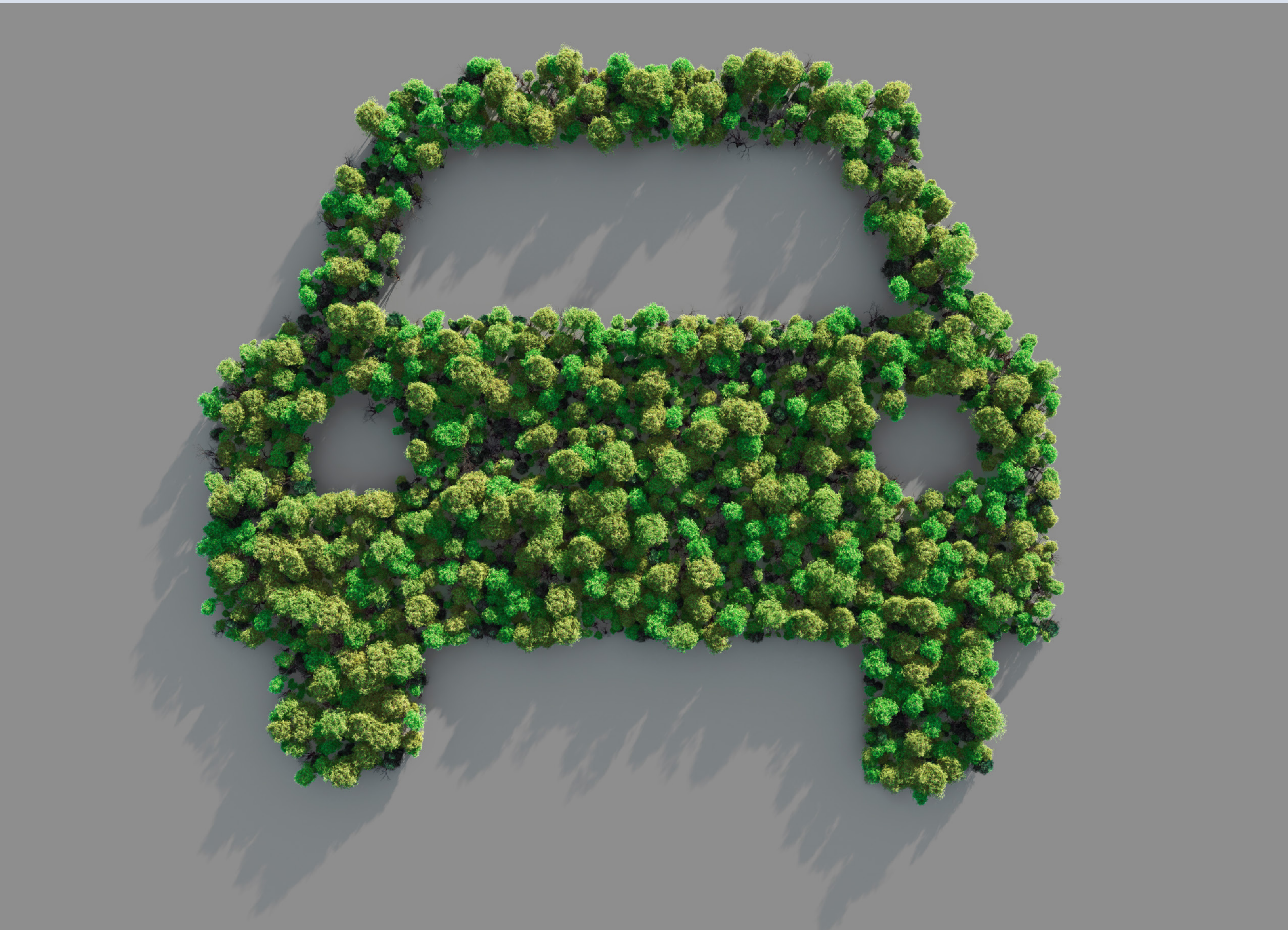
PTI METHODOLOGY FOR INSPECTION OF NOx AND PARTICLE MATTER EMISSIONS



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ISVA «DUQUE DE SANTOMAURO»

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AECA La itv salva vidas

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CONTENTS

1. PURPOSE

This document is an executive summary of the two documents drawn up by the research personnel listed above who belong to the Institute of Motor Vehicle Safety of the Carlos III University of Madrid: PTI METHODOLOGY FOR INSPECTION OF NOx AND PARTICLE NUMBER EMISSIONS Volumes I and II drawn up between 2020 and 28 February 2022.

The automobile is so widely-used and so popular that today it can be said to constitute one of the most important pillars of the economic and social life in practically every country in the world, dominating the transport market with a share – in the case of Spain – of between 80 and 90%. It is of such importance and magnitude that the motor vehicle has become almost the exclusive and certainly the most essential urban and inter-urban means of transport for people and public services, in private use for business, family and tourism trips and, in general, for the vast majority of movements of people and carriage of goods. Consequently, it is essential to ensure that the vehicles in service are maintained in a roadworthy condition in terms of safety and environmental sustainability.

These conditions are expressly set forth in Directive 2014/45/EU of 3 April that directly connects achievement of this goal with technical inspection of vehicles (PTI): "Roadworthiness testing is a part of a wider regime designed to ensure that vehicles are kept in a safe and environmentally acceptable condition during their use. (...) Periodic testing should be the main tool to ensure roadworthiness." (Recital 3).

Article 10, "Technical Inspections of Vehicles", of the Spanish General Vehicle Regulations (GVR) approved by Royal Decree 2822/1998 of 23 December, provides as follows:

"Vehicles registered or placed in circulation must undergo a technical inspection at one of the PTI stations authorised for this purpose by the competent body in industry-related matters in the cases and with the frequency, requirements and exceptions set forth in Annex I. Once the vehicle has been duly identified, the technical inspection will deal with the conditions of the vehicle in relation to road safety, environmental protection, regulatory registrations, reforms and, where appropriate, the validity of the certificates for the transport of hazardous and perishable goods."

The above paragraph gives a general idea of the content of the technical inspection of vehicles. The fact that an express reference is made to vehicles registered or placed in circulation implies prior type-approval of the vehicle subject to inspection since article 1.1. of Royal Decree 2140/1985 that lays down the "Rules for official approval of types of motor vehicles, caravans, trailers and pieces and parts of such vehicles" expressly stipulates this condition.

This condition that vehicles must be registered requires an inspection task during their useful life which, by its very nature, must be quick and cheap, very different from the prior type-approval procedures which are extremely expensive and often seem interminable. These two procedures are conceptually antithetical: the PTI must never be an approval, nor should the approval process resemble a roadworthiness test. If this were so, two procedures would be one too many. Type approval, on the one hand, involves testing prototypes using tests that are sometimes dynamic and require the use of large, expensive measuring tools and facilities. Inspection, on the other, is universal and open to vehicles of all eras and technologies. The devices and facilities must be adapted to quick, economical inspection that requires the use of equipment very different from that employed in type approval. The ISO 17020 and 17025 standards, common to both procedures must also be interpreted very differently since the goals and purposes they pursue are diametrically opposed. In type approval, the pass or fail is granted to a prototype for the subsequent approval of the type of vehicle that it represents for use on the public thoroughfare. The tests are performed on new, unregistered vehicles. In contrast, all makes, models, types and ages of vehicle are tested in the PTI. They are all used and have suffered wear and tear to a greater or lesser extent. Consequently, we define the technical inspection at PTI stations as a social service that ensures road safety and mitigates pollution by systems which, if they are poorly maintained by the user, degrade the environment in our towns and cities. One thing must be emphatically stated: technical inspection can never be conceived as type-approval, just as it cannot use the same equipment and facilities and its procedures must be different by its very nature despite the fact that the ultimate goal of both is the same: to ensure the safety of citizens when travelling in motor vehicles on public roads.

In spite of the fact that these requirements are initially restricted by the manufacturer's design technology – which is, however, getting a little closer to achieving these goals every day – the maxim of the PTI should be *zero accidents and reduction of prohibited polluting emissions in all vehicles*.

This paper has been drawn up within the framework of the Spanish PTI body (AECA - ITV) with the aim of fostering a rapid procedure of proven efficacy that employs purpose-designed equipment quite different from that used in the vehicle's type-approval process. Limited use of the facilities must also be considered, and the service must achieve all this without detriment to the accuracy of the results.

The European directives that require emission reduction (code-named "Euro X") are aimed at reducing, as far as possible, the incidence of certain diseases in human beings. They place increasing emphasis on diseases related, on the one hand, to emission of nitrogen oxide chemical compounds and on the other to particle emissions, since it there is conclusive evidence that these are the factors that cause the greatest damage to the human body. Figure 1 shows the tendency of the Euro regulations to drastically reduce the emission levels of these two pollutants.

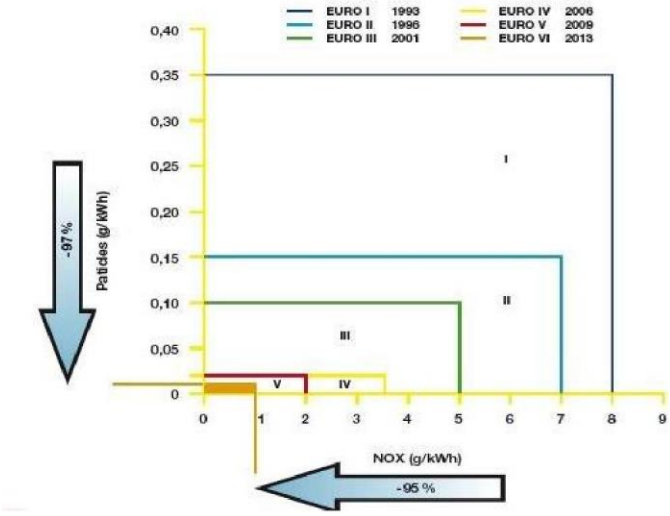


Figure 1: Variation in restrictions of the EURO regulations.

New response protocols for vehicle inspection must be introduced with the advent of innovative technologies in the motor, since the current anti-pollution systems built into the new vehicles cannot be tested with the current procedures available to the PTI.

Moreover, the Ministry of Agriculture and Fisheries, Food and the Environment published the National Clean Air Plan 2013-2016 that sets forth a series of objectives that seek to improve air quality and protect the atmosphere. Subsequently, the same body published the National Air Quality Plan 2017-2019 (Plan II) that summarises the degree of implementation of the 78 measures proposed in the initial Plan. They have all been implemented to a greater or lesser degree except for the measure related to the provision of information to citizens regarding NOx and the emission of particles by new vehicles. The justification for failure to implement this measure is the impossibility of accessing the results of these emissions under real driving conditions since the type-approval emissions are very different from those pertaining to real use on the highway or on urban roads.

This study develops a universal PTI inspection method that effectively determines the levels of NOx pollution and the concentration of particles emitted in the vehicle's exhaust gases. It is a universal method because it is designed for the inspection of both petrol and diesel vehicles. It covers all kinds of anti-pollution technologies that the manufacturers have integrated into their vehicles since their inception. The higher the technology, the higher the type approval demands and the less pollution is emitted. The Euro type-approval coding indicates that the higher the number (Euro 6, for example, compared to Euro 3), the less pollutants the vehicle should emit. To achieve this effect, the manufacturer has to incorporate more sophisticated technologies.

Using sophisticated equipment to implement a universal procedure that can be applied any type of vehicle, the study takes inspection of vehicles that have these technologies and also of those that do not into account. More specifically, it has been developed mainly for passenger cars (M-class vehicles).

Having done that, the paper will subsequently be submitted to the competent Ministry as an alternative route to implement measures to achieve the TRA 8 objective III (to provide consumers with information regarding NOx and particulate matter emissions from new passenger cars) of the Spanish AIRE Plan.

Having clarified the purpose of the document, we shall now give a short account of the work carried out: tasks that gave rise to the aforesaid method (with which we shall deal in due course). Consequently, the first step is to describe the existing inspection methods available in Spain. In this respect there are three options: the first is a dynamic test consisting of measuring the emissions once the engine has been started up. The second is also dynamic but consists of making the vehicle perform a dynamic circuit on rollers while reaching predetermined speeds. The third and last is a static test. They are different tests, but they all lead to the same result: detection and identification of the clearly polluting vehicles that will fail the inspection.

This paper has two complementary goals: firstly, to determine which of the three methods is the most suitable for PTI purposes and secondly to select the device or unit with which these pollutants are measured.

It is a question of selecting the one that, according to our criteria, is most suitable for the PTI. The three methods under analysis all turn out to be efficient and meet the requirements for assessment of the target pollutants. In short, the method most suitable for the PTI in its current form will be selected. But that does not mean that the other technologies are ineffective or erroneous. One of the aspects taken into account is the level of maintenance required by the equipment. It must not be forgotten that to be fast, the inspection must be organised on production-line criteria. Each vehicle that transits the inspection line precedes another in an uninterrupted flow (a very desirable aspect for the user). This coming and going severely stresses the equipment which, logically, must be subjected to regular maintenance.

As a conclusion to this first section, it should be kept in mind that the study always considers existing methods and technologies available on the open market, never sourced from the manufacturers.

2. HARM TO HUMAN HEALTH CAUSED BY NOx EMISSIONS AND PARTICLE EMISSIONS

Airborne particles can be defined as ambient particulate matter (PM) that can be classified as coarse, fine and ultrafine particles (UFP). This classification is based on the particles' aerodynamic diameters: between 2.5 and 10 µm (PM 10), less than 2.5 µm (PM 2.5) and less than 0.1 µm (PM 0.1). The smaller the particle, the deeper it is able to penetrate into the human body. Figure 2 shows that the penetration level is inversely proportional to the diameter of the particle, which means that ultrafine particles are the most harmful to human health since the body has no filters capable of stopping them. Therefore, it is especially important to measure the quantity and size of these particles in atmospheric emissions.

- Ultrafine particles (PM 0.1): These particles are formed in the nucleation process, the initial phase in which the gas is transformed into a particle.
- Fine Particles (≤ PM 2.5): These are formed from the combustion material that becomes volatile and condenses, thus forming the primary structure of the particle. They may also be produced by the composition of gases that interact with the atmosphere to generate secondary particles. This gas nucleation occurs by condensation, coagulation or by liquid-phase reactions. These particles are mainly composed of sulphates and nitrates, ammonium, elemental carbon, organic compounds and metals. They are used to measure the daily air pollution level in several analysis methods.
- Coarse particles (PM 2.5 – PM 10): These particles are mainly formed by mechanical processes such as surface or mineral wear.

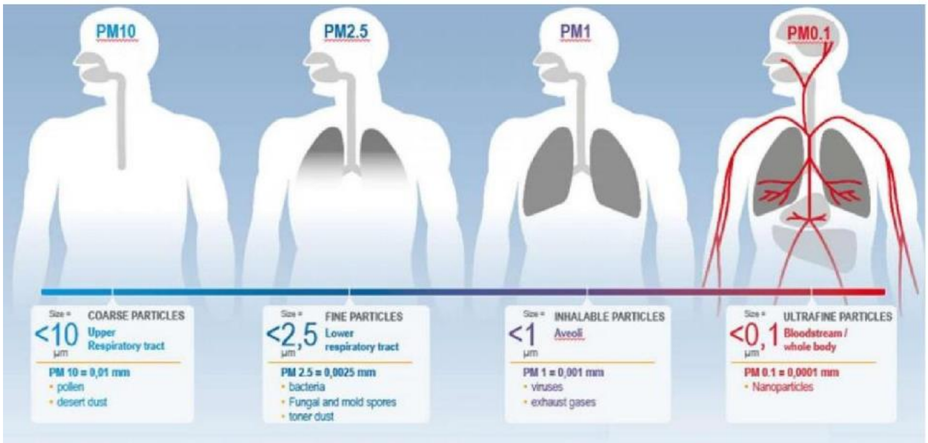


Figure 2: Degree of penetration into the human body depending on particle type

To put the size of the particles into perspective, Figure 3 shows a comparison of fine and coarse particles and a human hair.

Figure 3: Particle size comparison

The following table 1 shows the admissible limits set by the Ambient Air Quality Directives currently in force: Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 on arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air and Directive 2008/50/EC on ambient air quality and a cleaner atmosphere in Europe. A distinction is made between the hourly limit value and the annual limit value.

Table 1: Admissible thresholds for the protection of human health according to the European Directives on ambient air quality.

Pollutant	Averaging period	Legal nature and concentration	Comments
PM_{10}	1 day	Limit value: 50 µg/m³	Not to be exceeded on more than 35 days per year
	Calendar year	Limit value: 40 µg/m³	
$PM_{2.5}$	Calendar year	Limit value: 25 µg/m³	
		Exposure concentration obligation: 20 µg/m³	Average exposure indicator (AEI) (ᵃ) in 2015 (2013-2015 average)
		National exposure reduction target: 0-20 % reduction in exposure	AEI (ᵃ) in 2020, the percentage reduction depends on the initial AEI
O_3	Maximum daily 8-hour mean	Target value: 120 µg/m³	Not to be exceeded on more than 25 days/year, averaged over 3 years (ᵇ)
		Long-term objective: 120 µg/m³	
	1 hour	Information threshold: 180 µg/m³	
		Alert threshold: 240 µg/m³	
NO_2	1 hour	Limit value: 200 µg/m³	Not to be exceeded on more than 18 hours per year
		Alert threshold: 400 µg/m³	To be measured over 3 consecutive hours over 100 km² or an entire zone
	Calendar year	Limit value: 40 µg/m³	
BaP	Calendar year	Target value: 1 ng/m³	Measured as content in PM_{10}
SO_2	1 hour	Limit value: 350 µg/m³	Not to be exceeded on more than 24 hours per year
		Alert threshold: 500 µg/m³	To be measured over 3 consecutive hours over 100 km² or an entire zone
	1 day	Limit value: 125 µg/m³	Not to be exceeded on more than 3 days per year
CO	Maximum daily 8-hour mean	Limit value: 10 mg/m³	
C_6H_6	Calendar year	Limit value: 5 µg/m³	
Pb	Calendar year	Limit value: 0.5 µg/m³	Measured as content in PM_{10}
As	Calendar year	Target value: 6 ng/m³	Measured as content in PM_{10}
Cd	Calendar year	Target value: 5 ng/m³	Measured as content in PM_{10}
Ni	Calendar year	Target value: 20 ng/m³	Measured as content in PM_{10}

Notes: (ᵃ) AEI: based upon measurements in urban background locations established for this purpose by the Member States, assessed as a 3-year running annual mean.

(ᵇ) In the context of this report, only the maximum daily 8-hour means in 2017 are considered, so no average over the period 2015-2017 is presented.

Source: Air Quality in Europe [98]

In view of the high number of premature deaths attributed to particles, there is overwhelming scientific evidence of the harmful effects that pollutants caused by road transport have on human health. These pollutants are mainly related to short, medium and long-term cardiovascular and respiratory diseases. They also aggravate other pathologies and significantly affect young children. Among the main pollutants, PM 2.5 particles penetrate deeper into the pulmonary alveoli due to their small diameter and therefore have the most detrimental impact on human health. The main source of emission of this pollutant is diesel engines, which also emit even finer particles.

Exposure to NOx pollutants (the main source of which is road traffic in general) causes various respiratory diseases that affect both adults and children such as asthma, allergies and lung cancer. Among cardiovascular diseases, NOx compounds can provoke leukaemia, type-II diabetes, breast cancer and depression, among other pathologies. The strong influence of NO_2 emissions on deaths attributed to natural causes has also been demonstrated. It can cause asthma, premature birth, sudden death, malformations and leukaemia in children.

We need to focus attention on the youngest age groups since they are the most vulnerable because their immune systems have not yet matured. In the foetal period and early childhood, they breathe more rapidly and inhale a higher quantity of air compared to their physical size, compounded by the fact that their stature also exposes them more directly vehicles' exhaust gases and the heaviest pollutants that affect them to a greater extent than adults. It must also be remembered that they spend more time outdoors for leisure purposes and have a lower capacity to expel external contaminants. A study carried out in Madrid to assess the effect of PM 2.5 on hospital admissions of children under 10 years of age concluded that admissions among the under-one-year age group show a linear variation that increases sharply as of a PM 2.5 concentration of approximately 25 $\mu g/m^3$.

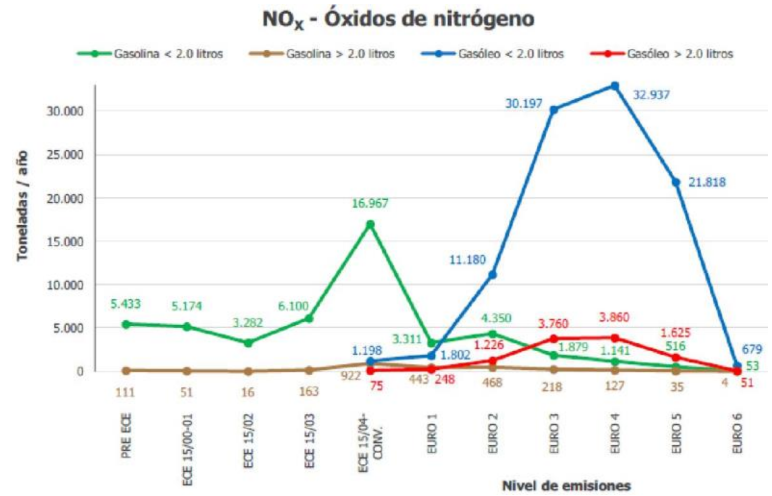
The data for variation in penetration for another age group (under 10 years old) on the basis of the concentration of PM 2.5 paints a very similar picture. Inadequate lung volume, bronchitis, asthma attacks and pneumonia due to short-term exposure to this pollutant are among the diseases related to the effect of PM 2.5 during childhood.

3. MEASUREMENT OF NITROGEN OXIDES EMISSIONS

Nitrogen (N_2) forms part of the air we breathe and its presence poses absolutely no risk. Nitrogen oxides (NO_x) cause acid rain, respiratory illnesses and photochemical smog (smog, responsible for the pinkish cap that envelops many cities). They originate in the combination of O_2 and N_2 in the air. They are extremely reactive compounds that generate ozone (O_3) in the presence of sunlight and react with volatile organic compounds to form carcinogenic molecules (nitrosamines). Moreover, volatile organic compounds (VOCs) are organic solvent vapours. They are mainly emitted by industrial and domestic solvents. They are carcinogenic themselves but they also react with NOx to create even more dangerous compounds.

Nitrogen, isolated as such, is an innocuous gas that forms part of the air we breathe, but when combined in the form of nitrogen oxides, it is transformed into a polluting gas. Nitrogen oxides are produced by the high pressure inside the cylinders of internal combustion engines (ICE) when working with lean mixtures. These engines work at very high internal temperatures and pressure that favour the reaction of nitrogen with other elements in the cylinders. An oxygen-poor mixture improves emissions of carbon monoxide and volatile organic compounds, but exacerbates the emission of nitrogen oxides and particulate matter. This occurs mainly in diesel vehicles, although currently it has also been verified in petrol engines that use direct injection. They require lean mixtures during parts of the journey when the vehicle is not accelerating.

This means that we need to test even the most modern petrol and diesel-powered vehicles for NOx emissions during inspections. The following graph shows data related to the emission of nitrogen oxides based on the associated Euro regulations for four types of vehicle, expressed in t/km (Figure 4).



Source: Castilla López, doctoral thesis

Figure 4: Total emissions of nitrogen oxides from the Spanish vehicle fleet in 2015 (considering the number of kilometres travelled on the basis of the age of the vehicle).

The measurement of nitrogen oxides (NOx) in the technical inspection of vehicles is more complex than counting solid particles. This is mainly due to two reasons: firstly, generation of NOx requires the engine to be working under a load and secondly, the components that reduce emissions of these harmful gases may or may not work in accordance with the strategy defined by the vehicle manufacturer. Manufacturers do not make their anti-NOx system management strategy public, and the European regulatory framework does not, for the time being, force them to place the information at the disposal of government agencies for periodic inspection. In practice, the manufacturers decide when and under what conditions the systems designed to restrict nitrogen oxide emissions will be activated and this has a direct impact on tailpipe emissions. It means that a value that would be unacceptable on a mild day with a temperature of around 20 ºC could be perfectly valid on a winter day with temperatures around 5 ºC.

The difficulty of detecting the level of NOx emissions that can be expected under the vehicle's different operating conditions is a serious obstacle. It affects any measure designed to determine whether a vehicle behaves properly in terms of its emissions of this pollutant: scheduled inspection, roadside inspection, remote sensing, market surveillance, etc. These difficulties are forcing the regulatory bodies to take some highly complex measures such as the one implemented by Færdselsstyrelsen, the Danish Road traffic authority. It consists of a vehicle equipped with sensors that analyse the exhaust gasses left behind by another, usually a truck, to determine whether or not its emission control system has been tampered with (Figures 5 and 6).

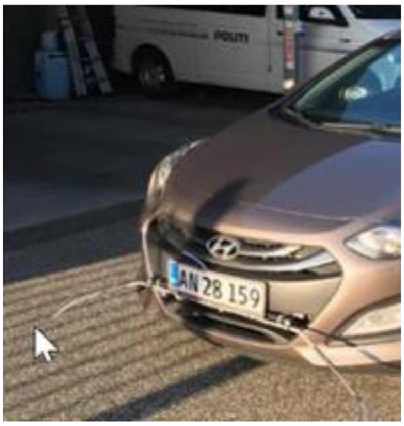


Figure 5. - Vehicle equipped with sensors to analyse the exhaust gases of vehicles suspected of tampering with the NOx control systems.

Figure 6. - Image of a vehicle fitted with sensors following the vehicle under analysis.
Photograph by Færdselsstyrelsen

4. MEASUREMENT OF PARTICLES CONCENTRATION

Optical opacity is the traditional measurement parameter for solid particles emitted by compression ignition engines. This method originated in western European countries, especially Belgium, more for safety reasons than for environmental concerns. Indeed, the clouds of black smoke issuing from old trucks could even conceal the glow of the tail lights. With the passage of time, opacity measurement has come to be an environmental control tool and the optical sensors have been replaced by particle counts. This particle count currently focuses on particles with diameters in excess of 23 nm in the type-approval regulations within the scope of the European Union, although it may change to include lower figures in the future. The vehicle type-approval regulations set forth the requirements that a vehicle must meet to be registered, but they fail to take the entire life of the vehicle into account.

The various technologies used for control of particulate emissions have been compared in several studies. High resolution opacimeters, laser light-scattering technology and both condensation (CPC) and diffusion (DC) particle counters have been used. The latter two are the candidates chosen by the Spanish PTI authority.

Diffusion particle (DC) counting is based on electrostatically-charging particles generated by combustion and emitted in the exhaust gas flow. The particles are charged by collisions of ions with their surface and end up generating a current that enables sensors to take an electrical reading. They are detected because their electrostatic charge generates a current proportional to the concentration and diameter of the particles. (Figure 7). Subsequently, these particles are fed into a two-stage electrometer, where the particles are filtered and detected. They are then segregated and classified by size. The quantity of particles is determined by measuring the electrostatic charge. Particles with dimensions between 10 and 700 nm can generally be analysed using this technology. The electrometer can detect concentrations of between 1.000 and 1.000.000 particles/cm^3. The measurement depends on the size and concentration of the particles, which affects its measurement range.

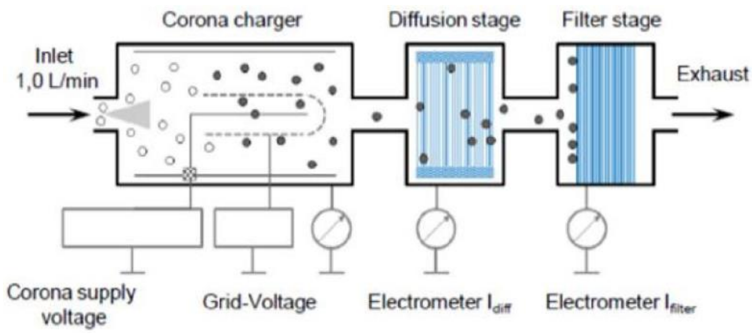


Figure 7: Diagram of operation of diffusion chargers (DC)

Condensation particle counting (CPC) is based on nucleation of gas particles to supersaturate the gas in order to measure the particles. These counters can detect particles as small as 2 nm. The meters work by passing the gas flow through the holes in a porous material which is heated by a fluid to obtain the required vapour content. Particle growth is triggered by creating vapour from a fluid (isopropanol, butanol, or water). Nucleation of the particles is heterogeneous, which means that the particles are discrete and do not form clusters. Subsequently, gas supersaturation of between 100 and 200% is produced by temperature differential. The heated gas is conducted into a cold condenser where butanol condenses on the surface of the particles. The resulting droplets are large enough to be analysed by laser nephelometry which enables measurement of the particles by means of the light scattering that they provoke (Figure 8). The CPC method is used in the type-approval of light and heavy vehicles, originally with diesel engines but recently also including petrol engines with direct fuel injection.

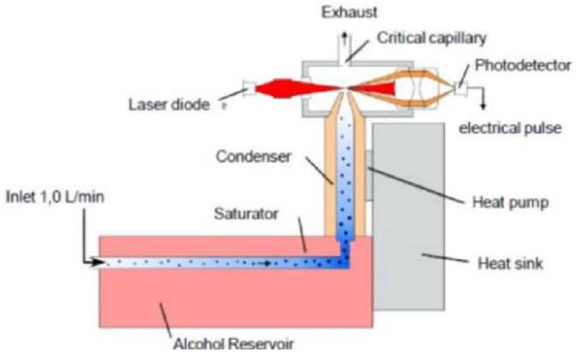


Figure 8: Diagram of operation of a condensation particle counter (CPC)

This study focuses on particle counting measured at the tailpipe outlet after combustion in an engine and subsequent filtering of the gases by anti-pollution systems.

5. PTI TESTING METHODS CONSIDERED IN THIS STUDY

It deals with the comparison between three existing and currently-available methods in Spain together with the associated equipment for NO_X measurement and particle counting. Two groups can be distinguished: methods that require the dynamic activity of the vehicle (the drive-by method and the method using wheel-driven rollers) and another method based on increasing the engine load without the need for wheel rotation. Since the first two are dynamic they take not only the engine load but also the effect of the vehicle's entire power transmission system into account including the inertial loads on the wheels when they begin to move the vehicle.

a. DYNAMIC TESTS

a.1.- Measurement of contaminants on roller test bench - acceleration simulation mode (ASM)

This first test enables detection of the concentration of the vehicle's exhaust system emissions under test conditions using a roller-based dynamometer that simulates driving under real traffic conditions. This measurement procedure enables inspection of both diesel and petrol vehicles. It is also suitable for all EURO classifications. The test bench employed belongs to MAHA, the manufacturer.

The ASM test uses a dynamometer that simulates the movement and acceleration of the vehicle to which a load or resistance is applied depending on the cycle. This enables it to obtain the approximate value of the actual emissions at the vehicle's tailpipe.

Based on the EPA Guidelines, the system automatically sets the testing power on the dynamometer on the basis of the Equivalent Inertia (EI) value in kg. Specific software calculates and adjusts the testing power on the dynamometer. To do so, the software must be configured with a list of vehicle makes and models and their parameters such as the year of manufacture, type of transmission, EI in kg, etc. Before starting the test the unit performs an automatic zero-base adjustment that includes the following gases: Hydrocarbons (HC), Carbon Monoxide (CO), Carbon Dioxide (CO_2) and Nitrous Oxide (NO).

Application of torque to obtain the testing power must be performed in a smooth transition during the acceleration phase. Dilution factor (DCF) and humidity (Kh) corrections are implemented and the air/fuel ratio (AFR) is calculated using the Brettschneider equation.

The following equation is used to calculate the load to be applied in each case depending on the vehicle's fiscal horsepower:

$$CV_{inst} = (11{,}677 + 0{,}041 \cdot V_{inst} + 0{,}003 \cdot V_{inst} \cdot V_{inst}) \cdot CVF$$

where:

CV_{inst}: load (N) applied to the bench as a function of instantaneous

CVF velocity: fiscal horsepower of the vehicle's specifications sheet

V_{inst}: instantaneous speed (km/h)

Figure 9: MAHA ASM bench installed in the facilities of the Carlos III University of Madrid

Figure 9 shows the facility employed. The roller brake is by Foucault and an on-board diagnosis (OBD) port is used to measure certain vehicle parameters. The test bench is fitted with a central lifting system with automatic roller blocking to enable the wheels to exit the test position. A MAHA MET 6.3 analyser was used to measure the gases.

Figure 10 shows the driving cycle that the driver must execute. The vehicle must accelerate to a constant speed of 24 km/h within the first 10 seconds and maintain this engine speed for 15 seconds. During the next 10 seconds it will accelerate again to reach a constant speed of 40 km/h which it will maintain for another 15 seconds. Finally, it will decelerate until it comes to a complete standstill.

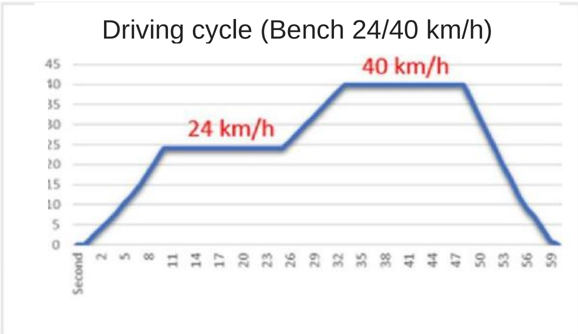


Figure 10. ASM2050 driving cycle used in this study.

The maximum NOx pollutant figures obtained in each of the two periods are recorded. The driver requires a certain amount of training to enable him/her to successfully execute the driving cycle. We have verified that after a few test drives or training runs, the operator is able to follow the cycle without too many problems, always staying within ± 2 km/h of the target speed, well inside the tolerance range of the test. The data of interest is obtained in the constant speed zone while the acceleration and deceleration ramps are considered to be less important (Figure 11).

Figure 11: Example of driver training

Figure 12 shows a number of results obtained for diesel engines. Taking three zones that delimit possible rejection limit figures into consideration, it can be observed that when the test is carried out at 24 km/h (see Table 2), 68.18% of diesel vehicles record NOx figures less than or equal to 233 ppm, while the remaining 31.82% exceed said threshold (22.73% return figures between 233 and 467 ppm, and 9.09% emissions in excess of or equal to 467 ppm). The percentage of vehicles classified in the first rejection section when driving diesel vehicles at 40 km/h (see Table 2) coincides with that obtained at 24 km/h for the selected thresholds.

Figures 13 and 14 show the highest figures obtained in different tests depending on the type of fuel and mileage.

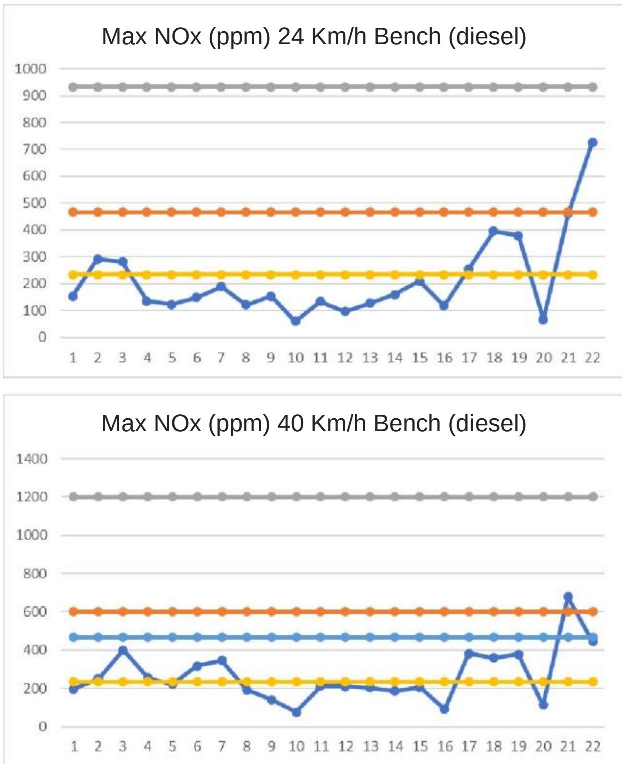
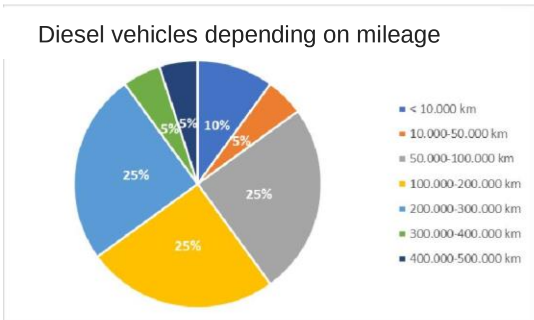


Figure 12. ASM bench NOx results for diesel vehicles at 24 km/h and 40 km/h.

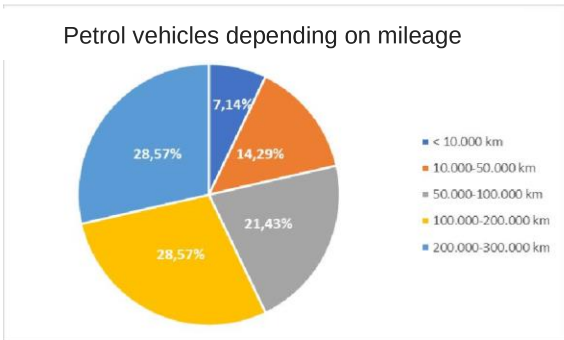
Table 2: Results for diesel vehicles (%) according to NOx threshold in ASM bench at 24 km/h and 40 km/h

	Diesel		
	24 km/h		
	x ≤ 233 ppm	233 < x < 467	x ≥ 467 ppm
%	**68,18**	**22,73**	**9,09**
	40 km/h		
	x ≤ 233 ppm	233 < x < 467	x ≥ 467 ppm
%	**68,18**	**27,27**	**4,55**



Mileage	Average Nox (24 km/h)	Average Nox (40 km/h)
<10.000 km	64	95
10.000-50.000 Km	135	256
50.000-100.000 Km	153	215
100.000-200.000 Km	194	248
200.000-300.000 Km	222	304
300.000-400.000 Km	379	379
400.000-500.000 Km	118	91

Figure 13. Emission results depending on mileage – diesel vehicles.



Mileage	Average Nox (24 km/h)	Average Nox (40 km/h)
<10.000 km	21	0
10.000-50.000 Km	259	336
50.000-100.000 Km	0	14
100.000-200.000 Km	380	460
200.000-300.000 Km	487	454
300.000-400.000 Km	-	-
400.000-500.000 Km	-	-

Figure 14. Result of emissions according to mileage – petrol vehicles.

a.2.- Measurement of contaminants at low speed (remote measurement with remote sensing system)

We present a new non-intrusive measurement procedure for a vehicle in PTI by means of a Remote Sensing Inspection System (RSIS). It enables remote measurement of the emissions of all types of both diesel and petrol-powered vehicles. It is also suitable for all EURO classifications.

It is a fixed facility and works by driving the vehicle to be tested past the device, emitting exhaust gases that are automatically analysed as it passes by (Figure 15).

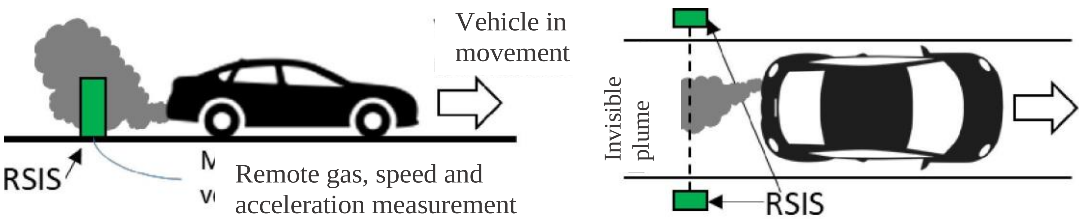
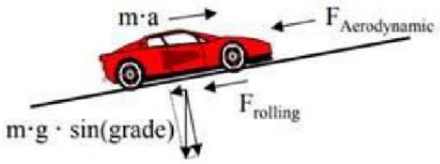


Figure 15. General and schematic representation of a remote vehicle emission measurement using the RSIS.

It measures the concentration of NO and NO_2 in the vehicle's exhaust plume separately with respect to the CO_2 content. It does not measure the particle concentration. Dr. Donald Stedman's work explains the principle and the mathematical expressions employed to convert the NO_x/CO_2 ratios detected into the tailpipe concentration. In addition to the emissions expelled through the tailpipe, RSIS measures the speed and acceleration of the vehicle at the time of the test. The system uses these two parameters to estimate the V*ehicle Specific Power* (VSP) at the time of the reading which, according to the manufacturer, ensures that the vehicle is assessed under a suitable power rating for proper classification. According to the manufacturer, the VSP measured as the vehicle passes the sensor station fulfils the same functions as the roller bench. The specific power of the vehicle is the power that the vehicle must exert to move its own mass within a range of 3 to 18 kW/tonne. This power is calculated as follows (see Figure 16).



$$VSP = \frac{Power}{Mass} = \frac{\frac{d}{dt}(E_{Kinetic} + E_{Potential}) + F_{Rolling} \cdot v + F_{Aerodynamic} \cdot v + F_{internal\ friction} \cdot v}{m} =$$

$$\approx v \cdot a \cdot (1+\varepsilon_i) + g \cdot grade \cdot v + g \cdot C_R \cdot v + \frac{1}{2}\rho_a C_D \frac{A}{m}(v+v_w)^2 \cdot v + C_{if} \cdot v$$

Figure 16. Equation of the movement of a vehicle considering an ascent velocity on a slope, the aerodynamic resistance and the rolling resistance coefficient.

For light vehicles, the manufacturer considers that the following formula provides a good approximation to the previous expression to estimate the VSP when the velocity, acceleration and slope of the road are the known factors:

$$VSP = \frac{Power}{Mass} \approx 1.1 \cdot v \cdot a + 9.81 \cdot grade \cdot v + 0.213 \cdot v + 0.000305 \cdot (v + v_w)^2 \cdot v$$

where *VSP* is in kW/t, *v* is velocity, v_w is wind speed (in m/s), *a* is vehicle acceleration (in m/s2) and *grade* is defined as vertical elevation / horizontal distance.

The device projects an infrared and ultraviolet beam from one side of the vehicle, crosses the roadway, passes through the vehicle's exhaust plume, reflects off a passive reflector placed on the opposite side of the roadway and returns to the detector. The detector records the changes in light intensity produced by absorption by the various gases that compose the vehicle’s exhaust plume. Each pollutant (or molecule) absorbs light at a characteristic wavelength. The concentrations are calculated based on this absorption factor by applying the Lambert-Beer law (an empirical ratio that relates the absorption of light to the properties of the material traversed, i.e., the intensity of light entering a medium with the intensity leaving the same after said absorption has taken place).

The system takes 100 readings of the exhaust plume in 0.5 seconds which enables it to perform a linear regression for each pollutant in order to obtain a single concentration value for each reading and for each pollutant. The system calculates the light absorbance produced by CO_2 and that produced by the pollutants (NO, NO_2, CO and HC). The absorbances of the pollutants are correlated with those of the CO_2 for the 100 readings acquired during measurement of the entire gas plume.

Figure 17. Positioning of the vehicle at the beginning of the test

The driver accelerates the vehicle from the starting line (initially stopped 2 metres away from the RSIS) to obtain a reading (Figure 17). To be properly assessed, the vehicle must accelerate as it passes through the RSIS beams in order to emit enough exhaust gases to obtain a reliable reading. The greater the acceleration, the higher the specific power (VSP). Once the vehicle's exhaust passes the RSIS station the vehicle must slow down and come to a standstill to inform the driver whether the test run has resulted in a satisfactory reading or if it has to be repeated. The most important test data are displayed on the RSIS user interface (Figure 18).

Figure 19 shows the results obtained from readings of NOx from diesel vehicles tested with this method. The highest reading obtained was 2,074.73 ppm of NOx.

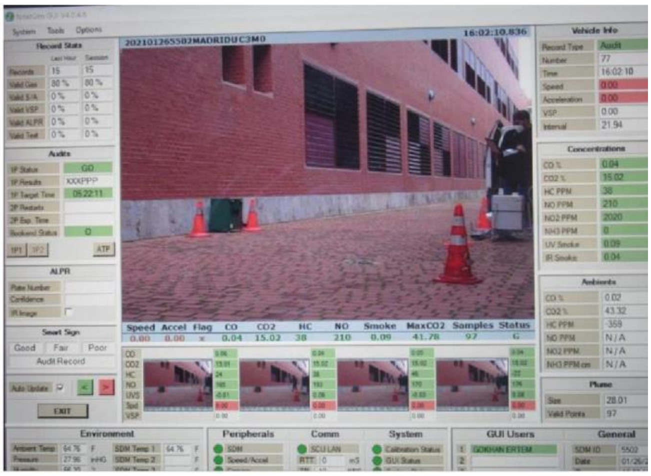


Figure 18. RSIS user interface.

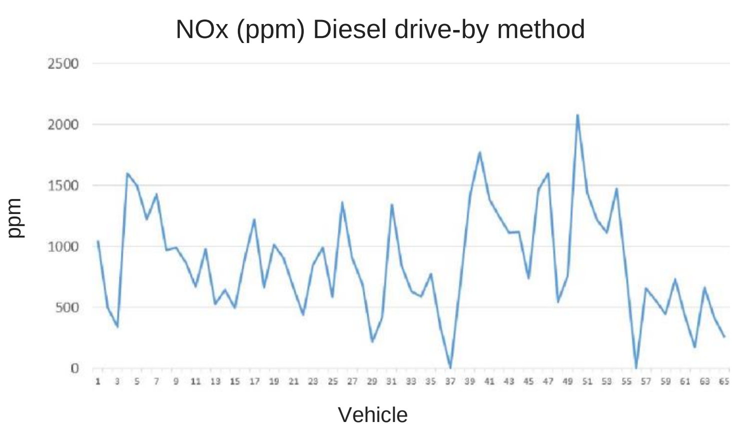


Figure 19. NOx results (ppm) of diesel vehicles with the drive-by method.

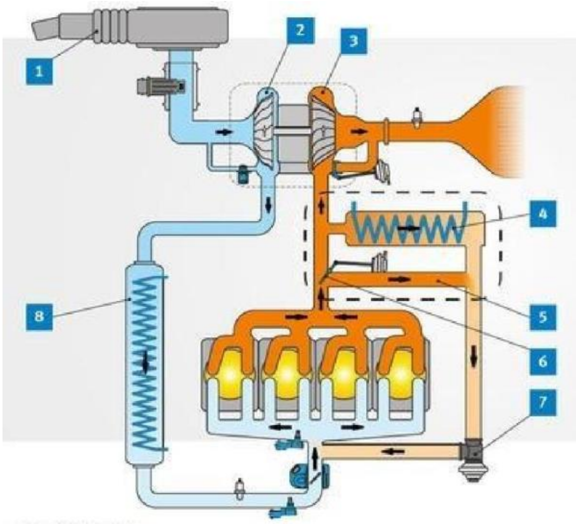
b. STATIC TEST

This proposal is based on analysis of the variation in NOx concentration at the vehicle's tailpipe as a function of the power demand when the engine is idling. Certain vehicle functions that require a power source are activated to increase the demand. For example, the lights demand power as does the air conditioning and forced ventilation of the inside of the windshield. This is a relatively quick, easily-applied and inexpensive test that does not require extensive facilities at the PTI station and enables a very similar procedural execution for all vehicles. The percentage of engine power used is a parameter provided by the engine control unit (ECU) and is related to this power demand.

Consequently, the scope of this procedure is confined to measurement of NOx emissions in diesel vehicles subject to EURO 5 and EURO 6. This procedure has not been applied to measurement of NOx in other EURO categories. Neither has it been applied to petrol vehicles.

This method requires data related to the relationship between the power demand to which the engine is subjected and the formation of NOx in the combustion chamber. The ECU provides this information.

As stated above, diesel engines burn lean (with a higher proportion air in the mixture compared to stoichiometric conditions) which results in a high oxygen concentration. This circumstance causes the excess oxygen molecules to bind to nitrogenous particles, thus producing NOx. Furthermore, production of NOx increases proportionally with rising temperature in the combustion chamber. These variables in turn are affected by the engine's operating requirements (power demand or revolution rate, among others). The concentration of O_2 and the temperature can be affected (note that Figure 20 suggests that in certain cases the recirculated gases are re-cooled) by on-board emission-reduction systems such as the EGR valve that recirculates a portion of the cooled exhaust gases back to the engine intake, lowering both the temperature and the oxygen concentration in the combustion chamber.



1	Air filter
2	Turbocharger (compressor
3	Turbocharger (turbo)
4	EGR Radiator
5	Canar bypass
6	Bypass valve (vacuum-controlled)
7	EGR valve
8	Intake air cooler

Figure 20. Diagram of cooled exhaust gas recirculation through the EGR valve

The engine parameters are known through the onboard diagnostic system: This value is calculated by the ECU using the ratio between the existing air intake flow and the peak intake flow. The value calculated by the equation represents the percentage of the engine's power capacity at the time it is being used.

$$Engine\ load\% = \frac{Current\ air\ flow}{Peak\ air\ flow \cdot \frac{Baro}{29{,}92} \cdot \sqrt{\frac{298}{T_{amb} + 273}}}$$

Peak (maximum) airflow is reached when the throttle is fully open at 25 °C and 1 atm (29,92 inHg). The figures required to adapt the units to the international system are given in the above equation. The engine can be subjected to different load statuses when idling, thereby varying the production of NOx during combustion. With the engine idling, part of the available torque is used by the accessories required for its operation (water pump, alternator, etc.). This torque consumption is related to the maximum torque available at the engine's inherent idle speed and it is this that provides us with the use or power demand percentage. This study applies software specifically designed to carry out this procedure. As can be seen in Figure 1, the OBD shows that the engine's own components consume power even when all the accessory systems are disconnected. We shall call this minimum power-demand engine status the "no-load status". The example shows that at 832 rpm there is a load of 28% on the engine.

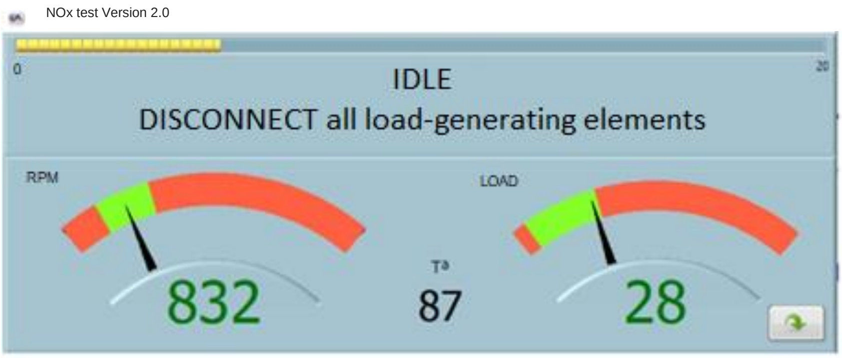


Figure 21. Vehicle idling with all accessory systems disconnected

Connecting certain systems such as the air conditioning or lights causes than increase in the engine load percentage with respect to the maximum available torque. NOx emissions can be related to engine operating parameters by combining real-time data from the OBD system with readings from the gas analyser inserted into the tailpipe.

5 data-collection stages or phases are performed after resetting the unit (see Table 3).

Table 3: Vehicle operating conditions in each phase

	PHASE 1: zero consumption NO-LOAD	**PHASE 2: with consumption LOADED**	**PHASE 3: ACCELERATION**	**PHASE 4: with consumption LOADED**	**PHASE 5: NO-LOAD**
Engine status	OK	OK	OK	OK	OK
Engine rev. rate	Idling	Idling	2.500 rpm approximately	Idling	Idling
Extra vehicle load	Disconnected	Various accessory items connected	Various accessory items connected	Various accessory items connected	Disconnected
The engine's load value	Depends on vehicle	Depends on vehicle	Irrelevant in the procedure	Depends on vehicle	Depends on vehicle

The empty vehicle accelerates (phase three) in order to activate its pollution reduction systems such as opening the EGR valve. Finally (phase five), all the loads are removed from the vehicle in the reverse order to which they were connected: first the heated rear window and the anti-fog system, then the entire lighting system and finally the air conditioning. This final data collection concludes the measurement process.

Figure 22 shows the variation of the parameters measured by the OBD and the NOx emissions provided by the gas analyser during each phase. It can be seen that emissions rise during the phases in which the load is higher and that opening the EGR valve in the acceleration phase clearly reduces them. In this figure, the power demand and opening of the EGR valve are expressed as percentages. NOx emissions are measured in ppm and engine speed in revolutions per minute.

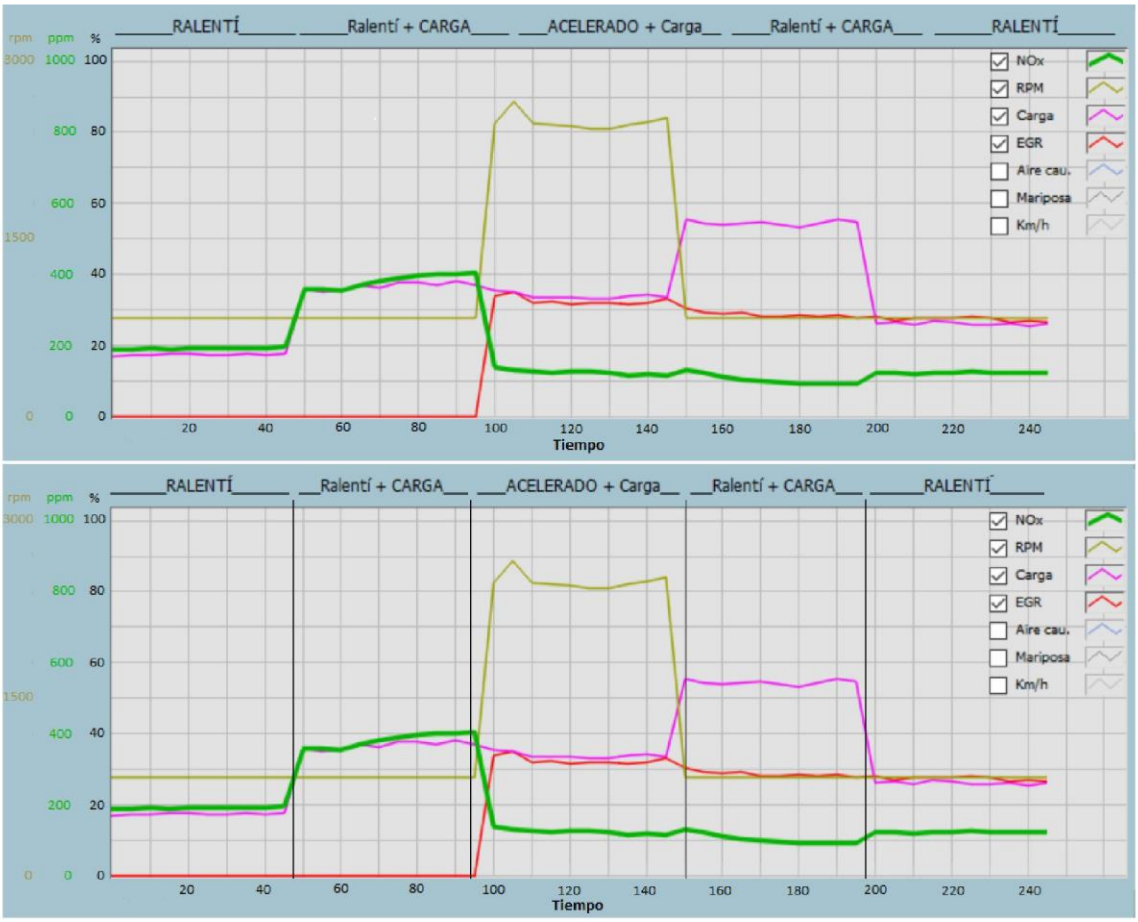


Figure 22. Example of static no-load vs. load measurement in idle regime.

All the phases through which the procedure passes are confined to the lower part of Figure 22. The duration of each phase may vary depending on how the engine operates. Each phase must last long enough for the engine to reach the required load and rpm figures. Data is collected for 20 seconds once the required conditions of each phase have been reached. A photo of the measurement process is shown in Figure 23.

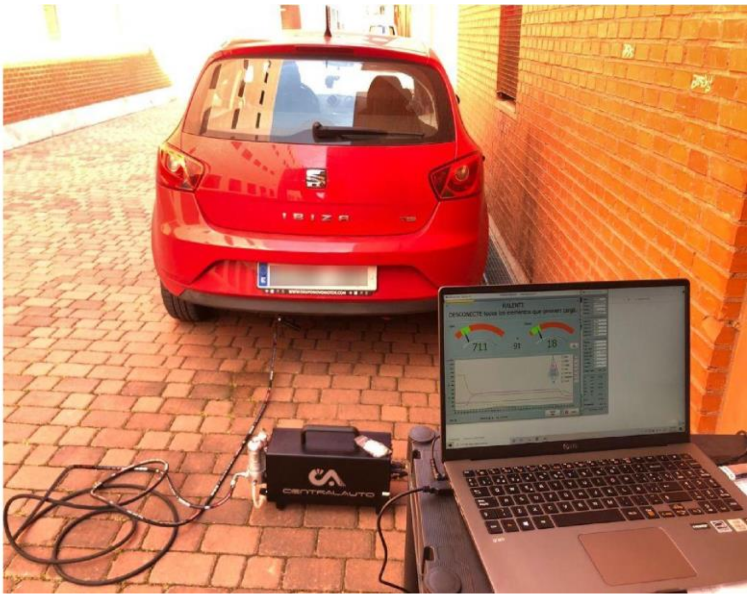


Figure 23. Conducting an emission test using the static method at the Carlos III University of Madrid.

Table 4 shows an example of the data obtained for each of the stages, as well as the estimate calculated for a load value of 100% obtained by extrapolation. Phase 1 (green) shows the figures obtained during the first two stages of the procedure before acceleration takes place. The average value during the no-load condition, the average value during the loaded condition and the peak value are calculated for this initial period. The maximum theoretical value obtained from the extrapolation that assumes 100% of maximum load is also shown (see Figure 24). Phase 2 (yellow) consists of the two stages following acceleration and the same calculations are performed as during the first phase. Finally, the readings taken before and after acceleration are averaged to obtain the final results of the test, which are shown in the first two rows of the blue column (TOTAL AVERAGE). These latter data are the figures used by this static method to analyse vehicle emissions.

Table 4: Results obtained in the static test

	PHASE 1 ± Before acceleration		PHASE 2 ± After acceleration		TOTAL AVERAGE	
	NOx (ppm)	% Loading	NOx (ppm)	% Loading	NOx (ppm)	% Loading
NO-LOAD AVERAGE	191	17	122	26	157	22
HALF LOAD	381	37	102	54	241	45
PEAK EMISSIONS	405	38	129	55	405	55
THEORETICAL MAXIMUM	1052	100	211	100	659	100

A theoretical NOx emission maximum for 100% engine load is calculated by linear extrapolation in both the total average results and in phases 1 and 2. This is done by linear extrapolation between the average obtained during the no-load status, the average of the loaded state, the maximum recorded and zero emission (green line in Figure 24). Similarly, a second line is obtained with the figures extracted from phase two and a third with those obtained in the blue *Total Average* column. The three lines thus obtained are set forth in Fig. 24. They clearly show that before acceleration (green line) NOx emissions are higher than after (yellow line) due to opening of the EGR valve and activation of the other anti-pollution the systems. The blue line represents the total test figures. The procedure considers that the theoretical value obtained with 100% of maximum load (blue column) is valid.

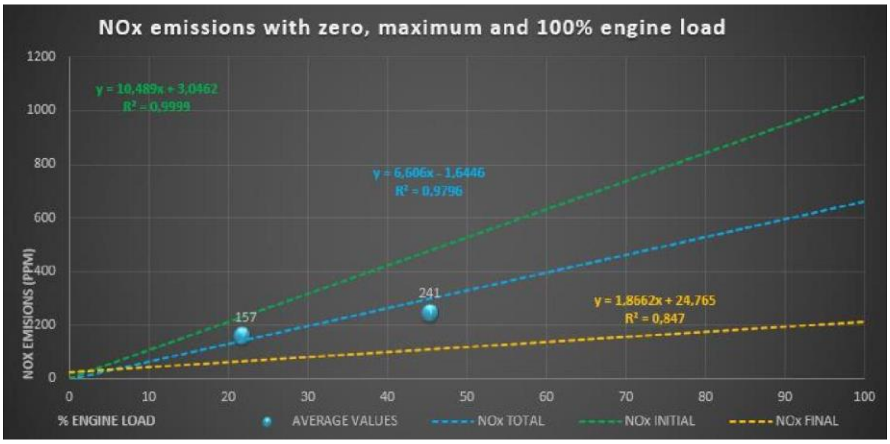


Figure 24. Extrapolation of results from a static measurement

Calculation of a 100% load condition is a theoretical abstraction since the engine can never reach this maximum power condition when the vehicle is stationary. But it is an ingenious way to calculate the maximum. In this way, the maximum emission result of the test shown above would be 659 ppm of NOx.

Table 5 shows some results obtained in diesel vehicles. Approximately half of the vehicles emit between 150 and 300 ppm. The rest is distributed between figures above and below this range.

Table 5: Results for diesel vehicles obtained according to the NOx thresholds

Range 1	Range 2	Range 3
x<150 ppm	150 ppm<x<300 ppm	x>300 ppm
23%	50%	27%

The EGR valve sometimes fails to open during acceleration. This causes NOx emissions to be the same under both no-load conditions and both loaded conditions (both before and after acceleration) since the vehicle parameters are the same. Figure 25 shows that the opening percentage of the EGR valve (red line) does not vary throughout the test and that the NOx emissions (green line) are therefore similar before and after acceleration.

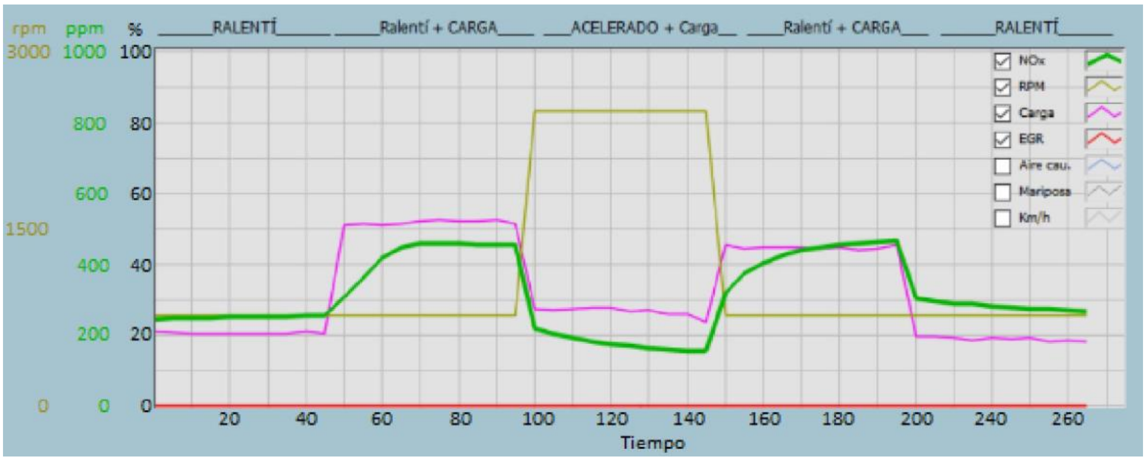


Figure 25. Test carried out on a vehicle in which the EGR valve fails to open

The amount the EGR valve opens depends on the vehicle's own conditions or configuration and therefore its operation can never be ensured. This method uses acceleration to cause two different conditions in the vehicle to enable extraction of an average. The average in this case will be higher, which means that failure to open the EGR valve is penalised.

6. SELECTION OF THE TEST AND INSPECTION METHOD PROPOSED IN THIS PAPER

6.1.- Measurement of NOx and particulate material taking the above methods into account

To sum up, analysing the three methods dealt with above, we could reach the conclusion that the roller bench represents a plausible but is cumbersome from the execution point of view and also occupies a lot of space in the PTI station. The results depend exclusively on the equipment made available to the research team. In this case we were only able to measure NOx for the entire range of vehicles, without distinguishing Euro-type approval regulations and without distinguishing the type of fuel used by the vehicles under study. The dynamic drive-by test suffers from similar constraints. The remote sensing equipment is very robust when measuring NOx but, despite the fact that the method incorporates measurement systems, it does not measure particulate matter either. Finally, the simple static inspection method is only proposed for Euro 5 and Euro 6 and for petrol vehicles. In short, all three methods are viable but incomplete.

One of the aims of this work is to define a PTI action protocol which, taking the current technology and state-of-the-art studied and analysed above into consideration, enables inspection of vehicles powered by internal combustion engines (ICE) that run on petrol or diesel and follows the chapter on polluting emissions in the Spanish Inspection Procedure Manual of PTI.

In the absence of methods that enable measurement of the particle count, a certain manufacturer provided the study with a particle count meter based on the condensation particle counter (CPC) method. To do so, reverse engineering –which we will briefly discuss in the next section – was used since there is no rejection limit figure in this sense.

6.2.- Empirical development of a new method for measuring the particle count

As stated in the above section, there is no known method that enables an ICE vehicle to be put into operation at a revolution regime above idling, which may or may not activate the anti-pollution systems that the manufacturer has built into its models. To do so, an empirical experiment was designed to provide the optimum engine speed compatible with the available measurement equipment.
Emission tests were carried out on various vehicles while engine speed was varied to determine its influence on the emission of particles in order to define the appropriate procedure for measurement of the same. The final emissions test protocol to be used will be determined on the basis of the results obtained and the baseline data.

An initial version of the test protocol was designed that included various rpm regimes increasing over time in addition to the idle rate. The procedure requires placing the vehicle in static position during the following times (see Figure 26):

- 60 seconds at idle,
- 60 seconds at 1.000 rpm,
- 60 seconds at 1.500 rpm,
- 60 seconds at 2.000 rpm,
- 40 seconds at 2.500 rpm, and
- 60 seconds at idle.

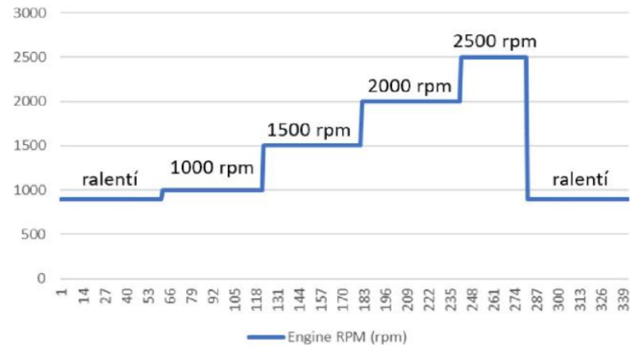


Figure 26. Established particle measurement test protocol [ralentí > idle]

This procedure aims to show how particle emission increases as a function of engine speed. After reviewing the results it was decided to shorten the test duration in order to reduce the PTI station inspection times. It can be seen that the quantity of particles emitted in the second idling phase (after reaching 2.000 / 2.500 rpm) is in a similar order of magnitude as that emitted during the 2.000 / 2.500 rpm phases themselves. This led to the conclusion that it would possible to eliminate the 2.000 and 2.500 rpm phases since they would emit a quantity of emissions similar to the final idling stage and because such high rpm can be harmful to the engines.

In addition to cancelling the 2.500-rpm phase to avoid damage to the engines, the first idle stage was also eliminated since its regime is close to 1.000 rpm in the vast majority of the vehicles subjected to testing. These decisions were based on the test results obtained under Protocol 1. Pursuant to the above, Protocol 2 tested the static vehicle at the following rpm phases: (Figure 27):

- 20 seconds at 1000 rpm,
- 20 seconds at 1500 rpm,
- 20 seconds at 2000 rpm, and
- 20 seconds at idle.

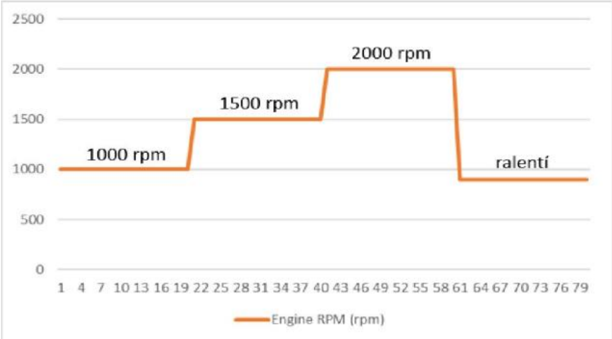


Figure 27. Established particle measurement test protocol (Test 2)

Some of the results of Test 2 with diesel and petrol vehicles are shown below. Figure 28 shows the results from a diesel engine and Figure 29 the results from a petrol engine. In these tests it can be seen that the highest particle emission figures are recorded during the idle and 1.500 rpm phases (it must be specified here that these results are obtained using a different CPC unit known commercially as 3DATX parSYNC®, an integrated Portable Emissions Measurement System (iPEMS), or *minipems.* It enables continuous measurement by varying the engine status. It was decided to extend the test protocol only for this unit, in order to observe once more what happens when the engine is running at 2.000 rpm. The aim was to verify that the protocol finally selected (idle + 1.500 rpm + idle) was the most suitable since increasing the engine speed to 2.000 rpm was unnecessary as no significant rise in the emission of contaminating particles was observed.

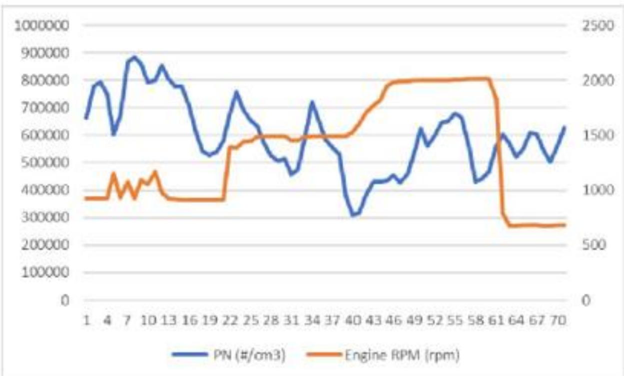


Figure 28. Test 2 results with diesel engine.

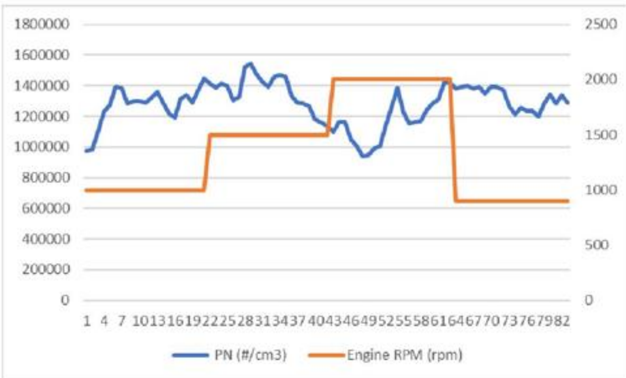


Figure 29. Test 2 results with petrol engine.

Figure 30 shows a photograph in which readings are taken both continuously and in sections using the two available technologies.


Figure 30. Continuous measurements using the 3DATX parSYNC iPEMS unit on a diesel engine.

The particle test protocol was finally established after observing the results of the tests described above. The measurement capacity of the available equipment other studies carried out in Europe were also taken into account. This final test for measuring contaminating particles consists of placing the vehicle in a static position during the following phases:

- 15 seconds at idle.
- 15 seconds at 1.500 rpm, and
- 15 seconds at idle.

This protocol is proposed a final method for counting particles for all types of petrol and diesel Euro vehicles.

We have conducted tests with a CPC technology unit that takes measurements in static states in order to obtain results from massive in situ testing, i.e. in a PTI station. Some results from these tests are set forth below.

6.3.- Proposal of a new unified method for NOx measurement and particle counting

This section proposes a new method for measuring motor vehicle emissions on the basis of the experience accumulated in this study and after reviewing numerous contributions from manufacturers and certain European experiences. It is a unified method because it is proposed for all types of ICE vehicle. The only limitation that may exist is associated with the equipment provided by the manufacturers.

The unified method proposed here is completely original and is presented as a basis for reflection on the future of PTI inspections. It saves inspection time and reduces number of technical devices required.

The method must address a complex problem: it will not only represent an innovation in this type of technology but said innovation must also help to improve the inspection and thereby to reduce the atmospheric pollution emitted by ICE vehicles.

The improvement in the inspection must be approached from the point of view of saving resources, both material and temporal. In other words, the proposed devices must be as economical as possible, universal in terms of adaptation to any type of PTI, easy to use (to avoid making the inspection technician's training even more complex) unified in that it enables the inspection of all ICE vehicles including hybrids, four-wheel drive, rear-wheel drive, etc.). The new unit’s acquisition price and cost of installation in the PTI facility must also be taken into consideration. Table 6 below is a schematic presentation of all the aspects that affect the economyof resources required for introduction of this new procedure.

Table 6: Schematic presentation of economic aspects

ECONOMIC ASPECTS	Unit cost		
	Calibration cost		
	Period between calibrations		
	Additional infrastructure		Yes
			No
	Universal equipment (common to both methods)		Yes
			No
	Times	Inspection	
		Staff training	
	Staff training cost		
	Degree of implementation in specific PTI		
		Compatibility with other units	
		Station software compatibility	
	General	Conceptual simplicity (user)	
		Ease of use (inspector)	
	Likelihood of causing breakdowns (insurance)		

A new unified method for inspection of polluting NO_x and particulate emissions is proposed below keeping all these conditioning factors in mind.

A device that simultaneously measures NO_x and particulate emissions does not exist today. Designing and producing one is the role of the manufacturer. When the technology is developed to measure both at the same time, the inspector will only need to insert a single probe. Meanwhile, we must either insert a probe into the tailpipe to measure NOx and then another to measure the particles or insert both simultaneously.

Another aspect that will require clarification is the level of compliance with the Euro regulation on emissions associated with the type approval of each vehicle. With the experience obtained in this study, we propose differentiating this circumstance when rejecting a vehicle, or consider the inspection test to have been passed, maintaining a single rejection criterion (Figure 31).

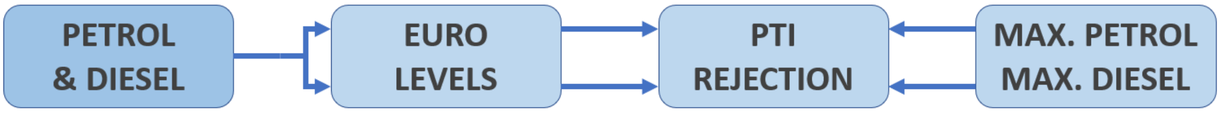


Figure 31: Correlation between rejection in the inspection with respect to the type of engine and the compliance level with the Euro type-approval

A static procedure was selected after analysing the content of this study. Special consideration has been given to the fact that no dynamic inspection method capable of measuring emissions of both NOx and particulate matter has been found to date. In spite of the fact that Spanish PTI is currently equipped with engine rpm measuring devices, we have decided to measure this parameter using the OBD. One of the reasons is that the future of inspection involves the use of this resource. All modern vehicles manage many important variables by means of an on-board computer. The nervous system of a vehicle, to coin a phrase, is the OBD (Figure 32).

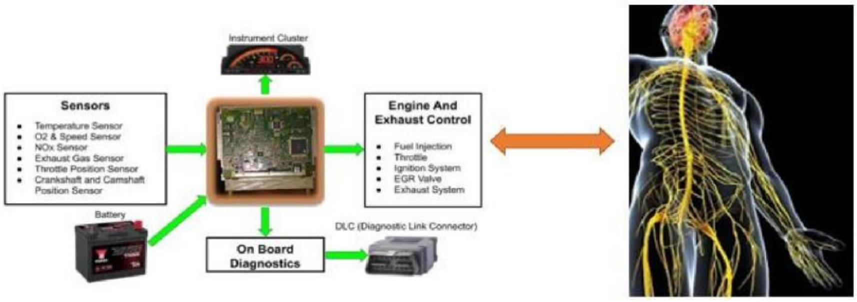


Figure 32: Comparison of the human nervous system with a vehicle's OBD.

Given the context in which the proposed method has been developed, the authors have taken the liberty of writing it in the terms of the Inspection Procedures Manual for Spanish PTI Stations published by the Ministry of Industry, Energy and Tourism.

Measurement of nitrogen oxides

a. GENERAL SPECIFICATIONS

The inspection procedure shall apply to vehicles equipped with spark- or compression-ignition engines registered after 01/01/1980, the emissions of which may or may not be regulated by an advanced emission-control system. This procedure is applicable to M1 vehicles.

The emission reading of the on-board diagnosis (EOBD/WWHOBD, hereinafter OBD)[1] will be used for vehicles with emission levels in EURO 5 and EURO 6.

b. METHOD

b.1) Vehicles the emissions of which are not regulated by an advanced emission control system.
- Visual inspection of the exhaust assembly to check that it is complete, in satisfactory condition and that no leaks are detected.
- After a reasonable warm-up period (taking the vehicle manufacturer's instructions into account) the content of nitrogen oxides (NOx) in the exhaust gas shall be measured with the engine idling (no-load).
- The following shall be the maximum authorised NOx content in the exhaust gases:
  for vehicles registered before 01/01/2004 (prior to EURO 4): NOx-TO BE DETERMINED % vol (rejection limits are proposed at the end of the section although they must be set by the competent authority).

b.2) Vehicles the emissions of which are regulated by an advanced emission-control system such as particulate filters, EGR valves, etc.

- Visual inspection of the exhaust assembly to check that it is complete, in satisfactory condition and that no leaks are detected.
- After a reasonable warm-up period (taking the vehicle manufacturer's instructions into account) the nitrogen oxide (NOx) content in the exhaust gas shall be measured with the engine idling (no-load) prior to accelerating to 1.500 rpm, maintaining this engine speed for 15 seconds and returning to idle.
- The following shall be the maximum authorised NOx content in the exhaust gases:
  for vehicles registered as of 01/01/2004 (EURO 4 and later): NOx-TO BE DETERMINED % vol (rejection limits are proposed at the end of the section although they must be set by the competent authority).

Vehicle conditions required to conduct the test

- The commercial fuel in the vehicle's tank shall be used to conduct the test.
- A visual inspection of the exhaust system shall be performed to check that it is in good condition and is free of apparent damage or modifications.
- Check that the vehicle under examination has an OBD2 port and that it is free of connection errors[2].
- Check that all items that can increase the power demand on the engine are turned off: lighting system, air conditioning, radio, etc.
- A visual inspection of the emission control devices shall be performed to verify that it is complete, in satisfactory condition and that there are no apparent leaks.
- If the vehicle is equipped with an exhaust system with more than one tailpipe, the test shall be conducted on each one and the permitted maximum figure must not be exceeded in any.
- The test shall be carried out with the gear lever in neutral and the clutch released in vehicles with manual or semi-automatic gearboxes. In vehicles with an automatic gearbox the test shall be carried out with the selector in the N or P position.

[1]WWHOBD: Worldwide Harmonized On-Board-Diagnostic/EOBD: European On Board Diagnostic.
[2]Most vehicles that comply with EURO 3 regulations or later are equipped with an OBD2 port. However, not all of them provide an accurate reading. In the absence of verification, it can only be ensured that communication and readings will be accurate in vehicles subject to the EURO 5 or later regulations.

Measurement conditions:

- The engine shall be properly warmed up (approximately 90 °C) and must comply with the manufacturer's specific recommendations, if any.
- The ICE ignition protocol set by the manufacturer shall be used where applicable in plug-in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV) and range-extended electric vehicles (REEV). If it is impossible to set the ICE speed to the aforesaid rpm regime, it shall be maintained at the speed that the vehicle can reach for as long as possible in order to reach the optimal catalytic converter temperature.
- When the inspection is subject to a special procedure that is available, the inspection shall be conducted as set forth in said procedure.
- In the case of multi-fuel vehicles, the test shall use the fuel that the vehicle is using at the time of the inspection and this circumstance shall be placed on record in the inspection report.

Test procedure:

- Couple the OBD reading device and check the connection to ensure proper data transmission.
- Insert the gas-sampling probe as far as possible into the exhaust pipe (either in the pipe itself or in a collector pipe coupled to the former) ensuring that it is inserted at least as far as the manufacturer's minimum penetration mark to prevent the entry of excess O2 that could affect the measurement.
- Take the NOx reading.
- Tailpipe emissions:

Measurement of the particle content shall be carried out in idling regime for 15 seconds before and after acceleration to 1.500 rpm maintained for 15 seconds.

1.- Measurement with the engine idling (b.1 and b.2):

Put the gear lever in neutral and release the clutch with the engine idling. Maintain this regime and take measurements for 15 seconds.

2.- Measurement at 1.500 rpm (b.2):

Put the gear lever in neutral and run the engine at 1.500 rpm with the clutch released. Maintain this regime and take measurements for 15 seconds.

3.- Measurement with the engine idling after acceleration (b.2):

Put the gear lever in neutral and release the clutch with the engine idling. Maintain this regime and take measurements for 15 seconds.

Limit figures:

- As measured at idle to be determined (b1)
- The resulting measurement shall be obtained by extracting the arithmetic mean between the measured value of the emissions obtained at 1.500 rpm and those obtained at idle after the acceleration phase (b.2).

A second measurement shall be taken if the first exceeds the maximum permitted value.

c. REFERENCE REGULATION

d. INTERPRETATION OF DEFECTS

	Score		
	MD	MD	DD
1.-The vehicle has emissions with NOx concentration in excess of the upper limit in the first and second readings. Idle after acceleration.		X	
2.-OBD connection inaccessible or inoperative. Serious defect only applied to EURO 5 or 6.	(X)	X	

[MD: minor deficiencies; MD: major deficiencies; DD: dangerous deficiencies]

Based on the results obtained in the tests carried out in the PTI, rejection limits shall be proposed on the basis of the Euro regulations for type-approval of each vehicle.

Particle count measurement

a. GENERAL SPECIFICATIONS

The inspection procedure shall apply to vehicles equipped with spark or compression ignition engine and direct injection registered as of 01/01/1980 the emissions of which may or may not be regulated by an advanced emission-control system. This procedure is applicable to M1 vehicles.

The OBD reading shall be used for vehicles with emission levels in EURO 5 and EURO 6. Particle DC or CPC technology shall be used to measure particle emissions.

b. METHOD

b.1) Vehicles the emissions of which are not regulated by an advanced emission control system.

- Visual inspection of the exhaust assembly to check that it is complete, in satisfactory condition and that no leaks are detected.
- After a reasonable warm-up period (taking the vehicle manufacturer's instructions into account) the content of particles of a given size in the exhaust gases shall be measured with the engine idling (no load).
- The following shall be the maximum authorised particulate matter content in the exhaust gases: for vehicles registered before 01/01/2004 (prior to EURO 4): TO BE DETERMINED particles/cm^3 (rejection limits are proposed at the end of the section although they must be set by the competent authority).

A second measurement shall be taken if the first exceeds the maximum permitted value.

b.2) Vehicles the emissions of which are regulated by an advanced emission-control system such as particulate filters, EGR valves, etc.

- Visual inspection of the exhaust assembly to check that it is complete, in satisfactory condition and that no leaks are detected.
- After a reasonable warm-up period (taking the vehicle manufacturer's instructions into account) the content of particles of a certain size in the exhaust gas shall be measured with the engine idling (no-load) prior to an acceleration to 1.500 rpm maintained for 15 seconds followed by return to idle.
- The maximum authorized content of particles per cm3 in exhaust gases will be as follows: for vehicles registered as of 01/01/2004 (EURO 4 and later): TO BE DETERMINED particles /cm3 (rejection limits are proposed at the end of the section although they must be set by the competent authority).

A second measurement shall be taken if the first result exceeds the maximum permitted value. **Vehicle conditions**

Required to conduct the test

- The commercial fuel in the vehicle’s tank shall be used to conduct the test.
- A visual inspection of the exhaust system shall be performed to check that it is in good condition and is free of apparent damage or modifications.
- Check that the vehicle under examination has an OBD2 port and that it is free of connection errors.
- Check that all items that can increase the power demand on the engine are turned off: lighting system, air conditioning, radio, etc.
- A visual inspection of the emission control devices shall be performed to verify that it is complete, in satisfactory condition and that there are no apparent leaks.
- If the vehicle is equipped with an exhaust system with more than one tailpipe, the test shall be conducted on each one and the permitted maximum figure must not be exceeded in any.
- The test shall be carried out with the gear lever in neutral and the clutch released in vehicle with manual or semi-automatic gearboxes.
- In vehicles with an automatic gearbox the test shall be carried out with the selector in the N or P position.

Measurement conditions:

- The engine shall be properly warmed up (approximately 90 °C) and must comply with the manufacturer's specific recommendations, if any.
- The ICE ignition protocol set by the manufacturer shall be used where applicable in plug-in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV) and range-extended electric vehicles (REEV). If it is impossible to set the ICE speed to the aforesaid rpm regime, it shall be maintained at the speed that the vehicle can reach for as long as possible in order to reach the optimal catalytic converter temperature.
- When the inspection is subject to a special procedure that is available, the inspection shall be conducted as set forth in said procedure.
- In the case of multi-fuel vehicles the test shall use the fuel that the vehicle is using at the time of the inspection and this circumstance shall be placed on record in the inspection report.

Test procedure:

- Couple the OBD reading device and check the connection to ensure proper transmission of the engine's revolution regime data.
- The gas sampling probe will be inserted as far as possible into the exhaust pipe, either in the pipe itself or in the collector pipe coupled to the former, ensuring the penetration distance set by the manufacturer.
- The particles are measured
- Tailpipe emissions:

Measurement of the particle content shall be carried out in idling regime for 15 seconds before and after acceleration to 1.500 rpm maintained for 15 seconds.

1.- Measurement with the engine idling (b.1 and b.2):

Put the gear lever in neutral and release the clutch with the engine idling. Maintain this regime and take measurements for 15 seconds.

2.- Measurement at 1.500 rpm (b.2):

Put the gear lever in neutral and run the engine at 1.500 rpm with the clutch released. Maintain this regime and take measurements for 15 seconds.

3.- Measurement with the engine idling after acceleration (b.2):

Put the gear lever in neutral and release the clutch with the engine idling. Maintain this regime and take measurements for 15 seconds.

Limit figures:

- As measured at idle to be determined (b1)
- The resulting measurement will be obtained by calculating the arithmetic mean between the measured value of the emissions obtained at 1.500 rpm and those obtained at idle after decelerating (b2).

A second measurement shall be taken if the first exceeds the maximum permitted value.

- Measurement with engine idling prior to acceleration: IT IS ADVISABLE TO KNOW THE REJECTION CRITERIA DATA IN THE TESTING PROCESS THIS. MAY NOT BE NECESSARY IN THE FINAL PROCEDURE
- Measurement with the motor revving at 1.500 rpm: IT IS ADVISABLE TO KNOW THE DATA FOR THE REJECTION CRITERIA IN THE TESTING PROCESS THIS MAY NOT BE NECESSARY IN THE FINAL PROCEDURE
- Measurement with engine idling after acceleration: TO BE DETERMINED

c. REFERENCE REGULATION

d. INTERPRETATION OF DEFECTS

	Score		
	MD	**MD**	**DD**
1.-The vehicle has emissions with NOx concentration in excess of the upper limit in the first and second readings. Idle after acceleration.		**X**	
2.-OBD connection inaccessible or inoperative. Serious defect only for EURO 5 or EURO 6	(X)	**X**	

[MD: minor deficiencies; MD: major deficiencies; DD: dangerous deficiencies]

Based on the results obtained in the tests carried out in the PTI, rejection limits shall be proposed on the basis of the Euro regulations for type-approval of each vehicle.

7. RESULTS OBTAINED AND CRITERIA FOR REJECTION IN THE INSPECTION PROPOSALS

As mentioned above, a series of field tests were still to be carried out at the PTI itself in order to test the proposed particle-counting procedure at a PTI using a conventional CPC technology unit.

We have reached the following conclusions on the basis of the results obtained so far:

a) The percentage of rejections is a function of the following law of proportionality: the stiffer the requirements of the EURO type-approval regulations, the lower the number of particles emitted by the vehicle will be and therefore the rejection limit will tend to diminish.
b) In accordance with the above, the rejection limits with respect to the EURO 3 and EURO 4 regulations will provide results similar to those currently obtained in technical inspections using the opacity method. In other words, the new percentage of vehicles rejected by counting particles emitted through the tailpipe will be equivalent to rejection due to opacity.

With these premises, the following graphs show results obtained from tests conducted at the PTI Station in Pinto (Madrid).

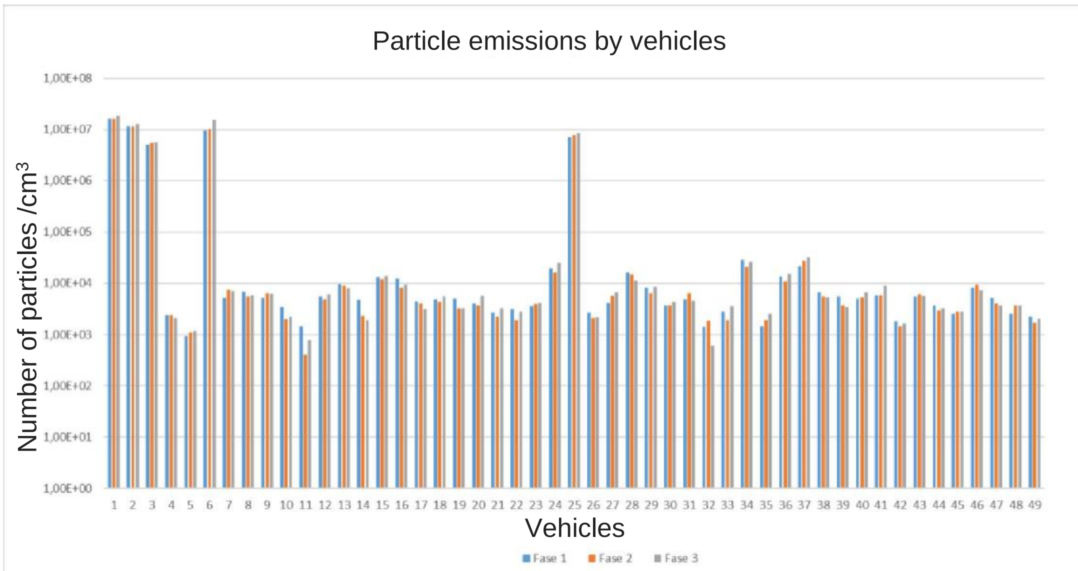


Figure 33: Particle count for diesel vehicles. All EURO categories

Figure 33 shows the number of particles emitted by diesel vehicles type-approved under EURO 3 to EURO 6, applying the inspection method developed by the UC3M research team and proposed in this paper. Three bars can be observed for each vehicle. They represent the maximum particle count per cm^3 at idle (blue), with the engine running at 1.500 rpm (orange) and idle after deceleration (grey), in phases of 15 seconds' duration.

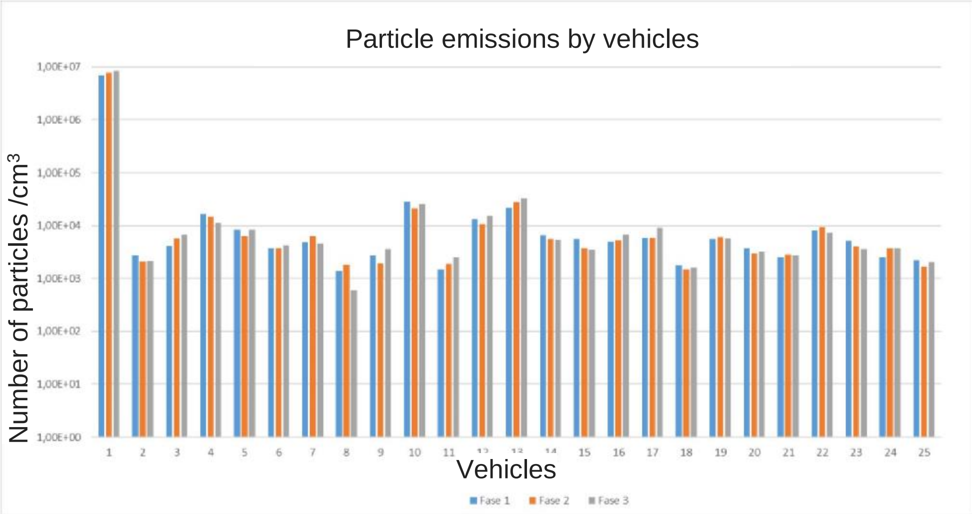


Figure 34: Particle count for diesel vehicles. All EURO 5 and EURO 6 categories

Different behaviour can be observed between the EURO category ranges. To focus on the EURO 5 and 6 study, the results of the same measurements are shown but only for this type-approval range (Figure 34).

In this second graph, as in the previous one, it should be noted that the behaviour of the particles, and therefore the validity of the measurement, depends on the technology used by the vehicle manufacturer. Some vehicles emit more particles when the engine returns to its idle regime than in the prior 1.500-rpm phase. The technology used to manage recirculation of exhaust gases and other similar functions sometimes fails to operate. This gives rise to the unexpected and paradoxical effect that the engine emits more polluting gases after it has accelerated, even though the revolutions then diminish. This paradoxical outcome occurs frequently among the vehicles in the sample under analysis.

The increase in particle number (PN) emissions after free acceleration can be explained by the fact that some diesel vehicles (predominantly EURO 5 and later) enter the so-called "Taxi Mode" after idling for a certain time. This happens because the vehicle's exhaust gas recirculation (EGR) valve closes after idling for a certain period to protect the system from contamination by accumulation of soot. The EGR system is fitted to vehicles initially to reduce NOx emission, but it also affects NOx emission. NOx emissions are reduced when the EGR valve is open but particulate emissions outside the engine are increased and vice versa (NOx particulate exchange). This effect is negligible in PN tailpipe emissions from vehicles with highly-effective particle filters, but the effect is measurable at the tailpipe of vehicles with filters in less-than-optimal condition. Free acceleration would trigger opening of the EGR which in turn could cause an increase in PN emissions.

This circumstance must be taken into account by the PTI. The following considerations must be kept in mind when preparing the vehicle for testing to ensure that it exits "taxi mode" but that emissions of particles generated with the anti-pollution systems in action are measured.

- Perform free acceleration (to open the EGR) prior to taking the reading at idle.
- Consider a stabilisation phase of 30 seconds following the acceleration.

In view of the fact that the units' response time is 15 sec, when taking readings in the accelerated phase it is recommended to allow these 15s to stabilise the emissions between readings to ensure that the particles measured are those generated under the established conditions.

The following are the rejection criteria proposed in this study:

Future testing technique may enable fine-tuning of these limits.

- Rejection limit for measurement of NOx emissions: 300 ppm
- Rejection limit for particle count: 1.000.000 particles /cm^3

8. CONCLUSIONS

An inspection method has been developed to simultaneously measure NOx emissions and particulate matter emitted by M1 petrol and diesel vehicles that comply with all Euro type-approval standards.

The following are some of the advantages associated with the method:

- Simple.
- Universal.
- Effective.
- Space-saving.
- Does not require special facilities in the PTI station.
- Optimises inspection times viz-à-viz two different tests carried out sequentially.

Other particle measurement technologies oriented to the PTI sector will naturally enter the market in the near future. As mentioned above, in addition to the CPC technology applied in this study there is a promising DC technology that has not lent itself to testing in PTI stations so far.

To conclude the study, the authors believe that the following considerations must be placed on record. All the tests in this study have been conducted using various currently-available technologies provided by the respective manufacturers that we have consulted throughout the work. The appearance of other new technologies could entail drastic changes to the suggested rejection thresholds.

However, since these new technologies have not yet been embodied in viable measuring devices, the proposed rejection criteria are considered valid for this study. Numerous future tests are planned at other Spanish PTI stations when the new units becomes available. There results will be compared with those of the current state-of-the-art. We assume that the aforesaid rejection limits could be further refined. All measurements performed in new PTI stations on the basis of the proposals set forth in this paper will be attached as an annex hereto.