results of 0.9 to 9.8% for the 50 ppm threshold and 1.5 to 10.2% for the 100 ppm threshold.

For four examined vehicles with correct functioning SCR, NO_X hot idle tests lead to false fails (<6.5%) and for one examined vehicle with deactivated SCR, NO_X hot idle tests leads to false pass (<9.8%). The fractions of false fails and passes depend on the threshold applied. The occurrence of false fails could possibly be mitigated by allowing a second test where a sufficiently high temperature of the NO_X control system is ensured.

6 Discussion

6.1 Test readiness: conditioning drive to warm up the NO_X control system

Pre-test drive on the road necessary

Several studies in the EU have already looked into options for a NPTI (New Periodic Technical Inspection) NO_X test and it was generally concluded that for a proper test, the engine and catalytic NO_X control systems, e.g. using SCR (Selective Catalytic Reduction) need to be at working temperature, because only at working temperature and in good condition, the system reduces the NO_X concentration from the diesel engine to a certain low level which can be measured at the tail-pipe. Several studies also concluded that the vehicle should be tested under load. For the provisional test this is not the case as it encompasses testing during idling of the engine. When the NO_X control system and engine are not at working temperature, the provisional JRC NO_X hot idle test requires a short drive to warm up the engine and NO_X control system The provisional test procedure assumes that a 70 °C engine coolant temperature could be used as a threshold value to determine if a vehicle is test-ready. Only below 70 °C a 5 minute drive would be needed. A temperature of 70 °C and higher could occur when a PTI test vehicle is brought to the workshop by the customer and the vehicle is already driven sufficiently to reach the test criterion of minimal 70 °C and the test can be timely executed. A time limit for the test to start after arrival is not provided but could be needed.

For the tested light-duty vehicles, it was found that a drive of about 10 to 15 minutes is needed to bring engine coolant temperature (ECT) above the test criterion of 70 °C. SCR light-off happens usually sooner for modern diesels, after 2 to 5 minutes. This would be an absolute required minimum time for driving to warm up the SCR from normal stabilized ambient temperatures to working temperature when a vehicle is started with a cold engine. In certain cases this short drive may be too short and lead to false passes. The 5 minutes' drive seems too short to warm up ECT to 70 °C in many cases. E.g. when a vehicle is completely cooled down or when only mild driving at low urban speeds is possible near the workshop.

For heavy-duty vehicles, a trip of a few minutes does not suffice to warm up the NO_X control system and a longer warm up trip in the range 10 to 15 minutes is always needed. A tractor without semi-trailer cooled down rapidly when returning over urban roads to the workshop, even after a long warm up trip mainly at the motorway. Driving at low speeds leads to cool down of the NO_X control system which is a known issue for Euro VI heavy-duty vehicles. This could lead to practical problems for a workshop to bring vehicle in a suitable test conditioning. The given truck would probably have to be driven with payload, a semi-trailer for instance, to thoroughly warm up the SCR to prevent it from cooling down before arrival at the test location. For a 12t rigid truck warming up to ECT > 70 °C lasted 15 minutes but the SCR starts working earlier after 5-10 minutes depending on the trip. Just like for the tractor the SCR temperature can cool down rapidly when the vehicle is driving at low speeds.

When a vehicle started a conditioning trip with a warm engine the ECT reached 70 °C earlier than the SCR light-off temperature, meaning that the vehicle would be test ready while the SCR was still not at working temperature.

It is concluded that in many cases a pre-conditioning drive to warm up engine and NO_X control system would be necessary and in some individual cases, probably mainly heavy-duty tractors, it may be hard to achieve. A pre-conditioning drive on the public road is new for PTI and is presently not prescribed in any EU regulation.

Test readiness

The test assumes that a 70 °C engine coolant temperature could be used as a threshold value to determine if a vehicle is test-ready. This value can be estimated from dashboard meter but can't always be read accurately. For most vehicles this value can be obtained with an OBD diagnostic tool which needs to be connected to the OBD port in the cabin but this increases test complexity and lead time.

The minimum of 70 °C for engine coolant temperature as test requirement does not ensure sufficient temperature of the SCR catalyst to work in all cases and could thus lead to a false fail test result. For instance, a catalyst can cool down due to relative cool exhaust gases when idling or driving at low load, while engine coolant temperature remains above 70 °C. Only idling upfront the test, instead of a drive would eventually bring the coolant temperature above 70 °C but would not be sufficient to warm up the NO_x control system and may even cool down a warmed up catalyst. This is caused by the fact that the low load only results in relatively cold exhaust gases which does not warm up the catalytic converter sufficiently (or even cools down the catalyst).

Therefore, a minimum engine coolant temperature doesn't ensure test readiness.

If a test has a positive result (fail), the possibility that a vehicle has been warmed up insufficiently can be resolved by allowing a second test, after a vehicle has made another drive to sufficiently warm up the NO_X control system.

6.2 Effective threshold

The test requires a threshold value for the measured NO_X concentration value to determine if a vehicle passes or fails the test. This shall be without false fails or false passes and be selective enough to determine if a NOx control system works properly or determine that the system leads to 'excessive NO_X emissions' caused by malfunction, ignored refill or tampering of the NO_X control system. A provisional threshold of 15 ppm was applied for the tests. It was found that for the tested vehicles, a completely deactivated NO_X control system (EGR and SCR), or the complete deactivation of one of two control systems (EGR or SCR) could be detected if it is ensured that the NO_X control system is at working temperature. In one case the test was close to leading to a false pass because the EGR probably reduces the idling NO_X emissions to around or just below the threshold.

An effective threshold for an emissions test also means an accurately and reproducible measurable value which indicates if a NO_X control system fails to achieve the legally required emissions levels with a certain excess of emissions and as such can be marked as having a failed test result. The measured value shall have a strong correlation with a regulated emissions test, e.g. the real-driving test. Furthermore, more NO_X is formed at higher engine loads which a catalyst should be able to reduce.

Some studies [Frank Schneider et al., 2019], [A.Mayer et al., 2019] therefore concluded that for this reason the diesel engine should be running under load during the test but such a test would require a lot of effort and special equipment. Excess emissions during idling shall be of such quantity that it indicates a complete deactivation of the control system, certainly leading to a fail of a formal emissions test or a certain level of deactivation beyond established (per EU regulation) regulated thresholds, such as an RDE limit or an OBD threshold limit (OTL).

For the test vehicles, severe malfunctions were simulated by deactivating the EGR valve control and AdBlue dosage of the SCR system. This lead in 5 out of 6 cases to clearly higher measured concentrations of NO_X in the tailpipe than 15 ppm, compared to the cases where both systems worked well. This indicates that a complete deactivation of a single NO_X control systems could be detected by a hot idling test but in one case almost led to a false pass.

Typical NO_X tailpipe concentrations of a light-duty diesel engine when idling and with properly functioning NO_X control at working temperature are 0 to 4 parts per million (ppm) as observed for the tested light-duty vehicles. For one HDV it was possible to drive the vehicle (a N3 tractor) to warm up the engine coolant to >70 °C, but the SCR temperature dropped to a critical range concerning its working temperature before the test, resulting in NO_X concentrations of 25-30 and 70 ppm in one case. For the other N3 truck a rigid there is a clear difference between a well-functioning (0-1 ppm) and malfunctioning SCR (71-77 ppm) when the vehicle is warmed up thoroughly. The level can increase somewhat to 10-13 ppm when warming up time is less.

Manipulated vans where the AdBlue dosing was stopped showed NO_X concentrations of 35 to 100 ppm. In advance of the test with manipulated SCR, vehicles had to be driven to empty the NH_3 which is still stored in the catalyst. It took substantial time of driving of about an hour to use the remaining NH_3. It indicates that little ammonia stored in the catalyst can still reduce NO_X at idle to below threshold. In a few cases also EGR was manipulated (unplugged), then NO_X concentration was 140 to 185 ppm for two light-duty vans and 190-210 ppm for a heavy-duty truck. For a van with one malfunction (SCR deactivation), the NO_X concentration was about 50 ppm for the NO_X hot idling test.

EGR seems to have a large effect on NO_X reduction when engines are idling. This means NO_X concentrations are reduced compared to uncontrolled engine out NO_X concentrations. Technically, the share of EGR applied and the amount of NO_X reduced at idle is an engine, emissions tuning choice made by a manufacturer who in the end has to make sure that a vehicle is in compliance with the EU regulation, averaged over trips or test cycles. There is no specific requirement for the idling condition. A NO_X concentration threshold shall be at least below the level typically seen for deactivated SCR to detect at least a completely deactivated SCR.

One other aspect that affects the NO_X concentration at idle is the lambda, the air to fuel ratio which can differ from vehicle to vehicle and due to which concentrations may be biased. E.g. a higher lambda will lead to lower measured concentration of NO_X. In principle this could be corrected to e.g. a normalized lambda - or oxygen concentration value if oxygen concentration is measured as well.

The definition of a threshold (pass/fail criterion) for the NO_X hot idle test on a first glance seems more difficult and critical than for the particle number test for periodic inspection of diesel particle filters as being enforced in the Netherlands and some other Member States.

This is because NO_X concentration levels not only depend on the NO_X control technology itself but also depends on design and control choices made by an OEM for AdBlue dosage and EGR control strategy and NO_X can easily be reduced at idle with little performance required from the catalyst. Also the recent driving history of the vehicle has a potential large impact on the quantity of ammonia still present in the SCR catalyst for NO_X reduction for the idle test although for the tested vehicles it was seen that light-off happens fast and as a result dosing can start fast as well. A short preconditioning trip will warm up the catalyst and provide ammonia for NO_X reduction, meaning that the test can be conducted, probably also if the catalyst would have been fully depleted, which is already unlikely to happen. In current EU regulation there is no requirement directly related to or meant to control NO_X hot idle emissions, due to which the correlation between the hot idle test and an RDE test can be low. Because the NO_X control system is tested at idling and not under load, the test might pass vehicles with a partial failing system or reduced efficiency of a NO_X reduction system. The reason is that a low measured NO_X value with an idling engine does not mean that sufficient NO_X reduction would take place under normal driving conditions.

A test program should be held to determine what threshold is indeed suitable and effective. Especially, it should be investigated what the effect is of certain typical failures and deterioration of SCR system on both real driving emissions and the hot idle test result. Higher thresholds would still lead to detection of complete deactivation of SCR or EGR or SCR+EGR with a risk of false passes. For lower thresholds within the range, e.g. 10-20 ppm it is not clear if this could detect partial malfunctions or reduced efficiency of for instance a severely aged catalyst, but it will increase the risk for a false fail test result.

For all vehicles, electrically disconnecting the systems lead to diagnostic trouble codes being stored which can be read during an OBD test.

The test was limited in the sense that it aimed to get a first indication for the possibility of the simple NO_X hot idling test to detect only major malfunctions, not minor malfunctions or reduced efficiency of the catalyst that could lead to smaller increases of NO_X emissions. There is not much data of the frequency of malfunctions and degradation of SCR systems.

Possible causes for high emissions levels of NO_X.

There are several possible causes for complete deactivation. Complete deactivation can happen with tampering (usually by or ordered by the vehicle user), malfunctions of critical system parts (e.g. stopped AdBlue dosage, pump failure or injector failure / blockage), degradation (ageing of catalyst and components) and ignored maintenance such as a refill of AdBlue.

Tampering

Examples of tampering scenarios for SCR are where the SCR is either completely removed or the dosage of reagent is completely stopped (AdBlue emulators/killers, ECU flashing reprogramming) [2020a, van den Meiracker et al.], [2020b, van den Meiracker et al.]. In some cases, tampering targets to only reduce reagent to a certain extend and dosage can theoretically be adapted to work only when idling or can be de-activated to by-pass a test. For instance, certain types of tampering products, e.g. SCR or AdBlue emulators, could be made such that tampering can temporarily be deactivated to ensure a working SCR system for passing a PTI test. Temporary undoing ECU flashing, to by-pass a PTI test is probably much harder because an ECU flashing can't easily be undone.

Malfunctions
Malfunctions which are leading to high NO_X emissions and certainly to a formal RDE test fail, happen when components of the SCR system fail to such extend that reagent dosage is completely stopped or blocked, or when catalytic activity of the SCR catalyst is reduced to such extend that there is no or very limited NO_X reduction. Stopping of AdBlue dosage can happen when the tank is empty, but EU regulation requires vehicles to have a signaling, warning and inducement system to inform and eventually force users to refill the AdBlue timely, usually within a certain distance or time. Cases of blocked dosage have also been observed for heavy-duty engines, where white deposits from incomplete thermolysis and hydrolyses of AdBlue block the dosage nozzle and can also foul the catalyst surface. Furthermore, mechanical and electrical failures could cause parts involved in the system control to break down. Known failures are NO_X sensors, electrical (wiring, plugs) failures, AdBlue injector valve, AdBlue pump, Control Unit. Failure of these components is usually to be detected by OBD and repair to be advised by an indicator or forced by in the end inducement (speed or torque reduction). Inducement in turn brings up a new tampering motivation, namely, to prevent the inducement to actually happen.

Degradation
Ageing or degradation happens due to contamination by various substances (soot, oil, ash, urea by-products, fuel residues) blocking the catalyst surface hereby reducing chemical reactions to take place and (hydro-) thermal stress for instance by the numerous DPF regenerations upstream the SCR catalyst. Another possible cause for SCR degradation is the gradual decrease of the activity of the upstream oxidation catalyst.

Statistical data needed
For Euro 6 and Euro VI vehicles a tampering market exists through demand and supply and it is known through road-side inspections and interviews that a share of vehicles is tampered with. Statistics of tampering are hard to obtain, as is the case for malfunctions on NO_X reduction systems, ignored or postponed maintenance and degradation and the impact of this on NO_X reduction performance. Plume chasing, road-side inspection and workshop statistics could provide data needed to determine the magnitude of the problem.

6.3 Equipment

Current EU PTI regulation does not require the measurement of NO_X concentration. The 'NO_X hot idle test' therefore requires a new instrument which shall be specified and shall be acquired by PTI workshops to be able to conduct the test. This instrument is necessary to measure the NO_X concentration in the tail-pipe during idling of the engine in a similar manner as for the particle filter test (measurement of particle concentration).

6.4 Test execution

The programme provided some indications of the necessary actions to conduct a NO_X hot idle test in a PTI workshop.

For the part of preconditioning, the necessary time depends on whether the vehicle is handed in warm and test ready or not. If a vehicle is not test ready, the vehicle should drive a trip to achieve test readiness. The drive, when a vehicle is cooled down, would last 2-10 minutes for light-duty vehicles and 10-15 minutes for heavy-duty vehicles.

The actual measurement would last approximately 30s and entails the insertion of a probe in the tail-pipe to measure the NO_X concentration of the exhaust gas. This is similar to measurements that already have been prescribed and used in PTI (4-gas, opacity and the new diesel particle filter test).

A NO_X idle test would include the following elements:

- Prepare instrument (warm up, check, calibration assumed to be automated functions)
- Preconditioning ride: duration depends on what is required for test readiness, if a vehicle is handed in warm.
- Park, fix vehicle
- Insert and fix probe in tailpipe
- Test (measurement) 30s
- Remove probe from tailpipe
- Retrieve result from instrument
- Administration of result
- Remove fixation, move vehicle

The execution of the test fits within the current APK which generally requires a quick test with a measuring device in the exhaust, but the required preconditioning drive on the road does not (the necessity of taking an "extensive" warmup drive). The current European guidelines for periodic inspections however do not include a prescribed requirement to make a drive to warm up the vehicle.

6.5 Alternatives

Because it seems possible to detect major malfunctions it could be considered to investigate if the NO_X emission test is feasible at roadside inspections next to motorways, for instance in combination with stationary or mobile remote sensing (plume chase car) to effectively preselect suspected high NO_X-emitters and whereafter a NO_X hot idle test and technical inspection could determine if a vehicle is roadworthy with respect to NO_X emissions or not. For heavy-duty vehicles, which are harder to warm up, a test along the motorway seems better feasible than in a workshop since after exiting motorway trucks are most probably warm and a test can happen soon after the driver is informed, wheel chocks are placed and the probe is inserted in the tailpipe. In theory tampering can be deactivated by the driver using a switch in the cabin after which AdBlue dosage and NO_X reduction starts soon within minutes. The plume chase car results may however provide the information to decide for a thorough inspection of the vehicle where several methods can be applied to find evidence of tampering. The merit of this approach is that suspected vehicles can be preselected and not each vehicle needs to undergo the very time consuming technical inspection searching for possible tampering. Since possibly up to 10% of trucks are tampered, it saves at least technical inspection for 90% of the vehicles. It is not yet known what the rate is of correct positive tests of plume chasing in combination with a hot idle test. This could be investigated.

Figure 6.1: Left: test campaign using the NO_X hot idle test at a regular road-side inspection of RDW and KLPD on a RWS location along motorway A73 and right: test campaign near E40 motorway in Belgium where Danish police is assisting Flemish police with a technical inspection.

On-Board Diagnostics present on all modern vehicles uses diagnostics meant to determine if crucial components of NO_X control systems work well and efficient. OBD could therefore still be an effective means to check the proper functioning of the NO_X reduction system ensuring low NO_X emissions. OBD is not decisive in the current APK in the Netherlands and therefore it is recommended to investigate if an OBD reading at PTI (APK) of the latest generations of vehicles could effectively detect malfunctions or tampering leading to an increase of NO_X emissions. An additional option that can be investigated is to use the OBD reading to determine if a more extensive emissions test is necessary.

7 Conclusions and recommendations

An exploratory investigation was conducted to gain experience with the execution and effectiveness of the provisional ‘NO_X hot idle test’ procedure, which is developed for periodic technical inspection of Euro 6 diesel vehicles with NO_X control systems. Six diesel vehicles, 4 light-duty and 2 heavy-duty, where tested with the test under a variety of conditions, including complete deactivation of the NO_X control system(s). The following can be concluded based on the exploratory tests:

Based on the exploratory test program conducted on four vans and two trucks, we conclude the following:

- The 'NO_X hot idle test' can detect a NO_X control system which doesn’t work at all, but it is not clear if the test is suitable for identifying a NO_X control system which has certain smaller failures or are degraded, leading to a reduced efficiency. This limitation of the test may arise because ‘idling’ is a relatively easy test condition and may show low NO_X emissions even if the NO_X control system performs poorly under normal driving. Tightening the test threshold to improve the accuracy may increase the likelihood of false failures.
- The test program showed that idling alone is insufficient to bring the SCR catalyst to its operating temperature. Therefore the 'NO_X hot idle test' requires a pre-test drive to warm the SCR catalyst: 2 - 10 minutes for cars/vans, 10 - 15 minutes for heavy-duty vehicles. For heavy-duty tractors, the system may cool down on the return trip without payload, making a valid test impossible in certain cases.
- Without a clear indication to check if the catalytic NO_X control system is warmed up sufficiently, the test can potentially lead to false fails. An option to avoid false fails is to allow another test drive followed by a second test.
- The execution of the test itself seems to fit within the current Dutch PTI (APK: (Algemene Periodieke Keuring) because it is a quick test with a measuring probe in the tail-pipe, similar to the recently introduced particle filter test. However, currently EU guidelines for periodic inspections do not prescribe a pre-test drive on public roads. Such a requirement would add to the lead time and complexity of the overall test procedure, so it must be evaluated to determine if it is practical for PTI workshops and acceptable to the vehicle owners.
- For detection of tampered NO_X control systems, the test might be less effective because tampering devices can be switched off prior to the test. However, this extra effort may prevent some owners to tamper.
- The NO_X hot idle test is more suitable for cars and vans than for trucks. For trucks and especially tractors without semi-trailer, it is more difficult to heat up the SCR catalysts with a test drive and to maintain this temperature during the idle test.
- The test would require an instrument to measure the tailpipe NO_X concentration which is new for PTI. Requirements for this instrument would need to be specified by metrological institutes and PTI workshops would have to invest in the new test instrument.

Recommendations
Based on the findings of this investigation we make the following **recommendations**:

- More tests on cars, vans and heavy commercial vehicles would be needed to: - assess the effectiveness of the test to confirm not proper functioning in the case of typical defects that can lead to a reduced performance of a NO_X control system,- to investigate the risk for false test fails and passes and - to determine if the option for a second test after an initial test fail is an effective way to mitigate false test results.
- It needs to be investigated if the required pre-test drive on the road is feasible in the framework of the Dutch APK.
- The test might be suitable for indicating tampering of heavy-duty vehicles at road-side inspection near a motorway. Especially for tractors, the test may be more reliable than during a PTI test since the engine and NO_X control system are likely to be fully warm when a vehicle has a normal cargo load and is tested just after it leaves the motorway. We recommend to investigate the feasibility of this option. To increase the effectiveness of roadside inspection, a remote sensing vehicle (plume chase vehicle) could be deployed to screen vehicles on the motorway and select suspected NO_X high emitters for a NO_X hot idle test and a more thorough technical inspection at the roadside. It could also be considered to investigate the re-introduction of (parts of) the OBD (On-Board Diagnostics) test for newer vehicles.
- Although it is widely known that NO_X control systems can run without AdBlue, degrade, can fail and can be tampered with, there are few good statistics available which show the magnitude of the problem. We therefore recommend to collect the required statistical data and to conduct measurements.
- We recommend to follow the development of the diesel NO_X hot idle test for PTI in the EU.

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