

A new approach for static NO_x measurement in Periodic Technical Inspection

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Abstract

NO_x emissions in vehicles are currently only controlled through the homologation process. There is a lack of knowledge to reliably assess and control real NO_x emissions of vehicles, because although vehicles in EU-27 are subject to PTI (Periodic Technical Inspection), NO_x are not among the pollutants currently being controlled. In this paper, a new approach for measuring NO_x in PTI is proposed. At PTIs, a test needs to be simple, quick, inexpensive, representative, and accurate. To that end, it needs to be carried out under static conditions, so no power bench or complex equipment is required. The method shown in this paper has been developed and validated at a PTI Spanish station, to ensure feasibility and repeatability. This method is based on the relationship between % engine load and exhaust NO_x concentration at idle engine speed. The quality and representativity of this relationship have been checked with a p-value lower than 0.01. The method has been compared with a different NO_x measurement technique based on the simulation on a test bench and the ASM 20–50 cycle. The achieved quality and repeatability of the new approach shows that it could be a useful tool to be applied in PTI for detecting high NO_x emitting vehicles and get information from the diesel vehicles fleet.

1. Introduction

In recent years, frequent episodes of pollutants' high concentration in cities have increased the concern about urban pollution, some of which recognized as being harmful to human health and the environment. NO_x is among the most dangerous, as they are responsible among others for aggravating the consequences of pre-existing diseases, generating problems in the respiratory system of healthy people (EEA, 2017; WHO, 2005), and indirectly for acid deposition (Garcés Giraldo and Hernández Ángel, 2004; Larssen et al., 1999) and the generation of tropospheric ozone and secondary particulate matter (TAN et al., 2009).

Moreover, even if emissions restrictions on vehicle's approval have become stronger over the years (Carslaw et al., 2011) (Williams and Carslaw, 2011), a decreasing of the concentration in the air of these pollutants has not occurred with the same intensity. In fact, in certain areas, concentrations of these polluting substances have even stagnated (Hoekman and Robbins, 2012), and NO_x is a clear example. These compounds, which encompass both NO and NO₂, are generated to a large extent by the road transport (contribution of 40–70% worldwide NO_x emissions (Hooftman et al., 2018; Reşitoşlu et al., 2015)), and to a higher extent, from diesel engines, which generate about 85% of all NO_x emissions from road vehicles (Lee et al., 2013), (O'Driscoll et al., 2018; Wang et al., 2012).

Contrarily to what has happened with petrol engine vehicles, diesel engines have experienced a much lower real reduction in NO_x emissions than expected with the limits established by the successive emissions control regulations (Pujadas et al., 2017). From the introduction of Euro 3 standard emission levels to nowadays, newer vehicles can reach NO_x emission levels similar to older ones (Carslaw et al., 2011), or even vehicles with more severe emissions control regulations can have greater emissions than others with fewer restrictions (Pujadas et al., 2017). This fact has been confirmed through measurements of real driving emissions (RDE) (Hausberger et al., 2009; Ramos et al., 2018; Triantafyllopoulos et al., 2019; Weiss et al., 2012), with remote sensing detector systems (RDS) on a large number of vehicles (Chen and Borcken-

Kleefeld, 2014; Franco and Mock, 2015; Pielecha et al., 2016; Pujadas et al., 2017), as well as with theoretical models and portable emissions measurement systems (PEMS) (Degraeuwe and Weiss, 2016; Franco et al., 2014; Weiss et al., 2012).

Currently, NO_x emission levels of vehicles are only controlled in the process of homologation. To obtain approval for a new model, one of the procedures that will allow its commercialization is a test that measures the vehicle's emissions under specific conditions, to verify that a certain previously established level of emissions of different pollutants (NO_x among them) is not surpassed. This test is carried out on one individual vehicle. Leaving aside situations such as the Dieselgate, in which irregularities were identified in vehicles to pass homologation tests, it has been proven that the stipulated maximum NO_x levels are widely surpassed when vehicles circulate on public roads (Carslaw et al., 2011; Rexeis et al., 2013; Triantafyllopoulos et al., 2019). That is, the test carried out to certify vehicles according to emissions level (in terms of their NO_x emissions) is not representative of their behavior when they come to circulating in the real world (Degraeuwe and Weiss, 2016; Pielecha et al., 2016).

The fact that vehicles with diesel engines are the main NO_x emitters is a serious problem in Europe, given that the penetration of this type of vehicle is higher in the EU than in the rest of the world. Specifically, it is estimated that 70% of diesel passenger cars and vans worldwide are sold in the EU (Poliscanova, 2017). In 2015, 6.6 million diesel vehicles were registered in the EU, accounting for 53% of total vehicle registrations. In 2011, diesel vehicles accounted for 55% of the European fleet and went down slightly to 53% in 2013 and 2014. In some European countries, such as France, Spain, Belgium, and Ireland, diesel vehicles account for between 65% and 72% of the total passenger car fleet (ICCT, 2015).

In general, it is estimated that most pollutant emissions come from a proportionately small number of vehicles, which are known as "high emitters" (Zhang et al., 1995). Respect to NO_x emissions, according to the "Impact Assessment SWD (2012) 206 final" of the European Commission, if between 5% and 7% of the most polluting vehicles were identified, it would reduce approximately between 25% and 35% of the polluting emissions (Staff et al., 2013). Therefore, it becomes key to develop a system that allows detecting these 5% of vehicles that account for 25% of total emissions.

In most countries in Europe (including all the European Union countries (CITA, 2007; Package and Tests, 2012), vehicles in circulation are subjected to Periodic Technical Inspection (PTI), the scope of which varies according to the country of registration of the vehicle. That said, the minimum requirements for inspection (in European Union countries) are determined by European directives (European Union, 2014) and national regulations (Gobierno de España, 2012; Ministerio de Industria, Comercio y Turismo, 2020). This technical inspection of vehicles generally aims to determine, on the one hand, that the various vehicle systems work correctly (focused on guaranteeing road safety), and on the other hand that no polluting emissions are produced above the established limits (environmental protection). As is indicated in the European directive, testing should be relatively simple, quick, and inexpensive, while at the same time effective in achieving the objectives set by the established regulation (European Union, 2014).

In the case of petrol vehicles, PTI controls that the emissions of CO do not exceed the allowed percentages of % volume concentration. In the case of diesel vehicles, the opacity of the exhaust gases is measured,

which theoretically allows checking the amount of soot generated in vehicles. One of the modifications incorporated in the application of the last European directive is the use of vehicle OBD systems as a support for the control and measurement of the vehicle's polluting emissions. That said, currently the levels of NOx emission in vehicles are not being measured, although the directive has contemplated the possibility of adding NOx emissions on-road test to type-approval process (RDE test), and the establishment of NOx levels measurements test methods at PTI (European Union, 2014).

In this respect, several studies such as the one by CITA (International Motor Vehicle Inspection Committee), have tried to define PTI inspection methods that allow controlling NOx emissions and identifying EGR and SCR faults and manipulations. One of them was carried out in 2011, the TEDDIE Project (Boulter et al., 2011), which ended without defining a procedure but urging for further research. In 2015 the SET Project (Barlow et al., 2015), although not specifically focused on the measurement of NOx, ended with the recommendation to define an inexpensive test method to measure NOx, and determine applicable limit values for NOx. In 2017, a new project was again carried out to try to determine a method for measuring NOx emissions from vehicles with the SET II project (Buekenhoudt et al., 2019a, b), which results were presented in 2019, without a clear selection of a NOx measurement method, although suggesting the use of a combination of loaded ASM2050 method with an unloaded test method for EGR assessment.

Most of the procedures analyzed so far for measuring NOx emissions in a vehicle have been based on protocols that pretend to simulate vehicle conditions in circulation. To this end, a simulation power bench (usually reproducing a previously defined cycle) or free acceleration cycles in the static state have been used. Both procedures have presented similar reproducibility and representativity problems.

Moreover, some of these approaches to the NOx control are mainly focused on detecting breakdowns or manipulation on EGR and after-treatment systems. However, the spirit of the directive indicates that the priority should be to measure and know the level of emissions from vehicles (European Union, 2014).

Since it has been found that EGR and after-treatment systems themselves are in many cases designed more to pass the type-approval test (especially in the case of NEDC) than to reduce emissions in real-life traffic conditions (Triantafyllopoulos et al., 2019), it seems more interesting to focus efforts on knowing the level of emissions from vehicles, rather than on analyzing the proper functioning of these systems. It has also been found that sometimes the SCR system is ineffective in urban traffic (Delft, 2010), where NOx emissions are more harmful to health. From this, and given the current lack of information, it could seem more important to know in the first place the level of emissions from vehicles.

Hence, after various experiments and tests over the last years, a procedure that provides a reliable, repeatable, representative, simple and quick NOx measurement method to be performed in a PTI station has not yet been achieved.

In short, in the last years we are in a scenario with an increasing number of diesel vehicles in cities, that in turn have significantly greater NOx emissions than previously thought, and yet there is no way to measure and control these emissions. This paper proposes a new approach to define a method in a different way to the systems proposed until now: NOx emissions test for PTI through a static, robust, and fast way.

2. Nox Emissions Tests

2.1. EXISTING NO_x EMISSIONS TESTS

There is a large variety of NO_x emissions tests, focus on different aspects of NO_x emissions. Some of them are not suitable for PTI application, but they are listed below a sample of them used in various applications. According to concepts or equipment used, they can be divided into the following groups (Buekenhoudt et al., 2019a, b):

2.1.1. Unloaded tests

In this group of tests, none external load is applied to the vehicle, and analysis is carried out from an engine speed variation.

a) Idle tests. Usually, two engine speeds are measured (Boulter et al., 2011).

b) Free acceleration smoke (FAS) test. Is the test used in Europe to measure the exhaust smoke opacity (Boulter et al., 2011; Official Journal of the European Communities, n.d.).

c) INCOLL/AUTONAT. Both tests consist of rapid engine acceleration and deceleration (Samaras and Zachariadis, 1995).

d) Norris. Based on gentle engine accelerations to operate the EGR system (Norris, n.d.).

e) CAPELEC and AVL. Combination of several free accelerations developed by these equipment manufacturers.

2.1.2. Tests with power dynamometer bench at loaded steady state

In this group of tests, a power bench is used to place the vehicle. The vehicle can be driven at a specified speed and vary the brake load, define a loaded steady-state, and modify the speed of the vehicle, or a combination of both situations.

f) US Federal 3-Mode and CalVip, uses a combination of vehicle speed and brake load, defined according to characteristics of the vehicle (Samaras and Zachariadis, 1995).

g) D550, uses a constant load (equivalent to a 5% road gradient) and 50 km/h of constant speed (Anyon et al., 2000).

h) ASM (Acceleration Simulation Mode), uses a constant load equivalent to the road load of the vehicle (except the rolling resistance) during acceleration (Epa et al., 2004). It can be performed with various combinations of load and vehicle speed. The ASM2050 cycle analyses two speed points, 20 km/h and 50 km/h. It is being used to study emissions in urban driving conditions.

i) Lug-down test (Technical Committee : ISO/TC 22 Road vehicles, 1988) uses a constant speed while the brake load increase to full throttle vehicle condition. Then, the brake load is gradually increased until lugging the engine.

2.1.3. Tests with power dynamometer bench at loaded transient

In this group of tests, a power bench is used to place the vehicle (Buekenhoudt et al., 2019b). The engine power and speed of vehicles vary throughout the cycle. It is used to reduce engine damage's risk.

j) Hot EUDC test, derived from the NEDC cycle (Extra-urban Driving Cycle part of the NEDC) (The Council of the European Communities, n.d.). The manufacturer must provide the value to set the dynamometer inertia. During the driving cycle, one or more faults are introduced and should be detected by the EOBD system.

k) DT80 test (Anyon et al., 2000). It is a mix-mode cycle, over a dynamometer bench with inertia simulation, that includes three full-load accelerations to 80 km/h, and a steady-state at 80 km/h.

l) DT60 test (Anyon et al., 2000). It is similar to the DT80 test, but with two full load accelerations to 60 km/h and a steady-state at 60 km/h.

m) AC5080 test (Anyon et al., 2000). It is similar to the DT80 test, although with some important differences. A first full-load acceleration to 50 km/h is followed by a steady-state cruise at 50 km/h for 60 seconds, and then another full-load acceleration to 80 km/h with a final steady-state cruise at 80 km/h for 60 seconds.

n) IM240 test (Pidgeon et al., 1993). A dynamometer bench with associated flywheels is needed. The cycle duration is 240 seconds, and simulate a 3.1 km trip at an average speed of 47 km/h. It is a reduced version of the FTP-75 test.

2.1.4. On-road simulation tests with power dynamometer bench at loaded transient

In this group of tests, a power bench is used to place the vehicle. The vehicle reproduces defined speeds and acceleration patterns that simulate on-road circulation conditions.

o) NEDC (New European Driving Cycle). It consists of two parts, an Urban Driving Cycle (UDC) and an Extra-Urban Driving Cycle (EUDC). Duration is 1,180 seconds for Euro 3 and later vehicles (1,220 seconds for previous), and distance is 11 km. It consists of accelerations, steady speed, decelerations, and idling along with the two parts (in the EUDC there isn't idling) (European Parliament, 2019; European Parliament and Council of the European Union, 2009; The Council of the European Communities, n.d.).

p) WLTP (New Worldwide Harmonized Light Vehicles Test Procedure). It is based on UNECE GTR No. 15. Includes four parts (Low, Medium, High, and Extra High). Duration is 1,800 seconds, and the distance is 23.26 km. Like the NEDC, it consists of accelerations, steady speed, decelerations, and idling along with several parts. It was adopted in 2014 to replace the NEDC cycle (European Commission and Council of the European Union, 2016; Parliament and Union, 2016).

q) CADC (Common Artemis Driving Cycles) is a set of urban, rural, and motorway cycles, with more dynamic characteristics than NEDC and WLTP cycles (André, 2004). It is a result of the European ARTEMIS project.

2.1.5. On-road test

r) RDE (Real Driving Emissions) test with PEMS (Portable Emission Measurement System). Real emissions are measured from a vehicle with portable equipment while driving on a road with pre-defined characteristics (Hausberger et al., 2009).

2.1.6. Others

s) RSD (Remote Sensing Device). It is used to obtain a great number of measurements in a short time, in the fixed location on real driving conditions. It's a powerful tool to know the fleet emission by location (Pujadas et al., 2017).

2.2. PREMISES WHEN DESIGNING A NO_x EMISSIONS TEST FOR PTI

A test for PTI presents some differences and particularities concerning tests oriented to other objectives (laboratory measurements, test for homologation, control of pollution at a fixed location, ...). In the first place when designing a new test for PTI, inspection requirements must be met. According to the implementing PTI directive (European Union, 2014) "Testing during the life cycle of a vehicle should be relatively simple, quick and inexpensive, while at the same time effective in achieving the objectives of this Directive". Likewise, the regulations of European countries (e.g. Spanish regulations (Gobierno de España, 2012; Ministerio de Industria, Comercio y Turismo, 2020)) establish requirements in the same sense: "Testing should be as simple and direct as possible, and the inspection should be possible in a limited time". Of course, there are other requirements in common with other types of tests, like accuracy, precision, significance, and repeatability, although at a different grade. Another important aspect is to define exactly the technical situation the test will measure.

Existing methods to NO_x measurement are trying to simulate, in different ways, on-road conditions in vehicles. Yet these methods face a problem that is difficult to solve.

As is explained in Sect. 1 of the Appendices, the diesel engine NO_x generation mainly depends on O₂ concentration and temperature in the combustion chamber (Fenimore and Jones, 1957; Reşitoşlu et al., 2015; Zeldovich, 1946). But a vehicle is a complex combination of interacting systems regulated by the ECU, and the real on-road NO_x emission from the vehicle at the exhaust pipe depends on a large number of variables (see Fig. 1).

These variables can be divided into exogenous and endogenous (Fonseca González, 2012). The exogenous variables are those affected by the engine working conditions, like traffic congestion, road condition, road grade, driving style, fuel composition, among others. The endogenous variables are vehicle or engine inner working variables that affects emissions like engine speed, gear engaged, the power demanded, engine temperature, etc.

A variation from any of these variables causes a significant variation of the vehicle's NO_x emissions. For example, a severe driving style can increase NO_x emission by more than 250%, or an increase of road grade from 0–5% means a NO_x emission increase of 115% (Gallus et al., 2017).

As a result, it is complicated to design and carry out a test that takes into account all these variables, and also allows reproducing the test by keeping all these variables at values such that the results of two tests

over the same vehicle are similar (for the same conditions) and comparable, that is, a test with enough repeatability.

The way to simplify the test is to previously set-up these variables or to reduce the number of variables involved. The first one introduces a high complexity to the test, and the option to omit some variables can simplify the test, but the precision, accuracy, repeatability, and representativity of the test are reduced.

Another option is to develop the test in a situation where several of the variables involved do not influence NOx emissions. This situation is the engine idle state.

When the vehicle is at idle, the gear engaged, the speed, the acceleration, VSP, the throttle position, the road grade, the payload, the weight, the aerodynamic drag or the driving style, among others, do not influence the NOx emissions.

Moreover, the engine speed remains the same, and the engine operation temperature variation is small.

Only the variables that are out of test control, such as the EGR strategy and the post-treatment systems strategy, remain free. By theoretically, by reproducing the same engine behavior (at idle), these strategies should work on the same way when the test is repeated.

As such, only environmental conditions could affect the NOx emissions, although in a similar way than for other PTI tests. For example, low ambient temperatures are associated with higher NOx emissions. The use of EGR increases the water vapor concentration in the exhaust gas, and at lower ambient temperatures there are problems in the recirculating system when a high EGR rate is used because water vapor condensation can cause severe problems in the EGR line. For that reason, at low temperatures EGR rates are reduced or even canceled to avoid EGR components fails. The result of the EGR rate decreasing is a higher NOx emission at low ambient temperatures (Rexeis et al., 2013).

It should be said however that the period between inspections is usually 1 or 2 years, so the weather conditions may be similar when the PTI test is repeated, and the influence of this variation reduced. On average, only vehicles with 6 months between inspections could be affected by this variation. That said, the influence of variations in ambient temperature, pressure, or relative humidity over the test results should be further studied.

3. Proposal Of New Measurement Process

3.1. TECHNICAL PROPOSAL FOR NOx MEASUREMENT METHOD

As explained in Sect. 1 of the Appendices, NOx emissions from diesel vehicles have a strong relationship with engine power demand (Rexeis et al., 2013), and the % engine load is an ECU's parameter related to the engine power demand.

This proposal is based on the analysis of the variation of the NOx concentration at the vehicle exhaust gas pipe due to the modification of the % engine load at idling. The engine idle state is chosen to simplify the

test and to ensure repeatability, for the reasons explained in Sect. 2.2.

At this idling condition, the engine can be easily subjected at two different engine load states defined by the measurement of the % engine load, which causes variation in the NO_x concentration between them, while engine working parameters are read through the OBD system.

Experience tells us that the better way to increase the % engine load if the vehicle is in static conditions is not with a free acceleration from idling but increasing the power demand from the equipment in the vehicle. Simply switching on the engine, and working at a natural engine idle speed, some of the torque available is consumed by the necessary accessories of the engine (water pump, alternator, ...). This consumption translates directly into a % engine load value, which gives us the percent of torque used compared with the peak available torque at natural engine idle speed. From now, we will call "Unloaded state" to this situation of the engine with minimum power demand.

Increasing the power demand when the vehicle is idling will increase the % engine load in a significant way. One of the easiest ways to increase the power demand is connecting some equipment of the vehicle, like the Air Conditioning (A/C) system, the lighting and signaling system, and the rear window heater system.

The power demand from the Air Conditioning system and the electric equipment of the vehicle are not considered into the type approval NEDC test, although it is estimated that it may vary the CO₂ emissions. Instead, the USA SC03 Air Conditioning test is used to control the pollutant's emissions of the vehicles. Several previous measurements demonstrate that A/C system use increases the engine load and the NO_x emissions (Mock and German, 2015). Furthermore, the battery's state of charge at the start of the NEDC test can vary by as much as 3% the CO₂ emissions, so for the tests to be consistent between measurements, full battery charge must be ensured before each of them (Triantafyllopoulos et al., 2019). This gives an idea of the influence that electrical consumption can have on vehicle pollutant's emissions while idling. From now, we will call "Loaded state" to this situation of the engine with the vehicle's equipment connected.

Through this procedure, it is possible to double the % engine load from the initial Unloaded state to the Loaded state, and even reach a higher % engine load than in a simulation bench. Depending on the vehicle, a % engine load of more than 50% can be reached with the vehicle at the natural engine idle speed, and the average increase of % engine load from the Unloaded state to the Loaded state is about 100%.

Instead, free acceleration from natural engine idle speed without a gear engaged increase the % engine load for a short time, decreasing immediately to a lower natural engine idle speed level. If the engine speed is increased, the peak available torque is increased too, but the torque consumed from the engine remains constant if there are no new consumptions. As a consequence, the % engine load decreases. The initial increase of % engine load comes from the inertial forces of the engine that are necessary to overcome. But when the new engine speed is reached, the % engine load decreases. This behavior can be observed in Fig. 2.

To measure and register the % engine load of the vehicle, the gas analyzer uses an OBDII connector. This connector plugs on the OBDII port of the vehicle and transmits the required parameters to the measurement

equipment (Communities, 2009; EC of the European Parliament and of the Council, n.d.; Iso, 2006; Official Journal of the European Communities, n.d.).

Not only the % engine load is registered from the ECU of the vehicle. Other relevant parameters could be registered through the vehicle's OBD port if are available: the engine speed, the % EGR opening, the MAF (Mass Air Flow intake), and the engine temperature, among others.

Summarizing, through the OBDII port, several working parameters are read from the vehicle's ECU, being the % engine load the most important. Simultaneously, a gas analyzer measures NO_x concentration from the vehicle's exhaust pipe. The details of the equipment used are shown in Sect. 3 of the Appendices.

Combining the OBD data and the NO_x concentration measures from the gas analyzer it is possible to analyze the relationship between the exhaust gases NO_x concentration from the vehicle and the functioning engine parameters, specifically the % engine load.

3.2. PROTOCOL

To carry out the measurements, a protocol must be followed to ensure that every test is performed in the same way. This protocol consists of three steps: a) verification of vehicle conditions for the performance of the test, b) preconditioning of the vehicle, and c) execution of the defined cycle for the test.

The first and second steps are common with the current opacity measurement procedure (Official Journal of the European Communities, n.d.). The only difference is the measurement equipment used: for the current measure of opacity in diesel vehicles an opacimeter is used, and for the NO_x measurement, equipment able to measure NO_x concentration (like the equipment described in the Appendices, but not exclusively) will be used.

For the first step, the conditions of the vehicle must be verified, to ensure that the vehicle is suitable and is prepared to be subjected to the test. The following aspects must be checked: the state of the exhaust system is correct and does not show any apparent damage or modifications (visual checking), any extra loads and equipment of the vehicle are disconnected, the vehicle shows an adequate mechanical and electrical condition, and the vehicle does not indicate faults using the MIL indicator (or OBD). In the second step, it must be checked if the engine is at normal working condition temperature.

The third step consists in the execution of the cycle defined in Table 1. For this, the blowpipe of the measurement equipment is introduced into the exhaust pipe and the OBD connector is plugged into the OBD port of the vehicle. Once the measurement equipment is ready, the five stages indicated in Table 1 must be followed while NO_x concentration is measured.

As OBD data reading is necessary, only vehicles with OBDII port and supported communication protocol available are suitable to apply the test. That includes most of Euro 4 vehicles, as well as Euro 5 and Euro 6 vehicles. Some Euro 3 vehicles are suitable to apply this type of measurement, but OBD reading isn't ensured in all of them.

To illustrate the testing process, below is shown and commented, as an example, the procedure and results obtained for a vehicle (vehicle Nr. 20, Table 6). Along with the test, and for each of the stages from Table 1, the data indicated in Table 2 are registered through the Gas Analyser and the OBD system. The results of the test are compiled following the instructions from Table 1. With these data, the graph shown in Fig. 2 is built. The time of measurement is along the x-axis, NOx concentration and mass flow are on the left y-axis, and engine speed, % engine load, and % EGR aperture are on the right y-axis.

Reading time for each stage can be defined at convenience, but 20 seconds for each stage can be enough. With the engine working at a steady-state, it is not necessary to wait for a long time to get enough representative values. Yet if engine working is irregular, a longer time might be required to get enough measures to reach a representative average. The simplicity of the method allows using as much time as necessary to get a correct measure.

For each stage, the average value of the recorded parameters is calculated. The combination of the average concentration of NOx and the average of the corresponding % engine load provides the numeric results for the test. To calculate the average values of NOx concentration, only data of steady emissions and % engine load are selected, avoiding sections of data where emissions are increasing or decreasing (limits between stages). In this way, the average calculated represents more accurately the NOx emissions for the corresponding engine load state.

Table 1. Engine running conditions for the test cycle

	Stage 1: Unloaded	Stage 2: Loaded	Stage 3: Loaded & Accelerated	Stage 4: Loaded	Stage 5: Unloaded
Engine state	On	On	On	On	On
Engine rotation speed	Natural idle speed	Natural idle speed	> 2000 rpm < 3000 rpm	Natural idle speed	Natural idle speed
Vehicle extra load equipment	Disconnected	Connected	Connected	Connected	Disconnected
Engine load value	< 25%*	> 25%*	Irrelevant	> 25%*	< 25%*
*Reference values, depending on the vehicle.					

In Fig. 2, we can see the five stages described before. In the first place, we can see the first Unloaded stage, where average engine load is 13% and the average NOx concentration read is about 150 ppm. In the second stage (Loaded state), the % engine load increase until an average value of 36% engine load, while an increase of average NOx concentration to 465 ppm is observed.

In these two stages, the EGR system was inactive, so the value of NO_x concentration read is not affected by the control emissions system. That means, the correlation between NO_x concentration and % engine load, if exists, is not modified from the influence of another parameter. The results of the tests carried out show that the indicators of the correlation (R^2 and p-value, see Sect. 5 of Appendices) between data of both variables are generally higher in these two stages than in other parts of the cycle, where other parameters may affect the concentration of NO_x. That the correlation between both variables is so strong in the absence of other influences at this stage, seems to be evidence that NO_x concentration and the % engine load at idling are related.

In stage 3 engine was accelerated to an average speed of 2163 rpm, and this acceleration provoked some changes in the behavior of the engine.

In the first place, to make a free acceleration reduces the % engine load. When engine speed is increased, the available torque and power from the engine also increase, but the power demand in stage 3 remains the same as in stage 2 (after an initial peak of power the engine needs to overcome the inertial forces from the engine acceleration). Consequently, if available torque and power are higher, but the power demand remains the same, the % engine load value decreases. This situation can be observed in Fig. 2: as soon as the engine speed increases, the % engine load decreases. The same situation was observed in every test carried out.

A second change is when the engine speed increases, NO_x concentration decreases. This reduction comes because of the % engine load reduction. This is another confirmation of the relationship between NO_x concentration and % engine load. Although power demand is steady in stages 2 and 3, the NO_x concentration in stage 3 decreases. This reduction is related to the % engine load reduction. The same behavior was observed in every test carried out.

Besides this, the engine acceleration causes the opening of the EGR valve and an additional reduction of NO_x concentration. As can be seen in Table 2, in the Loaded & Accelerated section the EGR valve is 56% opened on average. As a consequence, the average NO_x concentration in this 3rd stage is similar to the 1st stage, but with the following difference: in the 1st stage, the NO_x concentration was steady and continuous, while in the 3rd stage the NO_x concentration is strongly decreasing from a maximum value of 478 ppm to a value near to 100 ppm. Meanwhile, the engine load was reduced and maintained at 11% throughout this stage (slightly lower than at unloaded conditions).

In the 4th stage, the engine speed goes back to 750 rpm, the same speed as the 1st and 2nd stages and engine load returns to 35% engine load, the same level of the 2nd loaded stage. However, the NO_x concentration in the 4th stage is lower than in the 2nd stage. This is because the EGR valve remains open at 30%, reducing the NO_x emissions of the vehicle. As a result, the average NO_x concentration in the 4th stage is slightly higher than in the 1st stage and significantly lower than in the 2nd stage.

Finally, in the 5th stage, the EGR valve remains open (even more than in the 4th stage), while % engine load is reduced to the same level of the 1st stage. As a consequence, NO_x concentration in the 5th stage is lower than in the 1st stage.

This behavior supports the hypothesis that NOx concentration is related to % engine load at idling, and % EGR reduces the NOx concentration in the vehicle exhaust gas.

As a result of the static NOx test, Table 2 is obtained. To build this table, data from stage 1 and stage 5 are joined in the "Unloaded idle state", and data from stage 2 and stage 4 are joined in the "Loaded idle state", while data from step 3 are placed in the "Loaded & Accelerated state". The average values of NOx concentration, % engine load and the other emissions and parameters are summarized and calculated for each one of the states.

The accelerated section is necessary to make sure that the EGR system or other after-treatment systems are working if they were not previously activated (usually they are not), although these NOx values are not used to define the NOx emissions level. In this way, EGR and after-treatment systems works along stages 4 and 5 (according to ECU programming), and the influence over the NOx concentration from this system is accounted for the average values in the final result.

This behavior simulates what happens in real urban driving, where once the vehicle is stopped usually EGR and after treatment systems stop working too, and do not resume their action until the vehicle is put back into motion and reaches the operating conditions set in the ECU's programming.

From these results, it is possible to use the average NOx concentration at both states as a simple indicator of NOx concentration level, and Unloaded state concentration or Loaded state concentration could be used to make a comparison between vehicles (Table 2).

The results summary includes the maximum value of NOx concentration read in the test (in the Unloaded or Loaded state) because it will be used to estimate the maximum value of NOx concentration, by extrapolation with the unloaded and loaded values.

Table 2
Average measures in static NOx test.

		Engine speed (rpm)	NOx (ppm)	CO2 (% vol.)	HC (ppm)	CO (% vol.)	O2 (% vol.)	% Engine load	% EGR	Engine Temp. (°C)
Idle Unloaded	<i>Av.</i>	750	136	0	11	0	2.05	13	21	77
	<i>Max.</i>	774	178	0	12	0	2.20	24	43	79
Idle Loaded	<i>Av.</i>	750	306	0	11	0	1.99	36	30	77
	<i>Max.</i>	755	481	0	12	0	2.20	37	31	79
Loaded & Accelerated	<i>Av.</i>	2157	147	0	11	0	2.02	10	56	76
	<i>Max.</i>	2203	200	0	11	0	2.02	12	63	76

Although NOx concentration could be used to compare the level of NOx emissions between vehicles (most of the NOx test methods explained in the Appendices provide NOx concentration as result), the most

interesting data to do this comparison is not the concentration, but the mass emissions.

This is because vehicles with higher engine size and/or higher engine idle speed will emit a greater mass of NO_x, even if the concentration is the same that to a smaller vehicle.

In approval type procedures, emission factors (g/km) are used to compare pollutant emissions, yet from a static test this value cannot be obtained. Instead, the NO_x mass emissions flow can be used to compare emissions. This value is not directly obtained from the measurement equipment and should be calculated. The procedure to do so is explained in Sect. 4 of the Appendices.

In this way, it is possible to calculate at any point of the test the instantaneous value in mg/s of the NO_x emission mass flow (see Fig. 2), and with these data, calculate the average value for the Unloaded idle state, for the Loaded idle state, and the maximum value read in both states, in the same way that the NO_x concentration average values were calculated.

These previous values are included in Table 3 for a complete overview of NO_x concentration and emissions at both states.

Once we have completed the set of values for both states, including the maximum instantaneous value, it is possible to define a linear regression function to extrapolate values from NO_x concentration and NO_x mass emission related to % engine load.

The pair of values 0% engine load and 0 ppm NO_x concentration (and 0 mg/s NO_x emission) are used as a point of the function. According to the definition of % engine load, its value is 0% at engine off and ignition on (Iso, 2006). With this (0,0) point, and the three points defined in Table 3 (pair NO_x (mg/s) - % engine load, pair NO_x (ppm)-% engine load), a linear regression function is defined to extrapolate the value of NO_x emissions mass flow at 100% engine load (Fig. 3.a), and another linear regression function is defined to extrapolate the value of NO_x concentration at 100% engine load (Fig. 3.b).

Finally, once both linear regression functions are available, Table 3 can be completed. The Maximum Theoretical Value of NO_x emission mass flow (mg/s) is the estimation of NO_x emissions mass flow if the vehicle was at 100% engine load at idling state, and is the estimated data which define the NO_x emissions level and can be used to compare NO_x emissions between vehicles. It is an indicator of NO_x emissions and it could be helpful to detect the NO_x high emitters and to classify the fleet according to this NO_x emissions level, and his calculation could be easily incorporated into measurement software as the final result of the test.

Moreover, Idle unloaded and Idle loaded average NO_x emissions mass flow provide a close estimation of the real value of NO_x emissions from the vehicle when, during urban circulation, it is stopped at a red light or remains stopped in a traffic jam. These are a significant part of the total NO_x emissions from a vehicle at urban driving because the percentage of the time that a vehicle is stopped is approximate from 6.7% in free

flow urban circulation, and it could be even 60% in congested urban driving conditions (André, 2004; O'Driscoll et al., 2018; Wang et al., 2012).

To know this information from the complete fleet could be highly interesting to quantify with real data the expected NOx emissions at a particular point if the implementation of a traffic light is being analyzed, or help to define the time that the traffic light must remain red before the emissions from vehicles stopped at that point reach a dangerous level. It could be specifically helpful to analyse the convenience of traffic lights near hospitals or schools, for example.

In summary, the averages values obtained from the test are a close estimation of NOx real emissions when the vehicle is stopped during real circulation, and the Maximum Theoretical Value of NOx emission mass flow (mg/s) could be a good indicator of the NOx emissions level, obtained from a test performed under the same operating conditions on all vehicles, so it may be a suitable way to compare emissions between vehicles.

Table 3
Summary of final results in static NOx test.

	NOx (mg/s)	NOx (ppm)	% Engine load
Avg. Idle Unloaded	2.72	136	13
Avg. Idle Loaded	6.10	306	36
Maximum Read	9.59	481	37
Maximum Theoretical	21.84	1096	100

3.3. REPEATABILITY

The test was carried out several times over the vehicle to check the repeatability of the test, and with the information obtained from this set of tests Table 4 was built with the most relevant results. Additionally, Fig. 4 shows in graphical mode the repeatability of results.

To check the repeatability of the method, from these results the usual statistical dispersion parameters of the registered data are calculated and showed in Table 5, the most important of which are the Standard Deviation (SD) and the Coefficient of Variation (CV).

The set of results shows that the method applied provides similar results for the various tests carried out over the vehicle, not only for unloaded idle but for loaded idle and Theor. Max. value too, in the same way for NOx concentration and NOx mass flow. As can be seen from the Standard Error of the Mean, the Standard Deviation, and the Coefficient of Variation, the repeatability of the measures was satisfactory. The quality of the relationship between NOx concentration and % engine load was also checked for this set of measurements, and results are explained in Sect. 5 of the Appendices through the R² and the p-value.

Table 4
Summary of results for the set of static NOx tests for Vehicle Nr. 20.

Test number	Idle Unloaded			Idle Loaded			Th. Max. Value	
	NOx (mg/s)	NOx (ppm)	% Engine load	NOx (mg/s)	NOx (ppm)	% Engine load	NOx (mg/s)	NOx (ppm)
1	2.67	133	16	5.94	296	39	18.29	912
2	2.27	114	16	7.55	380	35	23.04	1155
3	2.83	142	16	5.43	273	36	19.57	982
4	2.51	126	14	5.65	284	37	18.90	949
5	2.53	127	14	5.72	287	37	19.15	958
6	2.46	124	14	5.68	285	36	18.90	950
7	2.63	132	13	5.87	294	36	20.30	1018
8	2.66	133	13	5.92	297	35	20.59	1032
9	2.72	136	13	6.10	306	36	21.84	1096
10	2.84	142	15	6.04	303	36	20.61	1034

Table 5
Statistical parameters from the static NOx tests for Vehicle Nr. 20.

Statistical Parameters	Idle Unloaded			Idle Loaded			Th. Max. Value	
	NOx (mg/s)	NOx (ppm)	% Engine load	NOx (mg/s)	NOx (ppm)	% Engine load	NOx (mg/s)	NOx (ppm)
Min.	2.27	114	13	5	251	35	17.09	860
Max.	2.83	142	17	7.55	380	39	23.04	1155
Average	2.59	131	14.64	5.89	296	36.55	19.77	991
Standard Deviation	0.16	8.10	1.43	0.66	31.80	1.37	1.74	87.14
Coef. of Variation	6.02%	6.18%	9.79%	11.24%	10.74%	3.74%	8.80%	8.79%
Std. Error Mean	0.05	2.44	0.43	0.21	9.59	0.41	0.55	27.56
Lower limit	2.50	126.21	13.79	5.48	277.21	35.74	18.69	937.19
Upper limit	2.69	135.79	15.48	6.30	314.79	37.35	20.85	1045.21

3.4. RESULTS

The explained method has been applied to the diesel vehicles indicated in Table 6. The vehicles come from 14 different manufacturers representative of the European market and have emission levels from Euro 3 to Euro 6, with engine sizes from 1248 cm³ to 2993 cm³, and engine power from 66 kW to 210 kW. For each vehicle, several tests have been carried out to compare the dispersion of the results in a similar way as was explained before. One petrol vehicle (vehicle Nr. 18) has also been tested in the same way to compare the NOx emissions of diesel engine vehicles with petrol engine vehicles.

The average results of this complete set of measurements are shown in Table 7. The average NOx concentration at loaded idle was 152% higher than average NOx concentration at unloaded idle, and the average % engine load at loaded idle was 106% higher than average % engine load at unloaded idle. So, the increase of % engine load between both load states is large enough for the explained linear extrapolation. Furthermore, these results confirm the assumption used as a basis for the proposal, that the concentration of NOx in the exhaust pipe is related to the % engine load.

Table 6
Set of vehicles and engines analyzed ordered by Emissions level.

Reference Vehicle	Vehicle Manufacturer	Model	Engine Manufacturer	Engine model	Engine size (cm ³)	Engine Power (kW)	Emissions level
1	Volvo	V50	PSA	D4204T	1997	100	Euro 4
2	SEAT	Leon	Volkswagen	ARL	1896	110	Euro 3
3	Alfa Romeo	Mito	FIAT	19981000	1248	70	Euro 4
4	Audi	A4	Audi	CAG	1968	100	Euro 4
5	BMW	330D	BMW	306D3	2993	170	Euro 4
6	BMW	535d	BMW	306D5	2993	210	Euro 4
7	Peugeot	407	Peugeot	RHR	1997	100	Euro 4
8	Volkswagen	Passat	Volkswagen	BKP	1968	103	Euro 4
9	Skoda	Octavia	Volkswagen	BKD	1968	103	Euro 4
10	Audi	A5	Audi	CGKA	2698	140	Euro 5
11	Citroën	Berlingo	Citroën	9H06	1560	66	Euro 5
12	Volkswagen	Touran	Volkswagen	CFH	1968	103	Euro 5
13	Hyundai	i30	Hyundai	D4FB	1582	81	Euro 5
14	SEAT	Leon	Volkswagen	BLS	1896	77	Euro 5
15	Opel	Insignia	GMPTE	A20DTH	1956	118	Euro 5
16	Nissan	Juke	Renault	K9K	1461	81	Euro 5
17	Opel	Astra	GM	A17DTS	1686	81	Euro 5
18	Renault	Fluence	Renault	H4M D7	1598	84	Euro 6
19	Renault	Talisman	Renault	R9M E4	1598	96	Euro 6
20	Peugeot	Boxer	Peugeot	AH03	1997	96	Euro 6
21	Skoda	Superb	Volkswagen	CRL	1968	110	Euro 6
22	Kia	Sportage	Kia	D4FD	1685	85	Euro 6
23	Citroën	C4 Picasso	Citroën	BH01	1560	88	Euro 6

The same situation is observed for the NO_x mass flow emissions, where the average value of loaded state emissions is 146% higher than average unloaded idle emissions. Again, the increase of NO_x mass flow

emissions between both load states allows the building of a linear function.

Table 7
NOx emissions average values for the unloaded idle state, loaded idle states, and Theoretical Maximum Values from static NOx test.

Reference Vehicle	Idle Unloaded		Idle Loaded			Th. Max. Value		
	NOx (mg/s)	NOx (ppm)	% Engine load	NOx (mg/s)	NOx (ppm)	% Engine load	NOx (mg/s)	NOx (ppm)
1	0.87	40	21	1.65	73	37	5.15	259
2	1.80	77	17	5.29	226	34	15.67	668
3	2.70	199	19	7.30	495	42	17.44	1193
4	1.83	81	24	7.83	349	47	18.20	806
5	2.28	77	24	3.60	122	39	10.08	339
6	3.51	134	24	10.56	401	54	20.85	789
7	5.65	269	30	15.51	754	60	27.31	1296
8	2.74	138	15	5.39	261	31	21.01	1028
9	2.52	119	21	5.37	253	42	16.77	790
10	4.74	200	21	7.92	374	46	18.82	824
11	1.64	96	19	5.14	304	47	13.76	812
12	1.65	80	17	1.68	82	36	4.85	237
13	2.04	123	22	4.56	278	52	10.30	627
14	2.65	139	25	5.09	277	39	16.72	851
15	1.91	88	16	6.46	300	28	23.57	1093
16	1.88	117	22	3.98	236	42	9.90	582
17	3.71	208	15	7.23	405	37	26.26	1392
18	0.08	5	22	0.25	15	37	1.483	88
19	2.35	129	16	8.01	440	36	23.93	1306
20	2.59	131	15	5.89	296	37	19.77	991
21	1.73	91	22	3.22	169	39	8.31	436
22	2.22	128	17	6.47	373	45	14.29	826
23	2.45	141	21	10.52	599	53	23.68	1368

The average engine load reached at loaded idle is 41.7% (in some cases it went up to 60%), while the average engine load at unloaded idle is 20.3%. This shows how this static NO_x measurement method, without any additional equipment or simulation bench, makes it possible to double the % engine load between unloaded and loaded idle, which permits to analyze and compare NO_x emissions for two different load demand situations.

For the petrol engine vehicle, NO_x concentration at unloaded and loaded idle are more than 20 times smaller than average NO_x concentration for diesel engines. This difference is even higher for the NO_x mass flow emissions. However, the % engine load reached is similar to diesel engine vehicles, and the value for both states, 22% engine load for unloaded idle and 38% for loaded idle, are near to the mean of the complete set of vehicles previously mentioned. These results verify the fact that diesel vehicles are the main NO_x emitters (Lee et al., 2013), (O'Driscoll et al., 2018; Wang et al., 2012).

Summarizing, the results show that for the set of vehicles analyzed:

- a) There is an average increase of 106% of % engine load from unloaded idle to the loaded idle for the complete set of vehicles tested
- b) There is a significant increase of NO_x concentration from the unloaded idle to the loaded idle in all vehicles, with an average increase of 152%.
- c) There is a significant increase of NO_x flow mass emission from the unloaded idle to the loaded idle in all vehicles, with an average increase of 146%.
- d) Petrol engine vehicle shows the same levels of % engine load, but NO_x concentration values are 20 times smaller than average diesel vehicles NO_x concentration, and the difference is even higher for the NO_x mass flow emission.
- e) The relationship between NO_x concentration and % engine load is better for the Initial section, due to the inactivity of the EGR and after-treatment systems in this section.
- f) Standard Deviation for NO_x concentration and NO_x mass flow emissions is lower for unloaded idle than loaded idle.
- g) Standard Deviation for % engine load is lower for unloaded idle, but in both states is really low (1.4% unloaded idle, 2.6% loaded idle). That means that the % engine load shows low dispersion when carried out the test several times over the same vehicle.
- h) The average Coefficient of Variation is similar for the NO_x concentration and NO_x mass flow emission for unloaded idle and loaded idle (17%-18%). That means the dispersion of data is the same for both states and types of measurements.
- i) The Coefficient of Variation for % engine load is 7% for both idle states. It confirms that % engine load data dispersion is low, and the tests are always deployed under the same conditions of % engine load.

j) In general, data from the Initial section show a lower dispersion, due to the inactivity of the EGR and after-treatment systems in this section.

4. Comparison Between Methods

Once the quality of the relationship between NO_x concentration and % engine load has been checked, and the repeatability of the test has been verified, the proposed measurement process has been compared to another method designed for NO_x measurement. This procedure is accomplished according to the cycle ASM 20–50 shown in Fig. 5: the vehicle is “driven” on a dynamometer power bench, following instructions to reproduce the ASM 20–50 cycle.

To compare results, a vehicle (Nr. 12 from Table 6) has been tested using a power bench and following operating instructions from the equipment according to ASM 20–50 cycle, and subsequently, the same vehicle has been tested with the proposed static method, with the same mechanical and environmental conditions.

The comparison of both methods was developed by the following three Type Test:

Test Type 1) The vehicle was tested in the simulation bench according to ASM 20–50 cycle test. OBD data and exhaust gas composition were read with the ASM 20–50 cycle equipment. The % engine load was not registered, because the ASM 20–50 equipment does not allow this option.

Test Type 2) The vehicle was tested in the simulation bench according to ASM 20–50 cycle test. OBD data and exhaust gas composition were read with static method equipment. The % engine load was registered.

Test Type 3) The vehicle was tested according to the static test. OBD data and exhaust gas composition were read with static method equipment. The % engine load was registered.

For Tests Type 1 and Type 2, the vehicle was placed over the chassis dyno, and once the vehicle was secured and preconditioned, the test according to ASM 20–50 cycle was performed by a trained driver. The higher time required for the preparation of the test on the simulation bench has not been taken into account for the evaluation of the test. The only difference between Test Type 1 and Test Type 2 is the reading equipment, being performed in the same way.

Figure 5 shows the graphical representation of data read in a test from Test Type 2. Data from Test Type 1 should be similar to that from Test Type 2, but % engine load and % EGR are not registered by the chassis dyno equipment.

The black line shows the speed of the vehicle over the simulation bench. It is clear that the behavior of speed is similar to the reflected in the image of the theoretical cycle: starts with acceleration from 0 to 20 km/h, then the speed is maintained for a few seconds (the time required for the equipment) and after this, the vehicle is accelerated again to 50 km/h. After maintaining this speed for some time (required from the equipment), the speed decreases to 0 km/h. This behavior was similar in Test Type 1 and Test Type 2.

After this, the static method proposed in this paper was applied to the vehicle in the Test Type 3. Figure 6 shows a graphical representation of data from one of these tests, with the 5 stages of the test clearly visible.

The results from all the tests carried out according to the three Type Tests are included in Sect. 6 of the Appendices. According to registered data from the three Type Tests, we can state the following:

1. For the ASM 20–50 cycle, it is difficult to repeat the test with the same result.

As can be seen in Fig. 5, when the vehicle is at 20 km/h, the engine speed is not homogeneous. This makes that % engine load, % EGR and NO_x emissions are not homogeneous either. This suggests that NO_x emissions from this data section may not be very representative. Besides this, it is hard to maintain a constant speed of 20 km/h, and it is even harder to reproduce the test with the same conditions of rpm and % engine load several times. For both data sections (20 km/h and 50 km/h) the time used to calculate the average of NO_x emissions could be considered short to get an adequate average value. It is important to remember that test operations are determined by the test equipment, which gives the trained driver the instructions about how to operate the vehicle

2. For the ASM 20–50 cycle test, Standard Deviation and Coefficient of Variation are higher than for static cycle test.

Specifically, for Test Type 1, for both sections (20 km/h and 50 km/h) the Standard Deviation and Coefficient of Variation are remarkable. As is shown in Table A.5, at 20 km/h the highest NO_x concentration is 4 times greater than the lowest and at 50 km/h more than 2.3 times greater. The SD at 20 km/h is 168.15 ppm, while at 50 km/h it is 97.26 ppm, and the corresponding CV is 57.97% and 30.94%.

For Test Type 2, the SD is lower than for Type 1, but CV at 20 km/h is 39.08%. This indicates that the dispersion of data is high. On the contrary, this dispersion metrics are better for the static test than for the dynamic one. The unloaded idle presents an SD of 13.33 ppm and a CV of 8.10%, while for the loaded idle the SD was 58.85 ppm and CV was 12.37%. In short, the static test shows lower dispersion, that is, better repeatability.

3. For the ASM 20–50 cycle test (equally for Test Type 1 and Test type 2), the highest NO_x emissions are indistinctly reached at the 20 km/h or 50 km/h section, while for the static cycle test highest NO_x emissions are always reached at loaded state.

Difficulty to repeat the ASM 20–50 cycle test in the same conditions makes that % engine load presents high variability and consequently NO_x emissions are variable too. Instead, the simplicity of the static test allows us to achieve similar % engine load at unloaded and loaded states and consequently, similar NO_x emissions are reached from several tests: always the higher NO_x emissions are reached at loaded state.

4. There are important differences between NO_x emissions values from Tests Type 1 and Type 2. Although the test was developed in the same way, the average NO_x emissions from Test Type 1 were more 2 times greater than from Test Type 2. This could be attributed to the difference between the NO_x sensor of both

types of equipment. However, the behavior in both Type Test is different too, so not only the different NOx sensors can explain the differences.

5. In Test Type 2, the % engine load is higher for the 20 km/h section than for the 50 km/h section. Instead, NOx emissions are higher (on average) for the 50 km/h than for 20 km/h section.

This seems to indicate that in this type of test, data from NOx emissions are not correlated to % engine load. Calculating the significance of the model in Test 2 with the p-value, as was explained before, 7 of the 8 p-values calculated were higher than the significance level (Table A.7), so the null hypothesis can't be rejected for both situations.

We can see how when the vehicle is accelerated to 50 km/h engine speed and % engine load are more homogeneous than in the 20 km/h section, and % EGR is near to be closed. One could assume that for this section NOx emissions are more representative, but in this case, with rpm, % engine load, and % EGR with a homogeneous behavior, the NOx concentration (and the % engine load) fall from a maximum value to the same concentration than in the idle rate. Consequently, it is difficult to define a correlation between NOx emissions and % engine load in this section.

6. The % engine load reached from the static test is significantly higher than for the dynamic test with a chassis dyno.

In Test Type 2 the higher engine load was 38.08% at 20 km/h. Instead, in Test Type 3 the higher engine load was 51.66% at loaded idle, being the average engine load at loaded idle 49.76%.

The highest engine load in Test Type 3 generates also the highest NOx emissions, individually for every test, and on average. Instead, in Test Type 2 sometimes the highest engine load does not correspond to the highest NOx emissions. This occurs individually for some of the tests, and with the average value. The average NOx concentration for loaded idle was 475.80 ppm, while for the dynamic test the higher average NOx emissions read were 314.36 ppm at 50 km/h in Test Type 1, and 134.98 ppm at 50 k/h in Test Type 2.

So, NOx concentration measured with the static test is higher than NOx concentration read with the ASM 50 – 20 dynamic test (in this vehicle).

7. It is easier to reproduce the static test than the ASM 20– 50 dynamic test.

In this way, it is possible to make the static test repeatedly with similar results, and the duration of each step of the test can be deliberately extended to obtain a stable and adequate set of data to calculate the average NOx emissions easily.

For Test Type 1 and Type 2, the extension of the section to calculate average emissions was approx. 10 s for 20 km/h and 50 km/h respectively (indicated by the equipment to the driver).

Instead, in Test Type 3 duration of any of the steps of measurement is higher than 30 seconds. If it is not necessary, they could be shorter, but if necessary, they could be as long as required to get correct average NOx emissions, because the simplicity of the method allows it.

This is because, as it could be seen in Fig. 6, the behavior of % engine load, engine speed, and % EGR is much more stable in the static test than those shown in the dynamic one (Fig. 5). Consequently, NOx emissions are more stable, and therefore, it is easier to get a representative and accurate average NOx concentration value.

In summary, the main differences between both methods are that the repeatability, significance, and results in the dispersion of the static test are significantly better than for the dynamic one. Moreover, the % engine load reached and the NOx concentration read with the static test are higher, and yet the equipment and staff training requirements are lower than for the dynamic test.

Table 8
Main differences between dynamic and static tests.

Dynamic test	Static test	
Equipment	COMPLEX	SIMPLE
Procedure	COMPLEX	SIMPLE
% Engine load	LOW	MEDIUM
Repeatability	LOW	HIGH
Results dispersion	HIGH	LOW
Relation % Engine Load - NOx	LOW	HIGH

5. Conclusions

This new approach to NOx measurement could be an interesting way to include the NOx control at PTI. This method seems to be a reliable, accurate, fast, inexpensive, and simple way of measuring the NOx concentration and estimate the NOx emissions of a vehicle.

It accomplishes with directive requirements for PTI test indicated previously, and its main characteristics are:

- a) Fast and easy to incorporate it into PTI: it is not necessary additional preparation of the vehicle, and it can be accomplished together with the current opacity emissions test (Official Journal of the European Communities, n.d.). Besides this, the operation of the vehicle could be executed by the vehicle's driver (there is no need for a PTI inspector operating the vehicle). The time required to carry out the test is 2–3 minutes for the complete test.
- b) Accuracy: measuring at natural engine idle speed guarantees the stability of engine functioning and provides a stable and accurate measurement of NOx concentration.
- c) High repeatability: conditions for the test are easy to reproduce (idle rotation rate, and OBD reading of engine load), so the results of several tests over the same vehicle show through the low values of Standard

Deviation and Coefficient of Variation obtained that there is a low dispersion of the data, that is, high repeatability.

d) It does not need additional equipment like a Chassis Dynamometer, neither expert staff, so it is inexpensive: only a gas analyzer able to measure NO_x emissions concentration and an OBD equipment to read engine speed and % engine load is required.

e) The equipment's maintenance cost, both mechanical and metrological, is much lower than other systems like a power bench and similar to current costs.

f) It can be applied in the same way to any kind of passenger car or light-duty vehicle with the same equipment (e.g. 4 × 4 vehicles, automatic gearbox vehicles, non-disconnectable traction control vehicles,...).

g) It reproduces a real driving condition. It simulates closely one of the worst situations according to the NO_x emissions in urban areas: a vehicle in a city, standing at a red traffic light or in a traffic jam, with the engine switched on and with the air conditioning running. The time a vehicle is idling when it is in real on-road conditions varies from the driving condition, but for urban circulation is significant. In flow-urban circulation, the time the vehicle is at idling condition is between 6.7–9.1%, but in congested urban situations with high stop duration, this time can be from 40% to 50% of circulation time (Boulter et al., 2006), and even rise to 60% (André, 2004).

In conclusion, this proposal meets the requirements to ensure a correct, accurate, reliable and useful measurement and estimation of NO_x emissions from vehicles, and on the other hand, meets the requirements for a test that must be performed during the inspection in the process of PTI, that is: as simple, quick and inexpensive as possible.

With this method applied through PTI, it could be possible to classify vehicles according to their NO_x emissions in a real situation. So, it could be an important tool for the Anti-Pollution Protocols in large cities and allow the correct management of circulating vehicle fleet. And, as expensive and complicated equipment and expert staff are not required, the measurement method could be incorporated into PTIs in a short time.

So, the main future issue will be to define the adequate emission limits according to this test method. For this, the following step will be to conduct a measurement campaign following the proposed method. The objective of this campaign will be twofold: on the one hand, to check that in a sufficiently large number of measurements the characteristics observed in the development of the method are maintained in the same way, and on the other hand to define from a significant sample of vehicles the appropriate rejection NO_x emissions threshold in the PTI. As was said in the introduction, the European Commission suggests detecting 5% of vehicles with higher NO_x emissions (Staff et al., 2013). This value can be used as an orientation to define a PTI threshold. This measurement campaign is currently being carried out, and we hope that the results obtained from it can be made available in the coming months.

Moreover, if it is possible to maintain the study along a significant period, it could be analyzed the evolution of NO_x emissions, given that it seems from previous studies that the emissions worsen with the aging of

vehicles (Chen and Borken-Kleefeld, 2016).

Another further step to validate this approach will be a comparison between results from this measurement method and real on-road NOx measurement. In this way, it will be possible to quantify how far or close is the result of the static measurement from the real on-road emissions of vehicles.

It is important to remark that although the method has been developed and tested with passenger cars and light-duty vehicles, it could be applied in a similar way to heavy-duty vehicles or buses, although further research is needed to determine its suitability for heavy vehicle inspection, or even motorcycles and mopeds. In conclusion, it could be a powerful tool for monitoring NOx emissions to the whole fleet of vehicles.

Finally, this proposal confronts the measurement of NOx emissions with a different approach than other methods used so far, and it could be a good option to compare and classify vehicles according to the NOx emissions in urban circulation (where these emissions are most harmful to health), allowing a quick and inexpensive implementation into the PTI system, providing useful and reliable information, and filling the current gap of information about the vehicle urban NOx emissions.

Abbreviations

DOC:Diesel Oxidation Catalyst, DPF:Diesel Particulate Filter, ECU:Engine Control Unit, EGR:Exhaust Gas Recirculation, NOx:Nitrogen Oxides, OBD:On-Board Diagnostics, PEMS:Portable Emissions Measurement System, PGM:Precious Group Metals, PTI:Periodic Technical Inspection, RDE:Real-driving emissions, RDS:Remote Sensing Detector, SCR:Selective catalytic reduction, VSP:Vehicle Specific Power, WHO:World Health Organization.

Declarations

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Conflicts of interest

Not applicable

Availability of data and material

Additional data can be found in the supplementary material

Code availability

Not applicable

Authors' contributions

Eugenio Fernández developed the methodology with the supervision of Alicia Valero and Juan José Alba. Abel Ortego contributed in the verification of the methodology.

References

André, M., 2004. The ARTEMIS European driving cycles for measuring car pollutant emissions. *Science of the Total Environment* 334–335, 73–84. <https://doi.org/10.1016/j.scitotenv.2004.04.070>

Anyon, P., Beville-Anderson, J., Brown, S., Bryett, C., Pattison, D., Mowle, M., Walls G, 2000. Proposed Diesel Vehicle Emissions National Environment Protection Measure Preparatory Work. In-Service Emissions Performance - Drive Cycles. Volume 1. National Environment Protection Council Service Corporation, Adelaide.

Barlow, T., Müller, G., Mäurer, H.J., Buekenhoudt, P., Schulz, W.H., Geis, I., Multari, A., Petelet, G., 2015. CITA PROJECT: SET – Sustainable Emissions Test: Final Report 103.

Boulter, P., Nolte, C., Horn, M., Richter, A., 2011. TEDDIE: A new roadworthiness emission test for diesel vehicles involving NO, NO₂ and PM measurements. *Cita* 32.

Boulter, P.G., Barlow, T., Mccrae, I.S., Latham, S., 2006. OSCAR: On-board emission measurements in Central London.

Buekenhoudt, P., Müller, G., Mäurer, H.J., Sánchez González, A., Stephenson, J., Multari, A., Petelet, G., Schulz, W.H., 2019a. CITA SET II Project Final Report.

Buekenhoudt, P., Müller, G., Mäurer, H.J., Sánchez González, A., Stephenson, J., Multari, A., Petelet, G., Schulz, W.H., 2019b. CITA SET II Project Annexes to the Final Report.

Carslaw, D.C., Beevers, S.D., Tate, J.E., Westmoreland, E.J., Williams, M.L., 2011. Recent evidence concerning higher NO_x emissions from passenger cars and light duty vehicles. *Atmospheric Environment* 45, 7053–7063. <https://doi.org/10.1016/j.atmosenv.2011.09.063>

Chen, Y., Borken-Kleefeld, J., 2016. NO_x Emissions from Diesel Passenger Cars Worsen with Age. *Environmental Science and Technology*. <https://doi.org/10.1021/acs.est.5b04704>

Chen, Y., Borken-Kleefeld, J., 2014. Real-driving emissions from cars and light commercial vehicles e Results from 13 years remote sensing at Zurich/CH. *Atmospheric Environment* 88, 157–164. <https://doi.org/10.1016/j.atmosenv.2014.01.040>

CITA, 2007. AUTOFORE: Study on the Future Options for Roadworthiness Enforcement in the European Union.

Communities, O.J. of the E., 2009. DIRECTIVE 2009/40/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on roadworthiness tests for motor vehicles and their trailers (Recast) (Text with EEA relevance).

Degraeuwe, B., Weiss, M., 2016. Does the New European Driving Cycle (NEDC) really fail to capture the NO X emissions of diesel cars in Europe? *Environmental Pollution* 1–8.

<https://doi.org/10.1016/j.envpol.2016.12.050>

Delft, A.D., 2010. TNO Science and Industry The Netherlands Real world NOx emissions of Euro V vehicles Assignor number.

EC of the European Parliament and of the Council, n.d. Directive 2010/48/EU On roadworthiness tests for motor vehicles and their trailers (Text with EEA relevance).

EEA, 2017. Air quality in Europe – 2017 report. <https://doi.org/10.2800/850018>

Epa, U., of Transportation, O., Quality, A., 2004. Acceleration Simulation Mode Test Procedures, Emission Standards, Quality Control Requirements, and Equipment Specifications - Final Technical Guidance (EPA-420-B-04-011, July 2004).

European Commission and Council of the European Union, 2016. Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) (Text with EEA relevance). *Official journal of the European Union* 82, 1–98.

European Parliament, 2019. Working Document No . 11 on the inquiry into emission measurements in the automotive sector – Appendix D: Timeline 1–13.

European Parliament, Council of the European Union, 2009. Regulation (EC) no. 443/2009. *Official Journal of the European Union* 140, 1–15. <https://doi.org/10.1524/zkri.2009.1105>

European Union, 2014. Directive 2014/45/EU of the European Parliament and of the Council of 3 April 2014 on periodic roadworthiness tests for motor vehicles and their trailers 2014.

Fenimore, C.P., Jones, G.W., 1957. Nitric oxide decomposition at 2200-2400K. *The Journal of Physical Chemistry* 61, 654.

Fonseca González, N.E., 2012. Aspectos de la medición dinámica instantánea de emisiones de motores. Aplicación al desarrollo de un equipo portátil y una metodología para estudios de contaminación de vehículos en tráfico real.

Franco, V., Mock, P., 2015. ICCT Real driving Emissions: Challenges to Regulating Diesel Engines in Europe.

Franco, V., Posada Sánchez, F., German, J., Mock, P., 2014. ICCT Real-world exhaust emissions from modern diesel cars. A meta-analysis of PEMS emissions data from EU (Euro 6) and US (Tier 2 Bin 5/ULEV II) diesel

passenger cars. Part 1: Aggregated results 59.

Gallus, J., Kirchner, U., Vogt, R., Benter, T., 2017. Impact of driving style and road grade on gaseous exhaust emissions of passenger vehicles measured by a Portable Emission Measurement System (PEMS). *Transportation Research Part D: Transport and Environment* 52, 215–226. <https://doi.org/10.1016/j.trd.2017.03.011>

Garcés Giraldo, L.F., Hernández Ángel, M.L., 2004. La lluvia ácida: un fenómeno fisicoquímico de ocurrencia local. *Revista Lasallista de Investigación* 1, 66–72.

Gobierno de España, 2012. RD 920/2017 por el que se regula la inspección técnica de vehículos 47995. <https://doi.org/BOE-A-2012-5403>

Hausberger, S., Rexeis, M., Zallinger, M., Luz, R., 2009. Emission Factors from the Model PHEM for the HBEFA Version 3. University of Technology, Graz, Report Nr. I-20/2009 Haus-Em 33, 679.

Hoekman, S.K., Robbins, C., 2012. Review of the effects of biodiesel on NO_x emissions. *Fuel Processing Technology* 96, 237–249. <https://doi.org/10.1016/j.fuproc.2011.12.036>

Hooftman, N., Messagie, M., van Mierlo, J., Coosemans, T., 2018. A review of the European passenger car regulations – Real driving emissions vs local air quality. *Renewable and Sustainable Energy Reviews*. <https://doi.org/10.1016/j.rser.2018.01.012>

ICCT, 2015. NO_x control technologies for Euro 6 diesel passenger cars: Market penetration and experimental performance assessment (white paper). Washington: International Council on Clean Transportation 29.

Iso, B.S., 2006. BS ISO 15031-5:2006 Road vehicles – Communication between vehicle and external equipment for emissions related diagnosis 3.

Larssen, T., Seip, H.M., Semb, A., Mulder, J., Muniz, I.P., Vogt, R.D., Lydersen, E., Angell, V., Dagang, T., Eilertsen, O., 1999. Acid deposition and its effects in China: An overview. *Environmental Science and Policy* 2, 9–24. [https://doi.org/10.1016/S1462-9011\(98\)00043-4](https://doi.org/10.1016/S1462-9011(98)00043-4)

Lee, T., Park, J., Kwon, S., Lee, J., Kim, J., 2013. Variability in operation-based NO_x emission factors with different test routes, and its effects on the real-driving emissions of light diesel vehicles. *Science of the Total Environment* 461–462, 377–385. <https://doi.org/10.1016/j.scitotenv.2013.05.015>

Ministerio de Industria, Comercio y Turismo, G. de E., 2020. MANUAL DE PROCEDIMIENTO DE INSPECCION DE ESTACIONES ITV Versión 7.4.2.

Mock, P., German, J., 2015. The future of vehicle emissions testing and compliance. International Council on Clean Transportation.

Norris, J., n.d. Low Emission Diesel Research CP17/18/770 Phase 3-Report.

O'Driscoll, R., Stettler, M.E.J., Molden, N., Oxley, T., ApSimon, H.M., 2018. Real world CO₂ and NO_x emissions from 149 Euro 5 and 6 diesel, gasoline and hybrid passenger cars. *Science of the Total Environment* 621, 282–290. <https://doi.org/10.1016/j.scitotenv.2017.11.271>

Official Journal of the European Communities, n.d. Directive 72/306/EEC measures to be taken against the emission of pollutants from diesel engines for use in vehicles.

Package, R., Tests, P.R., 2012. Road Safety: The Roadworthiness Package – Tougher vehicle checks to save lives What is in the new Roadworthiness Package? Periodic Roadworthiness Tests - the main improvements.

Parliament, E., Union, C. of the E., 2016. Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6). *Official Journal of the European Union* L, 20–30.

Pidgeon, W.M., Sampson, D.J., Burgage IV, P.H., Landman, L.C., Clemmens, W.B., Herzog, E., Brzezinski, D.J., Sosnowski, D., 1993. Evaluation of a Four-Mode Steady-State Test with Acceleration Simulation Modes as an alternative Inspection and Maintenance Test for Enhanced I/M Programs.

Pielecha, J., Merkisz, J., Markowski, J., Jasiński, R., 2016. Analysis of Passenger Car Emission Factors in RDE Tests 00073, 1–7.

Poliscanova, J., 2017. Diesel, the true (dirty) story. *Transport and Environment*.

Pujadas, M., Domínguez-Sáez, A., de la Fuente, J., 2017. Real-driving emissions of circulating Spanish car fleet in 2015 using RSD Technology. *Science of The Total Environment* 576, 193–209. <https://doi.org/10.1016/j.scitotenv.2016.10.049>

Ramos, A., Muñoz, J., Andrés, F., Armas, O., 2018. NO_x emissions from diesel light duty vehicle tested under NEDC and real-word driving conditions. *Transportation Research Part D: Transport and Environment* 63, 37–48. <https://doi.org/10.1016/j.trd.2018.04.018>

Reşitoğlu, I.A., Altinişik, K., Keskin, A., 2015. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy* 17, 15–27. <https://doi.org/10.1007/s10098-014-0793-9>

Rexeis, M., Hausberger, S., Kühlwein, J., Luz, R., 2013. Update of Emission Factors for EURO 5 and EURO 6 vehicles for the HBEFA Version 3 . 2. University of Technology, Graz, Report Nr. I-31/2013 Rex-EM-I 43, 1–31. [https://doi.org/Report No. I-25/2013/ Rex EM-I 2011/20 679](https://doi.org/Report%20No.%20I-25/2013/Rex%20EM-I%202011/20%20679)

Samaras, Z., Zachariadis, T., 1995. The Inspection of In-Use Cars in Order to Attain Minimum Emissions of Pollutants and Optimum Energy Efficiency, LAT Report 9502. Thessaloniki.

Staff, C., Paper, W., Assessment, I., For, P., Of, A.R., European, T.H.E., Council, T.H.E., Registered, E.A., Programme, T., 2013. Impact Assessment (working paper) SWD(2012) 206 final European Commission.

TAN, J., DUAN, J., HE, K., MA, Y., DUAN, F., CHEN, Y., FU, J., 2009. Chemical characteristics of PM_{2.5} during a typical haze episode in Guangzhou. *Journal of Environmental Sciences* 21, 774–781.

[https://doi.org/10.1016/S1001-0742\(08\)62340-2](https://doi.org/10.1016/S1001-0742(08)62340-2)

Technical Committee: ISO/TC 22 Road vehicles, 1988. ISO 7644:1988 Road vehicles – Measurement of opacity of exhaust gas from compression-ignition (diesel) engines – Lug-down test.

The Council of the European Communities, n.d. COUNCIL DIRECTIVE 70/220/EEC, Official Journal of the European Communities.

Triantafyllopoulos, G., Dimaratos, A., Ntziachristos, L., Bernard, Y., Dornoff, J., Samaras, Z., 2019. A study on the CO₂ and NO_x emissions performance of Euro 6 diesel vehicles under various chassis dynamometer and on-road conditions including latest regulatory provisions. *Science of the Total Environment* 666, 337–346. <https://doi.org/10.1016/j.scitotenv.2019.02.144>

Wang, X., Westerdahl, D., Hu, J., Wu, Y., Yin, H., Pan, X., Max Zhang, K., 2012. On-road diesel vehicle emission factors for nitrogen oxides and black carbon in two Chinese cities. *Atmospheric Environment* 46, 45–55. <https://doi.org/10.1016/j.atmosenv.2011.10.033>

Weiss, M., Bonnel, P., Kühlwein, J., Provenza, A., Lambrecht, U., Alessandrini, S., Carriero, M., Colombo, R., Forni, F., Lanappe, G., le Lijour, P., Manfredi, U., Montigny, F., Sculati, M., 2012. Will Euro 6 reduce the NO_x emissions of new diesel cars? - Insights from on-road tests with Portable Emissions Measurement Systems (PEMS). *Atmospheric Environment* 62, 657–665. <https://doi.org/10.1016/j.atmosenv.2012.08.056>

WHO, 2005. Air Quality Guidelines - Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. WHO Europe Publication 67–105.

Williams, M.L., Carslaw, D.C., 2011. New Directions: Science and policy - Out of step on NO_x and NO₂? *Atmospheric Environment* 45, 3911–3912. <https://doi.org/10.1016/j.atmosenv.2011.04.067>

Zeldovich, Y., 1946. The oxidation of nitrogen in combustion explosions, in: *Acta Physicochimica USSR*. pp. 577–628.

Zhang, Y.I., Stedman, D.H., Bishop, G.A., Guenther, P.L., Beaton, S.P., 1995. Worldwide On-Road Vehicle Exhaust Emissions Study by Remote Sensing, *Environ. Sci. Technol.*

Figures

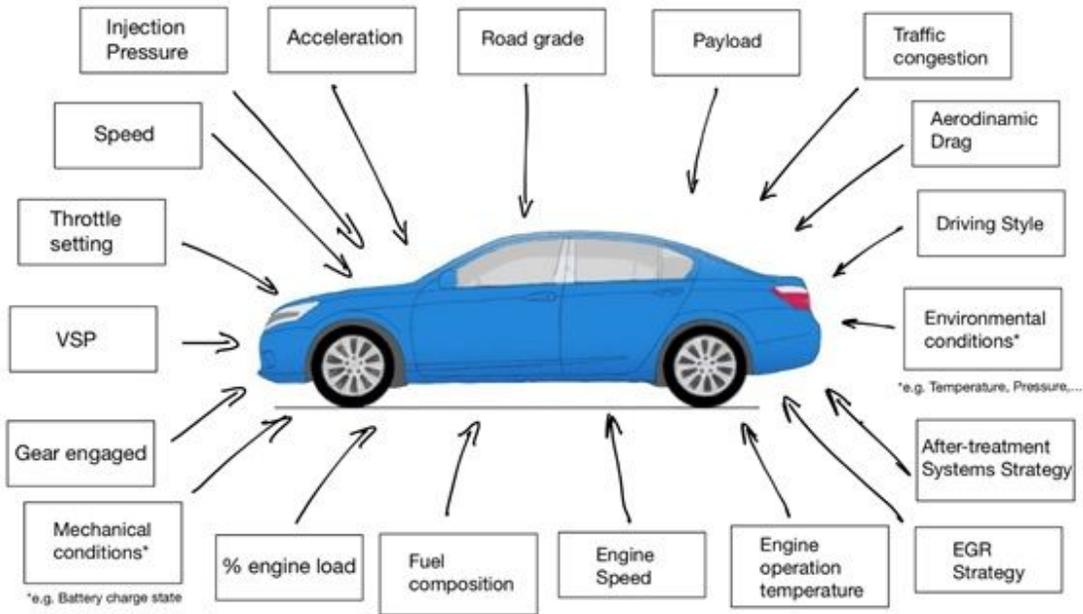


Figure 1

Some of the operating variables that affect vehicle NOx emissions.

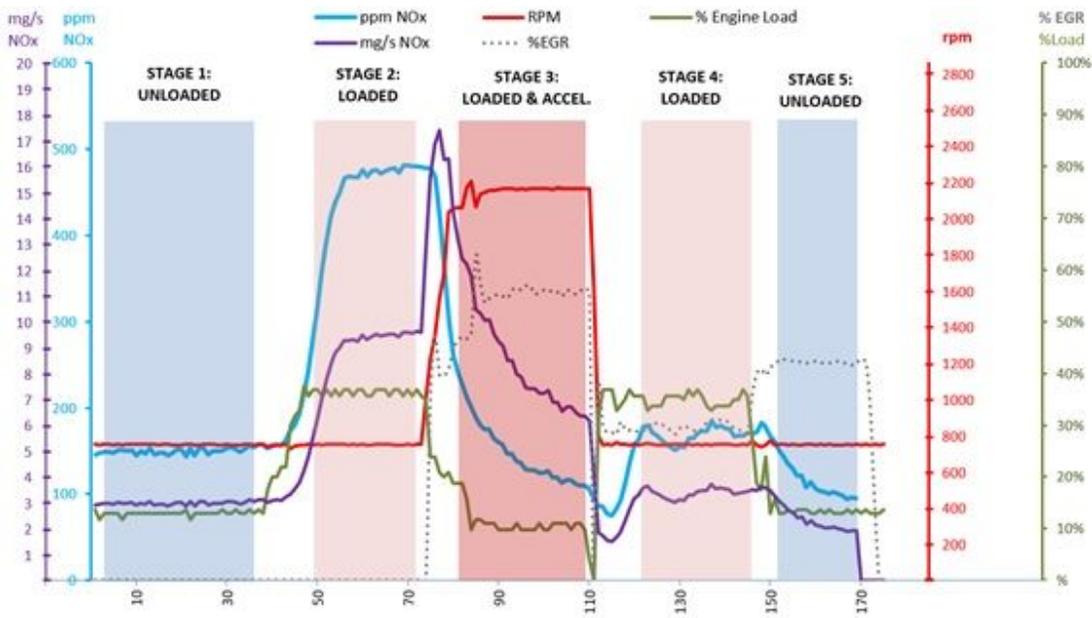


Figure 2

NOx test for Euro 6 vehicle Nr. 20

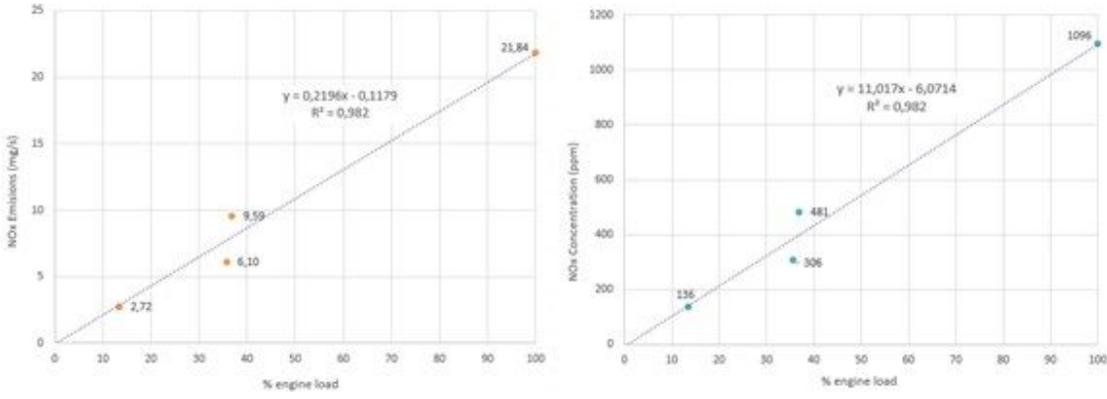


Figure 3

a) “NOx emission mass flow - % engine load” linear regression function b) “NOx concentration - % engine load” linear regression function

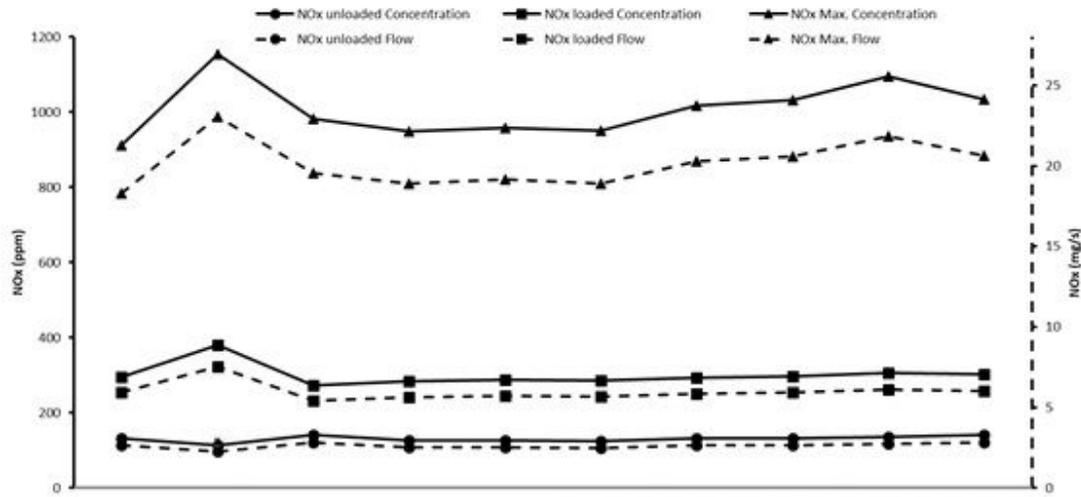


Figure 4

Results for the set of static NOx tests for Vehicle Nr. 20 (NOx concentration left axis, NOx mass flow right axis).

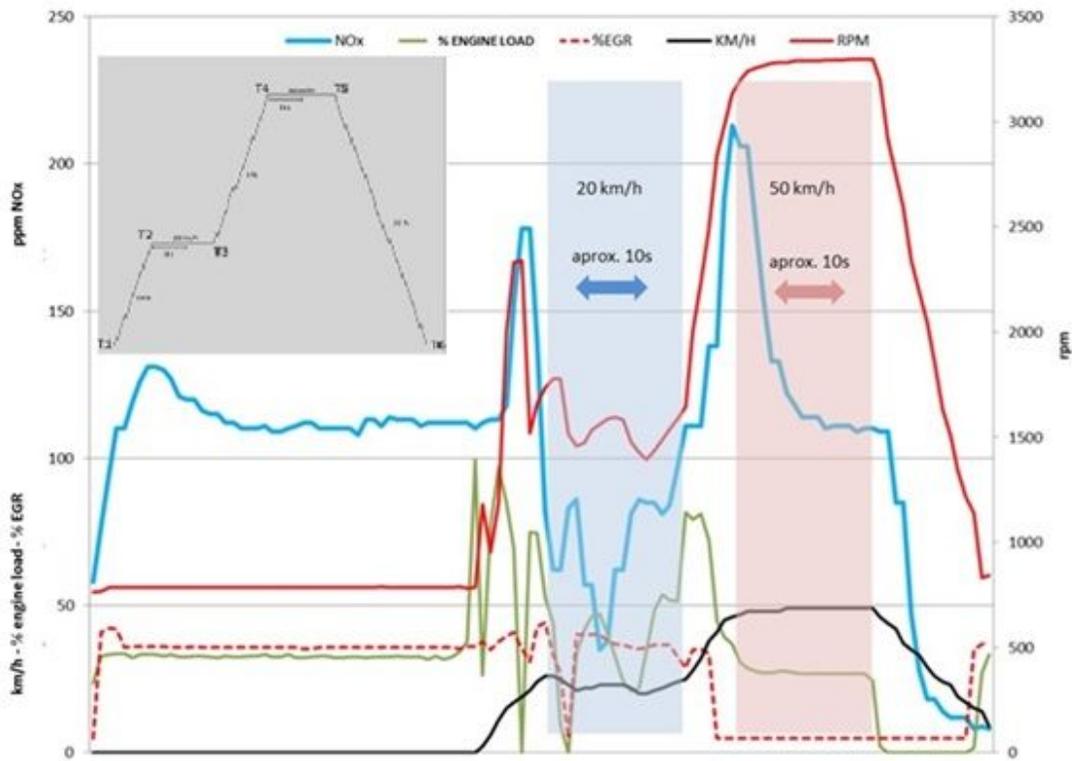


Figure 5

Data from dynamic ASM 20-50 test cycle Test Type 2.

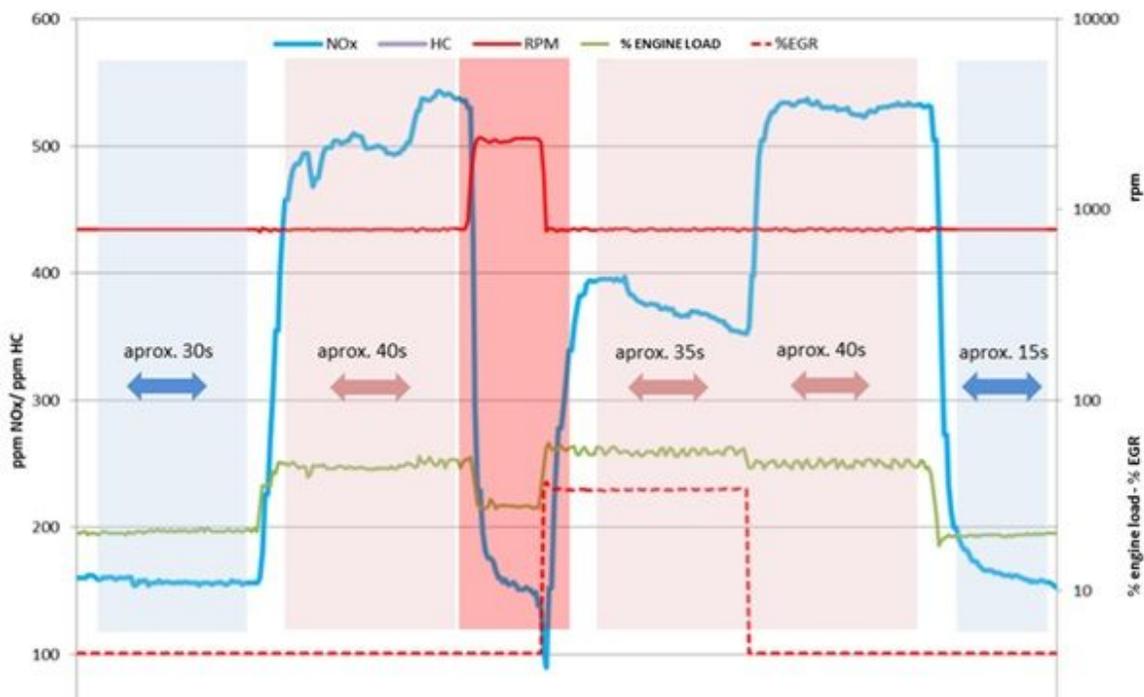


Figure 6

Data from static NOx test cycle Test Type 3.