Earth, Life & Social Sciences
Anna van Buerenplein 1
2595 DA Den Haag
P.O. Box 96800
2509 JE The Hague
The Netherlands

www.tno.nl

T +31 88 866 00 00

TNO report

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Investigation into a Periodic Technical Inspection (PTI) test method to check for presence and proper functioning of Diesel Particulate Filters in light-duty diesel vehicles – part 2

Date	1 May 2017
Author(s)	G. Kadijk M. Elstgeest N.E. Ligterink P.J. van der Mark
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Samenvatting

Aanleiding
Om de uitstoot van roetdeeltjes terug te dringen, zijn moderne dieselauto's uitgerust met een roetfilter. Roetfilters zijn zeer effectief: een goed werkend filter vermindert de uitstoot van roet met 95 tot 99%.

Roetfilters hebben in 2002 hun intrede gedaan op de Nederlandse markt voor personenauto's, en worden sinds 2007 grootschalig toegepast als gevolg van fiscale stimulering. De Europese Euro 5 norm heeft ertoe geleid dat roetfilters inmiddels worden toegepast op alle nieuwe dieselpersonenauto's (sinds 2011) en dieselbestelwagens (sinds 2012).

Een roetfilter kan verstopt raken of kapot gaan. Het filter moet dan worden gereinigd of vervangen. Met name het vervangen van een roetfilter kan een kostbare zaak zijn. Daarom kiezen autobezitters er soms voor om het filter te laten verwijderen. Ook wordt het verwijderen van een roetfilter aangeboden als onderdeel van *chip-tuning* van voertuigen. Uit in 2014 uitgevoerd veldonderzoek van TNO en de RDW blijkt dat bij circa 5 tot 7% van de dieselpersonenauto's met een af fabriek roetfilter het filter verwijderd of defect was.

Met de huidige APK is het niet mogelijk om vast te stellen of een goed werkend roetfilter aanwezig is. Moderne dieselvoertuigen met roetfilter worden op uitstoot gecontroleerd door het uitlezen van het Emissie On-Board-Diagnostics-systeem (EOBD). Omdat bij het fysieke verwijderen van het roetfilter het roetfilter ook wordt 'weggeprogrammeerd' in de software van de auto, wordt een verwijderd roetfilter in de EOBD-controle niet opgemerkt.

Als bij de OBD-uitlezing foutcodes worden aangetroffen moet, afhankelijk van de gevonden foutcode, een roetmeting worden uitgevoerd. Deze roetmeting is echter al decennia oud. De bijbehorende limieten voor de roetuitstoot zijn dermate ruim dat alleen (oude) dieselauto's met een zeer hoge uitstoot worden afgekeurd. Dieselauto's met een defect of verwijderd roetfilter voldoen in de regel aan deze test.

Controle op defecte roetfilters in de APK kan alleen als de eisen strenger worden en een nieuwe, meer nauwkeurige testmethode wordt ingevoerd. Als geen roetfiltertest in de APK wordt ingevoerd, kan dit tot gevolg hebben dat bij een aanzienlijk deel van de dieselauto's het roetfilter wordt verwijderd om onderhoudskosten uit te sparen.

Doel
In opdracht van het Ministerie van Infrastructuur en Milieu heeft TNO een onderzoek uitgevoerd naar de kwaliteit van de huidige rookemissietest en alternatieve testen waarmee in de toekomst in de APK kan worden gecontroleerd of een goed werkend roetfilter aanwezig is.

Aanpak
TNO heeft in dit onderzoek de volgende meetmethodes onderzocht en met elkaar vergeleken:

1. De nu bestaande conventionele roet- of opaciteitsmeting bij vrije acceleratie van de bedrijfswarme motor, uitgevoerd met een moderne, 'verbeterde' roet- of opaciteitsmeter, met een hogere nauwkeurigheid dan de oude meters.
   De daarbij gemeten grootheid is de opaciteit of roet- of rookwaarde uitgedrukt in m^{-1}. Bij vrije acceleratie wordt het gaspedaal maximaal ingetrapt, en wordt de maximale rookemissie gemeten;

2. Een meting van het aantal deeltjes (*Particle Number* of PN) bij een bedrijfswarme motor en stationair toerental in de uitlaatgassen met behulp van verschillende deeltjestellers. Dit is een meetmethode die momenteel niet in de APK wordt toegepast;

3. Testen op de rollenbank waarin de deeltjesmassa (PM) en deeltjes aantallen (PN) zijn gemeten.

In totaal zijn gedurende het onderzoek 14 voertuigen gemeten. De voertuigen zijn gehuurd of beschikbaar gesteld door de eigenaren.

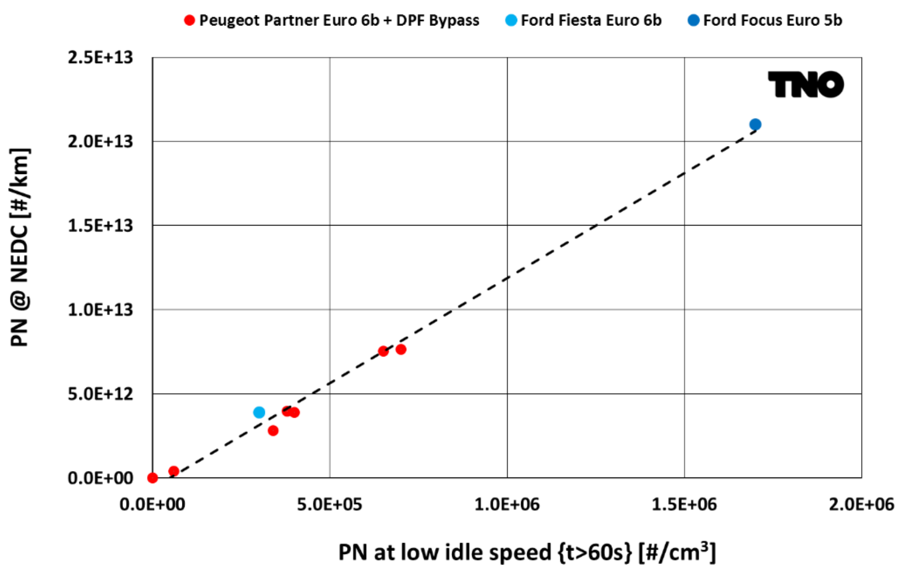
Conclusies
Wat is de kwaliteit van de huidige rookemissietest?
- De rookemissiemeting zoals die tot op heden in de APK wordt uitgevoerd is gedateerd en geeft geen goed beeld van de PM en PN emissies in de praktijk. Sinds de invoering van roetfilters op dieselvoertuigen zijn rookemissies zeer sterk gedaald. Voor de meeste dieselvoertuigen geldt dat rookemissies volledig zijn verdwenen, de meetwaarde is dan 0,00 m^{-1}.
- Voertuigen met defecte of verwijderde roetfilters hebben nog wel rookemissies, maar deze geven geen goed beeld van de PM/PN emissies op de weg omdat deze rookemissies niet representatief zijn voor praktijkgebruik.
- Ook is de kwaliteit van de gemeten rookemissies beperkt. De huidige opaciteitsmeters zijn relatief ongevoelig omdat filtering van de meetsignalen wettelijk verplicht is. Verder zijn het meetbereik (0-10 m^{-1}) en de meetnauwkeurigheid (+/- 0.3 m^{-1}) van de toegepaste rookmeters in de APK afgestemd op motoren met substantiële rookemissies (zonder roetfilter) en hierdoor kunnen lage rookemissies (< 0.30 m^{-1}) van huidige motoren niet nauwkeurig vastgesteld worden.
- Daarnaast is reproduceerbaarheid van de vrije acceleratietest slecht omdat het gaspedaal door een tester in één seconde volledig ingetrapt moet worden, maar deze bedieningstijd niet wordt gemeten. In de praktijk blijken rookemissies sterk afhankelijk van deze bedieningstijd van het gaspedaal.
- Ook kunnen rookemissiemetingen in de praktijk worden gemanipuleerd door o.a. toepassing van brandstofadditieven en ook hoogwaardige dieselbrandstoffen (zoals GTL) die minder rookemissies veroorzaken dan reguliere dieselbrandstoffen.

Welke zaken spelen een rol in een nieuwe APK-emissietest?
Alternatieve procedures voor APK emissietesten dienen rekening te houden met:

- de motor- en uitlaatgasnabehandelingstechnologie en type brandstof.
- het type emissietest.
- het meetprincipe.
- de toe te passen limietwaarde.

Is de huidige EOBD technologie die in voertuigen aanwezig is geschikt als alternatieve testmethode in de APK?
De huidige EOBD technologie die in alle voertuigen verplicht wordt toegepast biedt onvoldoende mogelijkheden voor een APK-test omdat de voertuigen niet over de benodigde PM of PN sensoren beschikken. Daarnaast wordt het EOBD systeem gemanipuleerd als het roetfilter wordt verwijderd.

Welke alternatieve test is geschikt als APK-emissietest voor dieselvoertuigen met roetfilter?
Een alternatief voor de vrije acceleratie rookemissietest die in de APK wordt toegepast is een test bij stationair toerental waarin de deeltjesaantallen (PN)-emissie wordt gemeten. Deze test wordt uitgevoerd met een opgewarmde motor en bij stationair toerental. Deze PN emissie bij stationair toerental blijkt een goede relatie te hebben met de PN-emissie in een NEDC test op de rollenbank (zie Figuur 1) en een minder goede relatie met de PM emissie.



Figuur 1: PN emissies bij stationair toerental en NEDC emissietesten van drie verschillende voertuigen met (defect) roetfilter of variabele bypass.

Welke deeltjesteller is geschikt als APK meetinstrument?
Mobiele deeltjestellers worden nu al toegepast voor de controle van roetfilters in de Zwitserse tunnelbouw. Deze gecertificeerde PN-meters zijn echter te duur voor de APK-praktijk en daarom is het gewenst een eenvoudigere PN-meter te ontwikkelen. Vooralsnog ziet het er naar uit dat voor het testen van roetfilters in de APK eenvoudigere en daardoor goedkope PN-tellers kunnen worden gebruikt. Hiervoor

is door een groep van wetenschappers en fabrikanten van meetinstrumenten een eerste voorlopige specificatie gedefinieerd.

Welke PN limietwaarden kunnen in een APK-emissietest worden gehanteerd?
Gezien de verschillende PM en PN limietwaarden in de typegoedkeuringstest voor Euro 5a en Euro 5b/6 voertuigen zijn verschillende PN limietwaarden in de APK-test een optie. In alle gevallen zal de limietwaarde voor een APK test minder streng moeten zijn dan In Service Conformity eisen die in de typegoedkeuring worden toegepast. De limietwaarde voor Euro 5b/6 voertuigen zou in een APK-test bij stationair toerentallen kunnen liggen op 250,000 #/cm^3 en voor Euro 5a voertuigen zal deze kunnen liggen rond de 1,000,000 à 1,500,000 #/cm^3. Deze limietwaarde kan ook worden gebruikt voor Euro 3 en Euro 4 voertuigen met een DPF.

Is deze nieuwe APK-PN-emissietest ook geschikt voor benzinemotoren?
Gezien de geheel andere uitlaatgassamenstelling van benzinemotoren dat relatief veel water bevat en het emissiegedrag van benzinemotoren is de nieuw te ontwikkelen PN-tester voor dieselmotoren niet geschikt voor benzinemotoren.

Aanbevelingen
In dit project is een nieuwe APK emissietest ontwikkeld voor dieselvoertuigen met roetfilter. Deze emissietest kan worden uitgevoerd met een eenvoudige PN-tester voor APK doeleinden die op verschillende voertuigen met roetfilters in verschillende condities gevalideerd moet worden.

Hoe kan de nieuwe APK-emissietest worden vastgelegd in de wetgeving?
De nieuwe testprocedure voor deze APK-emissietest is gemakkelijk in wetgeving vast te leggen omdat de huidige UNECE R83 type II test voor benzinevoertuigen (die ook wordt toegepast in de APK) zeer veel overeenkomsten heeft met deze voorgestelde nieuwe APK-test.

Vanwege het beperkte meetbereik van deze nieuwe PN-tester wordt geadviseerd de huidige rookemissietest voor voertuigen die niet zijn uitgerust met een roetfilter te handhaven.

Summary

Background
Wall flow diesel particulate filters (DPFs) are a very effective means to reduce emissions of soot particles in the exhaust gases of diesel cars. In 2002, diesel particulate filters made their appearance on the Dutch market for passenger cars and diesel particulate filters are used on a large scale since 2007, due to a fiscal stimulus. European Euro 5 and Euro 6 standards have meant that DPFs are now being applied to all new passenger diesel cars (since 2011) and diesel vehicles (since 2012). However, in 2014, research conducted by TNO and RDW shows that for approximately 5 to 7 % of diesel passenger cars with an DPF, the particulate filter was removed or defect.

It is known that possible losses in filtration efficiency or removal of DPF's significantly affect real-world PM emissions [2]. In first studies [3,4] at least 21 of the 355 assessed Dutch vehicles with a DPF (6%) showed elevated smoke emissions with a k-value higher than 0,3 m^{-1}. Another concern of PTI (Periodic Technical Inspection) DPF investigations is the quality (methodology) of the smoke emission test and the relation with real world PM&PN emissions [6], [7].

In this research study the current PTI smoke emission test procedure is assessed and alternative PTI test procedures are investigated.

Aim and approach
The Ministry of Infrastructure and the Environment asked TNO to investigate current and future PTI test methods and to obtain more reliable emission data as a basis for determination of emission limit values for periodic technical inspections (PTI). In this report the results of this project are described.

Within this project 14 light-duty vehicles were tested by TNO using different test procedures. The vehicles were Euro 3,4, 5 and 6 class vehicles. The test results were used to design and propose a new roadworthiness emission test procedure able to identify vehicles with a malfunctioning or removed DPF. A new test procedure is required because generally, the current PTI / roadworthiness test procedure is not able to identify such failures.

The 14 light-duty vehicles were subjected to different tests:

1. Free acceleration and high idle smoke emission tests with two opacimeters;
2. Idle speed emission test with different particulate number meters;
3. Chassis dynamometer tests.

Conclusions

What can be reported about the current smoke emission test procedure?

- The current PTI smoke emission test was developed in the fifties of last century. Generally diesel vehicles emit certain smoke emissions which don't correlate with real world PM&PN emissions[1]. In last decade diesel vehicles were

[1] Demonstrated in this and in earlier programs

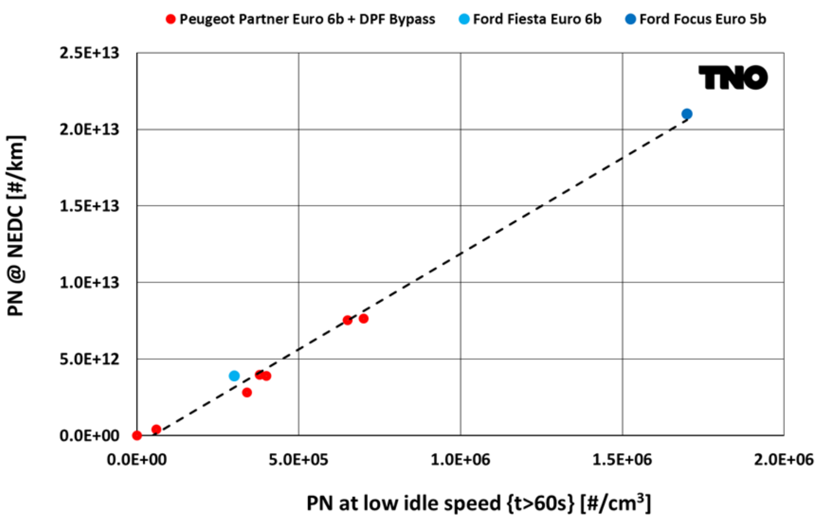
equipped with DPF's and their smoke emissions are near zero. Smoke testing became irrelevant because all emission tests yield the same result, 0,00 m^{-1}. However in case of a removed or cracked DPF (some) smoke emission can be measured.

- The quality of a smoke emission test results is poor. Current smoke emission signals are mandatory filtered and insensitive. Moreover the accuracy of current PTI smoke meters is +/- 0.3 m^{-1} which results in poor readings below 0.3 m^{-1}.
- Furthermore the reproducibility of a smoke emission test is not well defined because for every free acceleration test the accelerator should be pressed to the bottom in 1 second (which is not monitored). Smoke emissions are very dependent on this activation time of the accelerator.
- Finally the smoke emission test can be manipulated if high quality fuels are applied. I.e. GTL diesel fuel consists mainly of paraffin's which yield less smoke than a regular EN590 trade fuel.

What are the general requirements for a new PTI test?
Alternative PTI emission test should be based on
- engine and after treatment technology and fuel type;
- the type of emission test;
- the type of measurement;
- the emission limit value.

What is the potential of EOBD technology for the PTI?
Current EOBD technology is not suitable for judgements of DPF's in PTI tests because vehicles are not equipped with PM or PN sensors.

Which alternative test is suitable for the PTI?
A PN emission test at low idle speed with a hot DPF is suitable for PTI purposes. This PN emission correlates well with the PN emission in an NEDC test on the chassis dynamometer (see Figuur 2), the correlation with PM is less good.



Figuur 2: PN emissions at low idle speed and NEDC tests of 3 different diesel vehicles with (cracked) DPF or variable bypass.

Which PN-tester is suitable for the PTI?
Current mobile PN-testers are accurate but too expensive for most PTI workshops. An expert group of scientists and equipment manufacturers has drafted new specifications for a lower cost PTI-PN-tester. These new PTI-PN-testers can be engineered, built and validated.

Which PN limit values must be applied in the PTI?
The different type approval PM and PN limit values of Euro 5a and 5b/6 diesel vehicles require also different PN limit values in a new PTI-PN-test. In all cases the PTI PN limit value must be less stringent than the In Service Conformity limit values which are applied in the type approval test procedure. A suitable PTI-PN limit value for Euro 5b/6 vehicles might be 250,000 #/cm3 and the limit value of Euro 5a vehicles might be in the range of 1,000,000 – 1,500,000 #/cm3.

Can this new PTI-PN test procedure be applied in petrol vehicles?
The exhaust gas composition of petrol engines deviates strongly from diesel exhaust gas and a new simplified PN-tester for diesel vehicles cannot be applied to petrol vehicles.

Recommendations
In this project a new PTI emission test with mobile Particulate Number test equipment has been developed. Based on these results a very simple PN-tester for PTI purposes has been specified. It is recommended to validate dedicated PN meters for PTI purposes on different brands of diesel vehicles with different DPF leakages, and establish a reasonable limit value. In order to be able to measure higher PN concentrations, sample dilution with a factor 10 is advised.

A new PTI-PN-test procedure can easily be implemented in the current UNECE R83 type II test because a low idle speed test for petrol engines is already in use in the PTI. Additionally it might be considered to remove the traditional smoke emission tests from UNECE R24 and 72/306/EC.

Due to the restricted measuring range of this new PN-tester it is recommended to stick on the current free acceleration test with opacimeter for vehicles without DPF.
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Contents

1 Introduction

1.1 Backgrounds

1.1.1 Policy background

Since 10 years Diesel Particulate Filters (DPF's) have been mounted in large numbers on vehicles with diesel engines and the long term experiences with this technology are now available. From an air quality perspective, it is important that the presence and proper functioning of the DPF of a vehicle is adequately secured during the car's operational lifetime.

With respect to the DPF, its regeneration process and the use of the vehicle, there are some concerns. Not all conditions under which the vehicle is used (especially in case of low vehicle speeds) are suitable for the regeneration process of the DPF. The consequence is that a part of the vehicle users decide to remove the DPF. Particulate Matter (PM) emission levels of DPF equipped vehicles are extremely low. Currently there is no adequate legal PTI test procedure for judgement of the performance of the DPF.

Therefore, the Ministry of Infrastructure and the Environment asked TNO to perform research towards the design of a PTI test procedure that enables PTI inspectors to determine whether a DPF is present and functioning well.

1.1.2 Technical background DPF's and emission limit values

Engines of modern vehicles cannot meet current legislative emission levels. Use of exhaust after treatment systems such as catalysts and PM-filters (see Figure 1) with high reduction performances (up to 99%) is required to fulfil these legislative emission levels. Consequently the emission performance of a vehicle is mainly determined by the performance of these after treatment technologies. All vehicle categories must comply with the legal emission limit values in their legal defined life cycle (i.e. 160,000 km).

In order to meet particulate matter (PM) emission limit values modern diesel vehicles are equipped with a Diesel Particulate Filter (DPF). DPF's are a very effective means of reducing PM emissions: when functioning well, DPF's are able to reduce the PM emissions to practically zero.

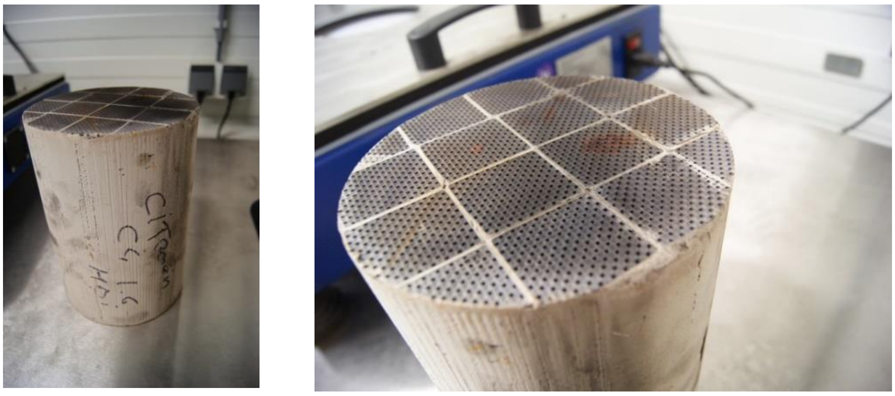


Figure 1: A deinstalled DPF, in this case originating from a Citroen C4 (left). Whereas DPF's vary in size and shape, the height of this DPF is approximately 20 cm; its radius is about 10 cm. A DPF is installed in the exhaust pipe of the vehicle. The zoom-in at the right clearly shows the channels designed to trap the particles.

Since 2011, next to a PM emission limit, a PN limit value for DPF-equipped vehicles is applied (Euro 5b). The exact determination of actual PM & PN emissions is only possible by performing measurements with a chassis dynamometer with a dilution tunnel. This sophisticated, expensive technique is available in specialised laboratories but is not available for everyday roadworthiness checks in service shops.

Table 1 shows an overview of type approval emission limit values.
In addition to emission legislation, roadworthiness tests or Periodic Technical Inspections (PTI's) have been prescribed to check the levels of some type of vehicle emissions in the course of a lifetime of a vehicle. The current PTI emission test or 'free acceleration test' for diesel engines was introduced in 1958, long before the introduction of DPFs, as a type approval test.
For verification of the smoke emission of vehicles in roadworthiness tests, the UNECE R24 free acceleration test was selected in which the peak smoke emission or opacity is determined. In general, no correlation between PM/PN emissions and smoke emission exists.

Table 1: PM and PN emission limit values of light-duty passenger cars.

		Type approval limit values		
Emission class	Entry into force	Particle Mass (PM) Diesel	Particle Number (PN) Diesel / Petrol	Most applied Exhaust after treatment Technology Diesel / Petrol
		[mg/km]	[#/km]	
Euro 1	1993	140	-	No / TWC
Euro 2	1996	80	-	No / TWC
Euro 3	2000	50	-	DOC / TWC
Euro 4	2005	25	-	DOC / TWC
Euro 5a	2009	5,0	-	DPF / TWC
Euro 5b	2011	4,5	6,0 * E11 / -------------	DPF / TWC
Euro 6b	2014	4,5	6,0 * E11 / 6,0 * E12	DPF / TWC
Euro 6c	2017	4,5	6,0 * E11 / 6,0 * E11	DPF / GPF

In type approval and roadworthiness free acceleration tests, the smoke emissions of diesel vehicles are determined with opacimeters with a so-called k-value, which has a range of 0 - 10 m^{-1}. Due to production variation of diesel engines the smoke emission in free acceleration tests also has a certain variation. Therefore, a margin of 0.5 m^{-1} is added to the measured type approval smoke emission. For example, an engine with a measured k-value of 0.04 m^{-1} will be registered with a plate value of 0.54 m^{-1}. In roadworthiness tests the plate value of this vehicle is valid and the measured smoke emission may not exceed a value of 0.54. Nowadays the margin of 0.5 m^{-1} is relative high in relation to the measured smoke values. The reason for this is that the 0.5 m^{-1} margin originates from some decades ago at a time when diesel cars were not equipped with DPF's and smoke emissions levels were in the order of 1,5 à 2,5 m^{-1}.
The maximum allowed smoke emission limit plate values are reported in Table 2.

Table 2: Maximum allowed smoke emissions of LD diesel vehicles in free acceleration tests over the years.

	Year	Maximum allowed k-value [m^{-1}]
With turbocharger	1980	3,0
Without turbocharger	1980	2,5
All diesel vehicles	2008	1,5
All diesel vehicles	2018	0,7

Diesel vehicles equipped with a DPF have very low smoke emissions, with k-values typically not exceeding 0,05 m^{-1} [4] . Consequently test equipment and test procedures that are currently used in PTI[2] testing are not capable of adequately measuring these low smoke emission levels of modern DPF-equipped diesel vehicles.

Furthermore, the applied procedure for determination of the plate value does not match the smoke emission levels of diesel vehicles with a DPF.

Little is known on the actual PM emissions of modern diesel cars in operation. Moreover, there have been indications of DPF's being removed or replaced by dummies to avoid maintenance, cleaning or replacement costs. Also, in some case, DPF's are removed as part of chip tuning of the engine. In case of DPF removal, the DPF is also 'removed' from the car's software, so that DPF removal cannot be detected in a PTI.

In the past several research projects and field tests for the development of new roadworthiness emission tests [1], [2], [3], [4], [5], [6], [7] were performed. Most of these experiments were carried out with opacimeters in so called free acceleration or increased engine idle speed tests. The overall conclusion of these experiments is that diesel vehicles with DPF must be tested in roadworthiness tests or PTI's by means of a free acceleration test and with an improved opacimeter. CITA [5] proposes a pass/fail limit k-value of 0.20 m^{-1}. This very low proposed limit value of 0.20 m^{-1} evokes a fundamental question: What is the quality of a free acceleration test result with such low smoke emissions? In this report a detailed assessment of the UNECE R24 smoke emission test procedure is carried out. Secondly a new Particulate Number (PN) test procedure is further investigated and proposed.

[2] PTI is a Periodic Technical Inspection or roadworthiness test

Investigations into alternative test procedures with PN-testers were earlier reported by TNO in [6], [7], [8].

1.2 Objectives and approach

The objectives of the research presented in this report are:

1. Detailed investigation and assessment of the UNECE R24 opacity test procedure and sensitivities;
2. Investigation of the potential of a Particulate Number test (procedure) for vehicles with particulate filter in a PTI;
3. Determination of a PTI PN emission limit values, and, subsequently;
4. To advise on a new PTI procedure capable of detecting cars with a removed or faulty DPF.

To this end, TNO performed various opacity measurements using two types of opacimeters or smoke meters. To get indicative results on the particulate number emissions of the cars, tailpipe tests were performed using (handheld) particle counters.
The tests were performed on a total of 10 diesel cars (7 trade marks) and 4 petrol cars (4 trade marks). Test cars were rented or kindly made available by private owners. For determination of PM&PN emissions five vehicles were also tested on a chassis dynamometer.

In order to create stable test results the measurements were carried out by a fixed test team in December 2016 and January of 2017. In this project the team members had defined and fixed tasks.

1.3 Project Partners

Measurement equipment and assistance was kindly made available by TEN Automotive Equipment, Testo SE & CO. KGaA and TSI / J.J. Bos BV.

1.4 Structure of this report

In this report vehicle emission test activities are the basis for the assessment of the current PTI smoke emission test procedure and investigations of new PTI emission test methods. The basic elements of the test programme are described in Chapter 2. In Chapter 3 a detailed assessment of the current PTI smoke emission test procedure is carried out. Chapter 4 describes investigations of potential new PTI test methods. Conclusions and recommendations are given in Chapters 5 and 6.

2 Test programme

In this research project different emission test procedures with different vehicles and test equipment were performed. In the next section more details of this test programme are specified.

2.1 Test protocols

2.1.1 Chassis dynamometer tests according to UNECE R83

Emission tests on the chassis dynamometer with six diesel vehicles were executed according to a standard protocol [7]. Special attention was given to the PM and PN test results in NEDC tests with cold and hot start. Before every NEDC test with a cold start the 3*EUDC preconditioning cycle was carried out.

2.1.2 Smoke emission test according to UNECE R24

All diesel vehicles were subjected to free acceleration smoke emission tests. Two different smoke meters were mostly applied at the same time. Special attention was given to emission tests in Mode A and B (unfiltered and filtered electronic measuring signals) and to different sample frequencies 2,5,10 and 20 Hz. Furthermore tests were carried out with different Accelerator pedal activation times. Special attention was paid to tests with different fuels and fuel additives.

2.1.3 Particulate Number tests at different engine speeds with unloaded engine

Particulate Number tests in raw exhaust gas for vehicles with an unloaded engine are new. In this project many investigations were carried out obtaining data of the PN emission behaviour of petrol vehicles (IDI and DI) and diesel vehicles with (cracked) DPF. The first proposals for a new PTI-PN emission tests are based on these test results.

2.2 Test equipment

2.2.1 Smoke meters

In Table 3 the specifications of the two applied opacimeters are reported.
In Figure 2 a PTI test set up with the two opacimeters is shown

Table 3: Specifications of TEN EDA2 and LPA smoke meters in this project.

Tester	**TEN**	**TEN**
Name	EDA2	LPA
Principle	Opacity (k)	Opacity (k)
Measuring unit	[m^{-1}]	[m^{-1}]
Measuring range	0 - 10	0 - 10
Maximum reading	10	10
Resolution	0.01	0.001
Minimum measurement value	0.01	0.001
Size range [nm]	n/a	n/a
Applied measurement frequency [Hz]	2 and 5	2,5,10 and 20
Accuracy [m^{-1}]	+/- 0.3	+/- 0.1
Response time T95 [s]	n/a	n/a
Sampling line	Non heated	Non heated
Sample pump	No	No
Sample flow [cm^3/min]	-	-

Figure 2: PTI test set up free acceleration smoke emission test with the two applied opacimeters.

2.2.2 *Particulate Number Counters*

In Table 4 an overview of the specifications of the applied PN counters is shown.

Table 4: Specifications of the Testo and TSI Particle Counters used in this project

Tester	**Testo**	**TSI**	**TSI**	**TSI**
Name	PEPA	-	P-Trak	NPET
Type number	-	3007	8525	3795
Principle	Charging	Condensation + laser	Condensation + laser	Condensation + laser
Measuring unit	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]
Minimum reading	1,000	1	1	10,000
Maximum reading	5,000,000	100,000	500,000	50,000,000
Resolution	1	1	1	1000
Dilution ratio	10	-	-	100
Particle size range [nm]	23 - 1000	10 – 1,000	20 – 1,000	23 – 1,000
Measuring frequency [Hz]	1	1	1	1
Accuracy [m^{-1}, %]	+/- 20%	+/-20%	+/-20%	+/-10%
Response time T90 [s]	< 3	< 9	8	8
Sampling line	Steel pipe + plastic hose	Rubber hose	Steel pipe + plastic hose	Steel pipe + hose
Sample pump	Yes	Yes	Yes	Yes
Sample flow [cm^3/min]	1000	700	700	700
Flow meas. Cell [cm^3/min]	≈100	100	100	100
Bypass flow [cm^3/min]	None	600	600	600

TSI 3795 (NPET)

Testo PEPA

TSI 3007

TSI 8525 (P-Trak)

2.3 Test samples

The selection of the test samples was based on specific vehicle condition properties such as: fuel, fuel injection type, with/without DPF, specific DPF failures, rather new as well as used samples. An overview of the test samples is given in Table 5 and detailed specifications are reported in Appendix A.

Table 5: Tested vehicles.

No.	Trade Mark & Type	Fuel	Euro Class	Odometer [km]	Typics	Chassis Dyno test
1	Ford Focus	Diesel	5a	155,082	DPF*	Y
2	Ford Focus	Diesel	5a	160,200	DPF*	Y
3	Ford Focus	Diesel	5b	39,400	DPF*	Y
4	Ford Fiesta	Diesel	6b	29,000	DPF*	Y
5	Volvo V40	Diesel	5b	92,315	DPF*	Y
6	Peugeot Partner	Diesel	6b	21,000	DPF**	Y
7	Peugeot 308	Diesel	6b	104,755	DPF	N
8	Seat Ibiza	Diesel	3	330,000	-	N
9	Peugeot 307 SW	Diesel	3	261,000	-	N
10	VW Passat	Diesel	3	425,000	-	N
11	Citroen C8	Petrol	3	201,000	IDI	N
12	Fiat Punto	Petrol	4	91,000	IDI	N
13	Peugeot 5008	Petrol	5	110,252	DI	N
14	Ford Focus	Petrol	5	139,592	DI	N

*DPF with failure

** DPF with variable bypass flow rate for simulation of DPF leakage

2.4 Fuels and fuel additives

Except one vehicle all vehicles were tested with EN590 diesel trade fuel or EN228 petrol trade fuel. One vehicle was investigated with two EN590 fuels (regular diesel fuel and a premium diesel fuel) and GTL[3]. The specific parameters of these applied fuels were not tested/determined.

In three different vehicles smoke emissions were investigated with in total four fuel additives. In Table 6 and Figure 3 some data of the additives are reported. Not all tested vehicles were tested with all fuel additives and as a result of this the test results with the different additives are anonymously reported.

Table 6: Fuel additives with claim of reduction of smoke emission.

Trade Mark	Bardahl	Forté	Wynn's	Wynn's
Type	Diesel Treatment	Advanced Diesel Fuel Conditioner	Diesel+ Plus+	Diesel Power 3
Article no.	13102	44417	51663	50392
Content [ml]	300	400	325	500
Recommended dosing ratio	~200	~250	~150	~100

Figure 3: Fuel additives.

[3] GTL (Gas To Liquid) is a high quality diesel fuel with a paraffinic molecule structure and made from natural gas.

3 Assessment of the current PTI smoke emission test procedure

3.1 Introduction and legislation

In order to control the emission performance of vehicles a defined test procedure is required. For diesel engines it all began with the development of a smoke emission test. In 1958 UNECE launched Regulation 24 that defines a test method for determination of smoke emissions of diesel engines.

In Figure 4 a picture of a vehicle with excessive smoke emission is shown.

Figure 4: Example of excessive black smoke emission of a diesel engine.

Smoke emissions should be measured with an opacimeter in a static full load test on an engine test bed and in an unloaded dynamic test. The black smoke emission (or opacity) has been regulated by means of specific limit values in both tests, the measuring unit of opacity (k) is m^{-1}. The dynamic test result is only a simple engine quality check of the engine and doesn't represent real world emissions.

Both tests must be executed on an engine test bed whereas the free acceleration test can also be applied for simple engine quality checks in the field (i.e. workshops). In this study the static smoke emission test procedure is not investigated because it has no direct relation with a PTI.

In 1970 the type approval smoke emission of European engines of on-road vehicles was regulated in Council Directive 72/306/EEC.
In 1996 the Periodic Technical Inspections (PTI) of light-duty vehicles with the free acceleration smoke emissions was regulated in Council Directive 96/96/EC.
Upfront of this legislation some member states introduced PTI's around 1985.

3.2 Description of the UNECE R24 smoke emission test procedure

Natural aspirated diesel engines without DPF tend to smoke at full load conditions and during accelerations caused by a temporary lack of air or a poor fuel injection spray. Regulation 24 of the UNECE was set up to measure the smoke emissions of diesel engines at these conditions.

In the type approval test, the static test procedure under full load conditions at several engine speeds is executed on an engine test bed which can load the engine; This test has a duration of approximately 30 minutes. In addition to this static test the engine is disconnected from the engine dynamometer and a dynamic free acceleration test with the unloaded engine is carried out.
In both tests the same opacimeter is connected to the exhaust of the engine which measures the black smoke emission.

The dynamic free acceleration smoke emission test is applied in type approval tests of diesel engines as well as in periodic technical inspections (PTI).

The dynamic free acceleration smoke emission tests
The dynamic smoke emission test or free acceleration test is carried out with an unloaded engine. After warming up of the engine the speed accelerator is activated within 1 second and consequently the engine ramps from low to high idle speed; during the engine speed ramp the peak smoke emission is measured.
In Figure 5 an example of a smoke emission test result with 8 free accelerations is shown, the average peak smoke emission is 0.07 m^{-1}.

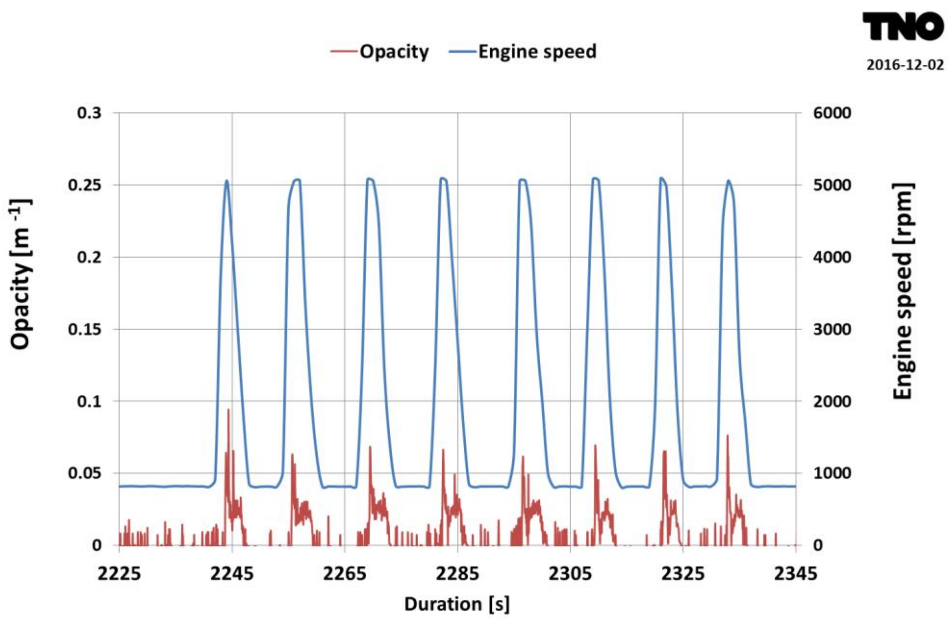


Figure 5: Free acceleration tests and measured smoke emissions of a Euro 6 LD-vehicle.

This measured peak smoke emission expresses the quality of the combustion at a very restricted operating window. For LD-engines without DPF the peak smoke emission is in the range of 0.30 to 2.50 m^{-1}.
Since the introduction of DPF's this smoke emission is reduced to zero (0.00) because a DPF has a very high filtration efficiency (>99%). Consequently the suitability of the dynamic smoke emission test procedure for DPF equipped vehicles must be investigated.

This assessment deals with the opacimeter, the execution of the smoke emission test, its sensitivities and robustness.

3.3 Opacity and the accuracy of the smoke emission tester or opacimeter

UNECE R24 applies the principle of opacity in a smoke emission test with an opacimeter. An opacimeter is an instrument for continuous measurement of the light absorption coefficients of the exhaust gases emitted by vehicles. The smoke emission is expressed in the so-called 'k-value' on a scale from 0-10 m^{-1}.
For type approval purposes the characteristics or detailed specifications of an opacimeter are described in ANNEX VII of UNECE R24. However the requirements of PTI smoke meters are specified in national legislations and they can differ per member state.

As already mentioned, nowadays diesel vehicles are equipped with particulate filters and their regular smoke emissions are negligible (near 0.00 m^{-1}). In order to assess the current smoke emission test procedure for current diesel vehicles a further investigation of the most relevant characteristics of the opacimeter is carried out.

3.3.1 Definition of accuracy of the smoke meter

In UNECE R24 the accuracy of the smoke meter is not directly defined but from a few statements a certain accuracy can be derived.

These are:

> *3.5.3 . The indicating dial of the opacimeter shall enable an absorption coefficient of 1,7 m^{-1} to be read with an accuracy of 0,025 m^{-1}.*
> *3.6.3 . An intermediate check shall be carried out by placing in the smoke chamber a screen representing a gas whose known light-absorption coefficient k, measured as described in item 3.5.1 , is between 1,6 m^{-1} and 1,8 m^{-1}. The value of k must be known to within 0,025 m^{-1}. The check consists in verifying that this value does not differ by more than 0,05 m^{-1} from that read on the opacimeter indicating dial when the screen is introduced between the source of light and the photoelectric cell.*
> *3.9.1 . At every point in the smoke chamber the gas temperature at the instant of measurement shall be between 70 °C and a maximum temperature, specified by the opacimeter manufacturer, such that the readings over this temperature range do not vary by more than 0,1 m^{-1} if the chamber is filled with a gas having an absorption coefficient of 1,7 m^{-1}.*

The details of the required accuracy are visualised in Figure 6.

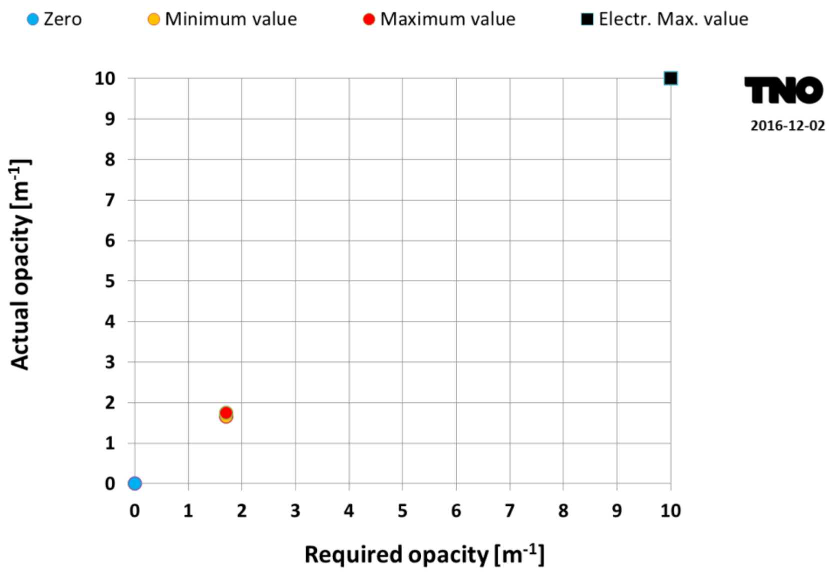


Figure 6: Specification of the accuracies of the opacimeter of UNECE R24. The accuracy of an opacimeter is only defined at a smoke emission value of 1.7 m^{-1}. No requirements for linearity over the total measuring range are specified.

The accuracy of the opacimeter (+/- 0.05 m^{-1}) is specified only at a smoke emission of 1.7 m^{-1}. Hence most readings below or above 1.7 m^{-1} are not well defined, they cannot be related to a calibrated value because the linearity of the full scale (0.00 – 10.00) is not specified.
If the accuracy of +/- 0.05 m^{-1} is applied to a reference smoke emission of 0.10 m^{-1}, which is currently a very common value and the accuracy of the smoke indicator is +/- 0.025 the measured smoke emission is in the range of 0.025 to 0.175 m^{-1}.

For PTI purposes less accurate smoke meters are specified. The common accuracy of the PTI opacimeter is +/- 0.3 m^{-1}. For engines without DPF and a smoke emission in the range of 0.5 – 2.0 this is acceptable. However for DPF equipped vehicles the smoke emissions are mostly far below 0.30 m^{-1} and consequently from measuring scale and accuracy perspective the current PTI smoke meter does not match with the smoke emissions of these vehicles.

> The current UNECE R24 specifications of opacimeters are very poor; The single specified accuracy of +/- 0.05 m^{-1} @ a smoke emission of 1.7 m^{-1} is not suitable for detection of DPF's with a failure because the linearity of the total measuring scale is not specified. Current PTI opacimeters are even less accurate (+/- 0.3 m^{-1}) and are not designed to measure low smoke emission values accurately.

3.4 Dynamic characteristics of the opacimeter

According to UNECE R24 all type approved smoke meters must meet certain requirements. However, the different smoke meters of the different manufacturers are not equally built and have different dynamic characteristics.
The dynamic characteristics and parameters of an opacimeter are mainly determined by:

- the length and volume of the sample hose,
- application of a sample pump or natural sample flow caused by a pressure difference,
- the size of the sample flow,
- the volume, dimensions and geometry of the measuring chamber and tubes,
- The electronic filtering of the measuring signal.

The total combination of the listed parameters of a opacimeter should meet a certain required dynamic response behaviour.
The required response time of the opacimeter, the characteristics of the electrical measuring circuit and the damping characteristics of the measuring signal are defined in the UNECE R24 articles 3.7.1. to 3.7.3.

3.7.1. The response time of the electrical measuring circuit, being the time necessary for the indicating dial to reach 90 per cent of full-scale deflection on removal of a screen fully obscuring the photoelectric cell, shall be 0,9 to 1,1 second.
3.7.2. The damping of the electrical measuring circuit shall be such that the initial overswing beyond the final steady reading after any momentary variation in input (e.g. the calibration screen) does not exceed 4 per cent of that reading in linear scale units.
3.7.3 . The response time of the opacimeter which is due to physical phenomena in the smoke chamber is the time between the entry of the gas into the measuring apparatus and the complete filling of the smoke chamber-; it shall not exceed 0,4 second.

These parameters heavily influence the smoke emission test result and seem to be of major importance. So a further detailed investigation is needed.

In order to create a common platform for all instrument manufacturers the electric measuring signals of the instruments are filtered in such a way that a defined dynamic measuring behaviour of the opacimeter is created; In fact the dynamic characteristics of the reference instrument (Hartridge opacimeter) must be copied. So electrical filtering of the measuring signal is needed for compensation of the different dynamic flow characteristics of opacimeters of the different manufacturers. Consequently current opacimeters can measure in two modes. Mode A delivers unfiltered measuring results without electronic signal filtering and Mode B yields filtered measuring signals. All type approval and PTI tests are executed in Mode B.

In Figure 7 an example of smoke emissions (mode B and A) in eight free accelerations tests is shown. The tests in both modes are carried out with the same vehicle in two consecutive test runs. The average filtered opacity result is 0.11 m^{-1} and the unfiltered result is 0.40 m^{-1}. In Figure 8 both signals are (time aligned) plotted and the effect of signal filtering is visualised.
Due to this filtering (with a time constant of approximately 1 second), in Mode B the initially very fast and sensitive measurement output signal of Mode A becomes relatively insensitive and slow.

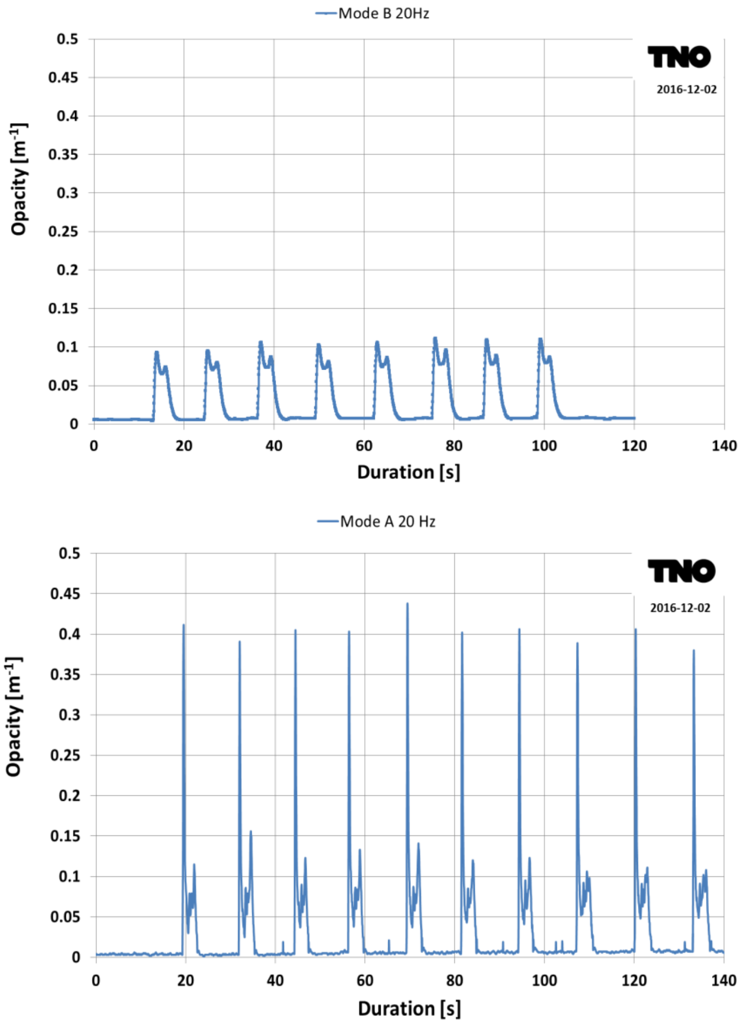


Figure 7: Examples of results of free acceleration smoke tests (Mode B and A).

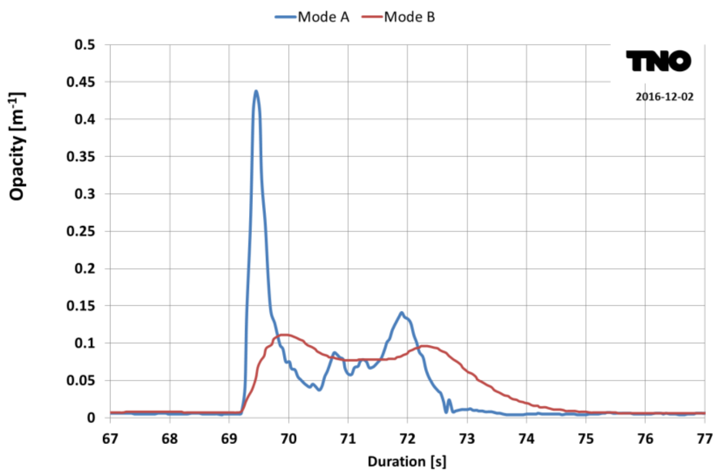


Figure 8: Unfiltered (Mode A) and filtered (Mode B) measuring signals of free acceleration tests with the same vehicle. For reasons of comparisons the signals are time aligned.

From these results it is obvious that filtering of electronic measuring signals creates the possibility to generate reproducible results over several test set ups with different smoke emission testers. However the test results are not representative because the main upper part of the measuring signal is removed in Mode B.

Current opacimeters are relatively insensitive:
In order to generate reproducible smoke emission values in dynamic emission tests with different opacimeters the measuring signals of current opacimeters are damped with an electronic filter (the so called ‘Mode B’); This results in a strong loss of sensitivity of the opacimeter and reduced smoke emission values.

3.4.1 *Assessment of the potential of a smoke emission test procedure with an opacimeter with unfiltered measuring signals (Mode A)*

For further optimisation of the smoke emission test procedure one could argue to adapt the procedure by measuring with unfiltered measuring signals (Mode A).

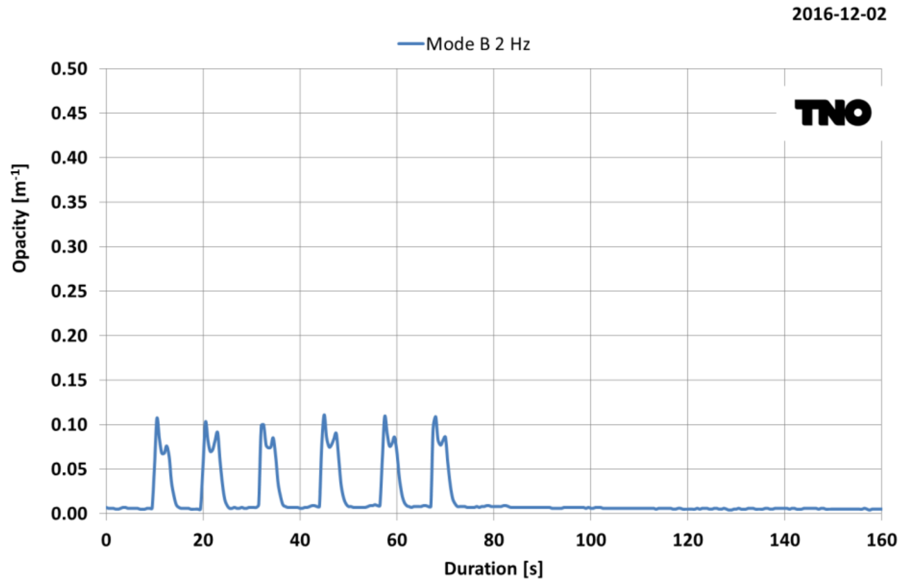
In Table 7 and Figure 10 and Figure 10 free acceleration smoke tests in Mode B and A with different sample frequencies are shown. Varying the measuring frequency in Mode A from 2 to 20 Hz generates very different results. Basically the opacimeter with the optical measuring principle is very fast and this requires a high measuring frequency (at least 10 Hz but preferably 20 Hz). Note: the sample frequency of the opacimeter is 50 Hz.
Due to the applied signal filtering in Mode B the measuring frequency has no influence on the test result.

Table 7: Free acceleration smoke test results (Mode A and B) of a Euro 6 vehicle with different sample frequencies.

Mode	No. of tests	Measuring frequency	Smoke average	Smoke st. dev.
	[-]	[Hz]	[m^{-1}]	[m^{-1}]
A	10	20	0.40	0.02
A	9	10	0.40	0.01
A	10	5	0.35	0.04
A	11	2	0.24	0.11
A	11	20*	0.40	0.02
B	6	2	0.11	0.00
B	8	20	0.11	0.01

*repeatability check of first measurements

Apart from the high measuring frequency, the potential opacimeters of different manufacturers must yield equal results in Mode A; With regard to dimensions of the opacimeter (i.e. the measuring chamber and inlet and outlet channels) and test set up and sample conditioning, measuring with unfiltered measuring signals requires a fully defined opacimeter and test set up because the dynamic response must be fixed. Facing the European situation with different instrument manufacturers and different PTI workshops this is not feasible.



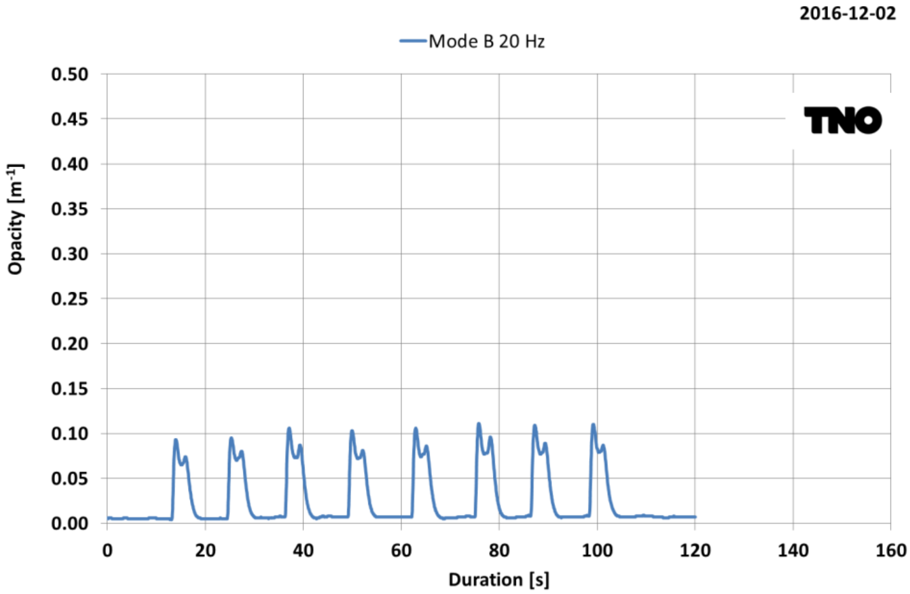


Figure 9: Free acceleration smoke emission test results (Mode B) of a Ford Fiesta Euro 6 diesel vehicle with a small DPF leakage with different sample frequencies (2 and 20 Hz).

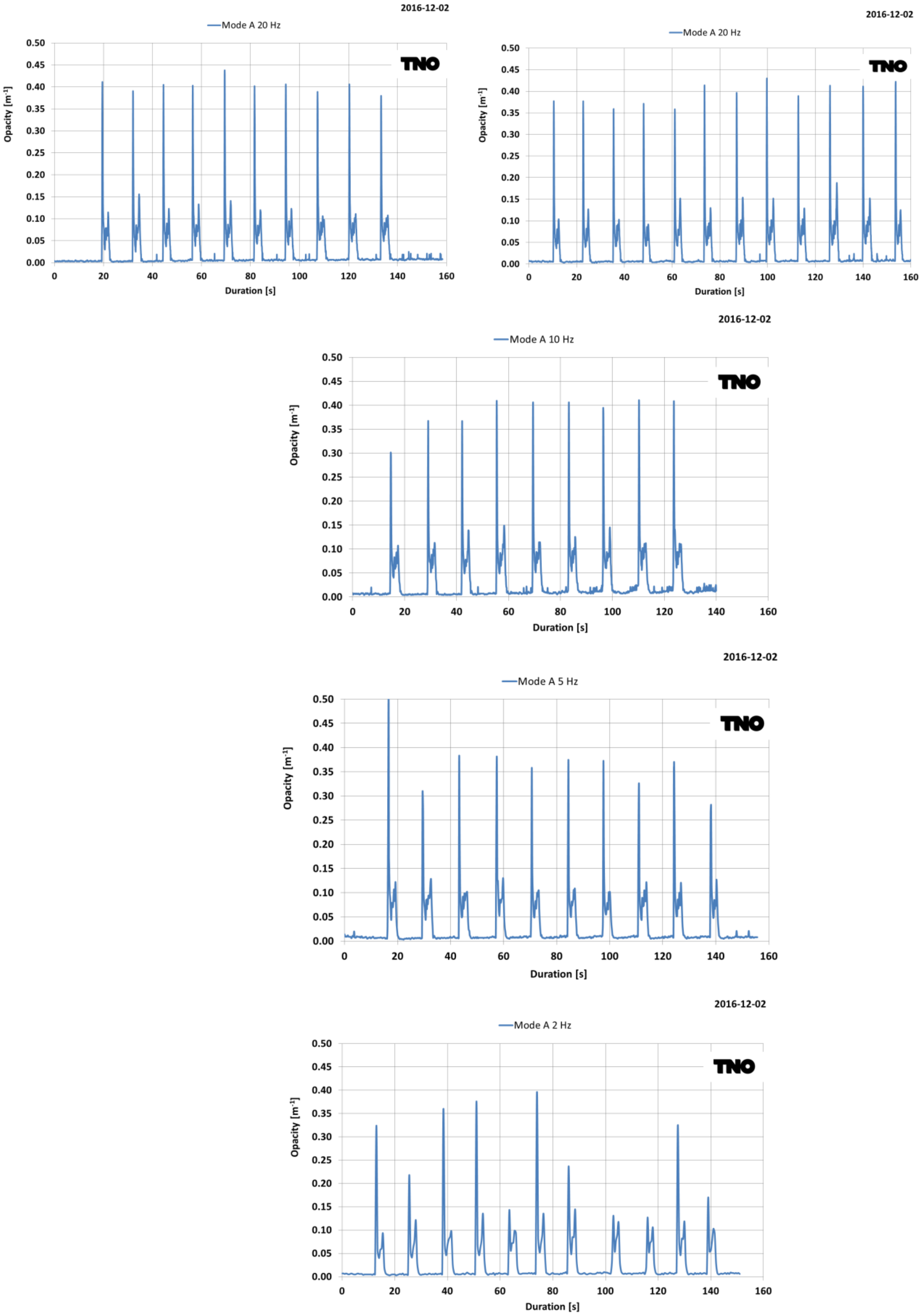


Figure 10: Free acceleration smoke emission test results (Mode A) of a Ford Fiesta Euro 6 diesel with a small DPF leakage with different sample frequencies (20, 10, 5 and 2 Hz).

For detection of faulty DPF's the sensitivity of the current opacimeters with filtered measuring signals is too low. An increase of this sensitivity might be realized by removal of the signal filtering. Consequently a clear detailed definition and specification of the dynamic response behaviour of the new opacimeter is required which will result in a substantial development effort for all manufacturers of test equipment. Moreover these more stringent specifications will increase the price of an opacimeter substantially. Finally, free acceleration tests still can be manipulated which is described in section 3.6 of this report.
It can be concluded that a further development of opacimeters for PTI tests with a higher sensitivity is not feasible.

3.5 Reproducibility and repeatability of the smoke emission test procedure

For assessment of the reproducibility and repeatability of the smoke emission test procedure special attention must be given to:
- The execution of the free acceleration test.
- The configuration and stability of the smoke meter.
- The number of tests which are needed to reach stable readings.
- The condition of the vehicle (combustion chamber, fuel injection equipment, exhaust system, operating temperature).
- The fuel type.

In addition several items influence the reproducibility and repeatability of a smoke emission test.

These are:
- The temperature of the engine because the air mass flow dynamics are mainly determined by flow dynamics, inertia of the turbocharger, the boost pressure and the air temperature.
- The condition of the exhaust system. This system is a carbon storage facility and by higher dynamic flows and higher temperatures the carbon deposits can be released. Annex IV, paragraph 2.4 of UNECE R24 defines:
  The operation described in item 2.3 above shall be repeated not less than six times in order to clear the exhaust system and to allow for any necessary adjustment of the apparatus. The maximum opacity values read at each successive acceleration shall be noted until stabilized values are obtained. No account shall be taken of the values read while the engine is idling after each acceleration. The values read shall be regarded as stabilized when four consecutive readings are situated within a band width of 0,25 m-1 and do not form a decreasing sequence. The absorption coefficient Xm to be recorded shall be the arithmetic mean of these four values .
  Normally a few free acceleration tests are conducted for stabilisation of the measuring signal. In Figure 11 an example of stabilisation of smoke emission tests is given.

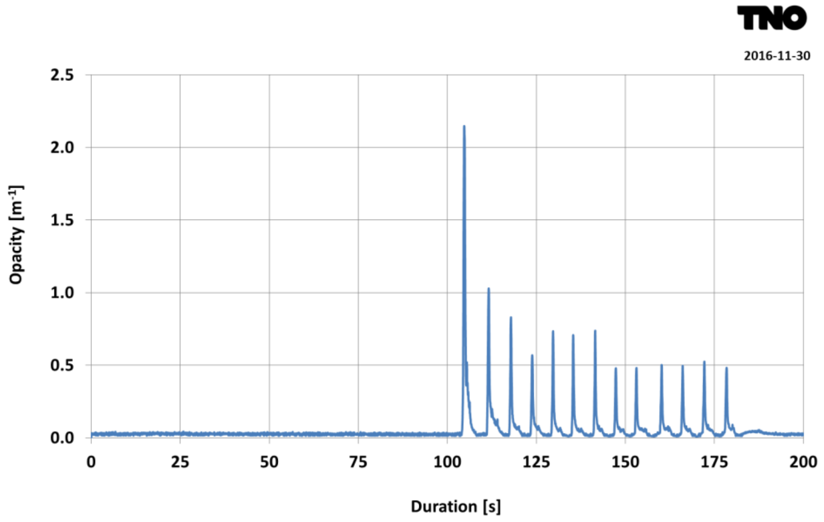


Figure 11: Stabilisation of engine and smoke meter in free acceleration tests

- The activation speed profile of the pedal for acceleration of the engine speed. UNECE R24 specifies as follows.
  Annex IV, 2.3: With the engine idling, the accelerator control shall be operated quickly, but not violently , so as to obtain maximum delivery from the injection pump. This position shall be maintained until maximum engine speed is reached and the governor comes into action. As soon as this speed is reached the accelerator shall be released until the engine resumes its idling speed and the opacimeter reverts to the corresponding conditions.

  For most engines the smoke emission is very dependent on the actuation time of the accelerator pedal because the actuation time determines the raise of the fuel injection quantity per stroke. Furthermore the inertia of the turbo charger in combination with the exhaust gas temperature and pressure determines the dynamics of the air mass flow.
  In Figure 12 results of smoke emissions of free acceleration tests with different accelerator pedal activation times are shown. In the first fifteen peaks the Accelerator pedal is activated as fast as possible (estimate of the activation time is 0.1 s). After four peak smoke emissions the test result is stable and the smoke emission in the next eleven peaks is in the range of 0.41 to 0,47 m^{-1}. In the next 27 peaks the Accelerator pedal is activated according to UNECE R24; the pedal is moved in 1 second completely to the maximum position (the Accelerator pedal touches the body of the vehicle). With this activation regime of the Accelerator pedal the smoke emission in the free acceleration tests is in the range of 0.14 to 0.68 m^{-1}.
  In Figure 13 a second example of free acceleration tests with different accelerator pedal activation times is shown. This vehicle in these tests is less sensitive for different activation times of the accelerator pedal because the stabilised smoke emissions are all around 0.60 m^{-1}.

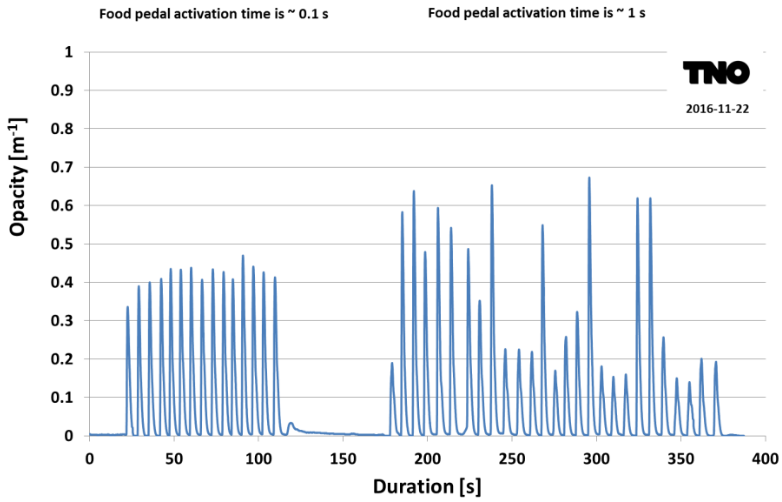


Figure 12: Smoke emission test results (Mode B) with fast and slow activation of the Accelerator pedal of a Ford Focus Euro 5b diesel with damaged DPF @ 38,780 km

- The condition of combustion chambers of diesel engines are heavily influenced by their long term operating load. Low engine loads (below appr. 30%) on the longer term facilitate the formation of carbon deposits in the combustion chamber. Especially deposits on fuel injectors increase the smoke emission levels because the fuel spray is disturbed. In Figure 13 and Figure 14 the effect of the condition of a combustion chamber is shown; In a period of 10 days (1500 km) the effect of application of a premium diesel fuel results in a smoke emission reduction of 0.6 to 0.2 m^{-1}. With an activation time of 1 second of the accelerator pedal the increase of the injected fuel quantity raises gradually. With a fast activation (0,1 s) the raise of injected fuel quantity is abrupt and this creates a certain stable fuel spray pattern. In case of more gradual raise of the injected fuel quantity the fuel pattern spray will probably be more disturbed by deposits on the fuel injector tip. Probably the long term use of a premium fuel removed some deposits on the fuel injector tips which resulted in lower smoke emissions in free accelerations tests with accelerator pedal activation times of 1 second.

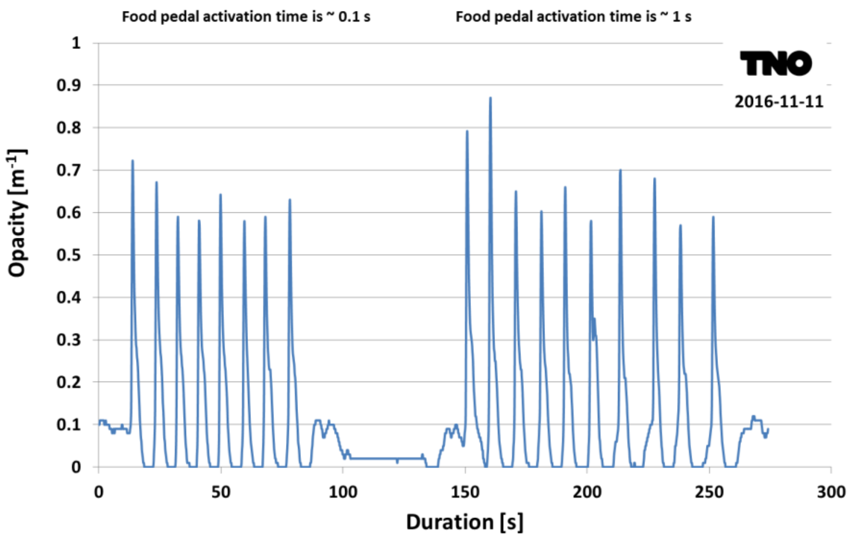


Figure 13: Smoke emission test results (Mode B) with fast and slow activation of the accelerator pedal of a Volkswagen Passat Euro 3 diesel @ 426,995 km

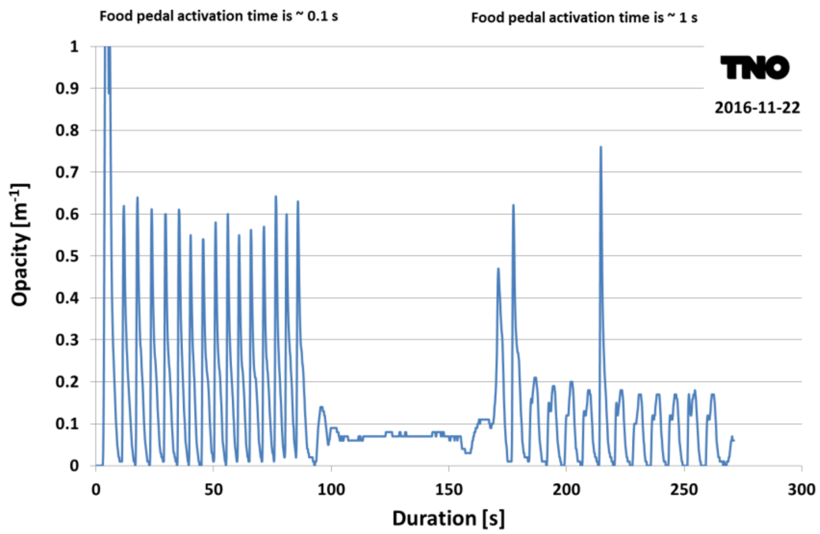


Figure 14: Smoke emission test results (Mode B) with fast and slow activation of the accelerator pedal of a Volkswagen Passat Euro 3 diesel @ 428,503 km after 10 days (1500 km) application of premium diesel fuel.

The reproducibility of free acceleration smoke emission tests is poor:
The current test procedure prescribes an activation time of the accelerator from the minimum to the maximum position of 1 second which is not measured and checked; This way of accelerator activation results in an irreproducible test procedure and may strongly effect the peak smoke emission in a free acceleration test.

3.6 Robustness of the smoke emission test procedure

This section describes issues which may have significant impact on the results of smoke emission tests in PTI's.

3.6.1 Issues which have impact on the smoke emission test result.

- Engine load: The condition of combustion chambers of diesel engines are heavily influenced by their long term operating load. Low engine loads (below appr. 30%), even after a few running hours, facilitate the formation of carbon deposits in the combustion chamber. It is well known that deposits on fuel injectors increase the smoke emission levels because the fuel spray is disturbed.

  In Figure 15 the smoke emissions of a Volkswagen Passat (Euro 3 and appr. 430,000 km) is shown). The initial free acceleration smoke emission is 0.68 m^{-1} and after application of premium fuel and GTL fuel over a distance of 4000 km this smoke emission is reduced to 0.35 m^{-1}.

- The fuel quality: Diesel fuel with high fractions of heavy hydrocarbons tend to create relative high smoke emission and consequently on the long term carbon deposits in the combustion chamber and on the fuel injector tip will be built up. In Figure 15 a Volkswagen Passat with Euro 3 engine (without DPF) is tested with several fuels and the results of smoke emission tests with regular and premium fuel are shown. The vehicle was daily used on journeys over 50 km. In all tests fast and slow activation of the accelerator pedal is applied in the free acceleration tests. The first two tests with regular and premium fuel are carried out on the same day.

  Application of a premium fuel on the short term results in a minor smoke emission decrease from 0.68 to 0.63 m^{-1} but after running with premium fuel over 1500 km the emission is reduced to 0.24 m^{-1}. Probably the cleaning performance of the fuel removes the carbon deposits in the combustion chambers and on the fuel injector tips. Application of GTL results in a smoke emission of 0.28 m^{-1} which is on the same level as the premium fuel. Finally the regular fuel returns to an emission of 0.35 m^{-1} which again shows the direct influence of fuel quality on smoke emission and the cleaning performance of the former applied fuels.

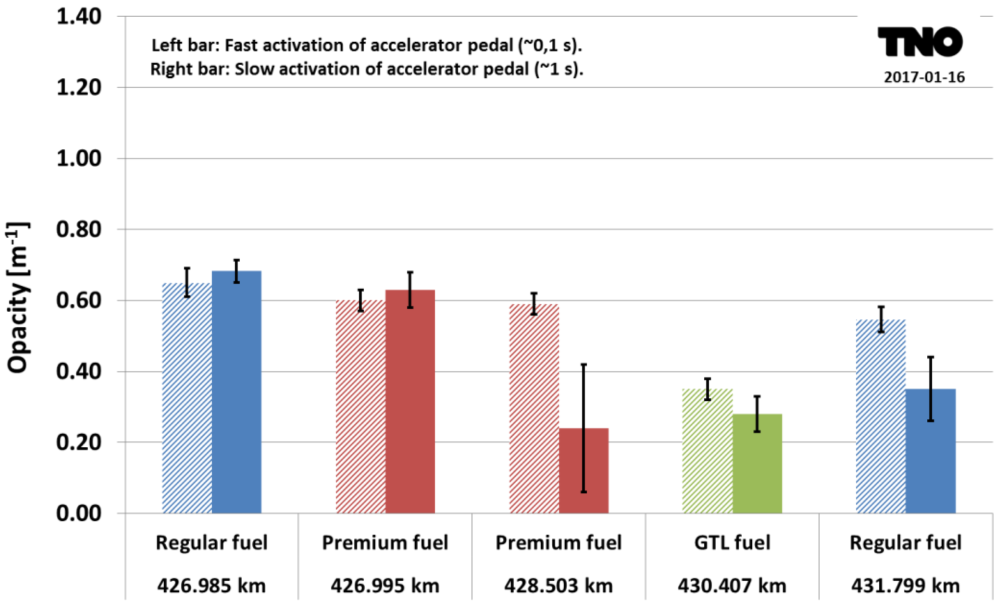


Figure 15: Smoke emission of free acceleration tests (Mode B) of a Volkswagen Passat Euro 3 diesel (without DPF) with different fuels.

- Fuel additives: In general certain fuel additives claim a reduction of smoke emissions. After adding the additive to the fuel it is claimed that engine cleaning takes place in the next 500-1000 km; Due to this cleaning performance (carbon deposits will be vanished) the air-fuel mixture is better and consequently smoke emissions will be reduced.
  - In Figure 16 the test results of a Seat Ibiza Euro 3 diesel (without DPF) with a mileage of 330,000 km are shown. This vehicle with a relative low smoke emission was tested with a fuel additive and was mainly used on journeys over 50 km. After 390 km the smoke emissions were measured again; In this case the smoke emission increased slightly from 0.09 to 0.15 m^{-1}. Probably this vehicle was in the first test with regular fuel in very good condition and cleaning of the combustion chamber with a fuel additive was not needed.
  - In Figure 17 the test results of a Peugeot 307 Euro 3 diesel (without DPF) with a mileage of 261,000 km are shown. The vehicle was tested with regular diesel fuel and with the same regular fuel with fuel additive after driving 400 km on this fuel. The vehicle was mainly used on journeys over 70 km. Due to the application of a fuel additive the smoke emission of the engine reduced from 1.52 to 1.27 m^{-1}.
  - In Figure 18 the test results of a Ford Focus Euro 5b diesel (with DPF) with a mileage of 39,000 km are shown. The vehicle was treated with a fuel additive and before and after this treatment smoke emissions were measured with regular diesel fuel. The vehicle was mainly used on highway routes. Due to the application of a fuel additive the smoke emission of the engine reduced from 0.44 to 0.33 m^{-1}.
- In most emission tests the smoke emission with fast activation of the accelerator pedal is higher than with slow activation. This issue is explained in section 0.

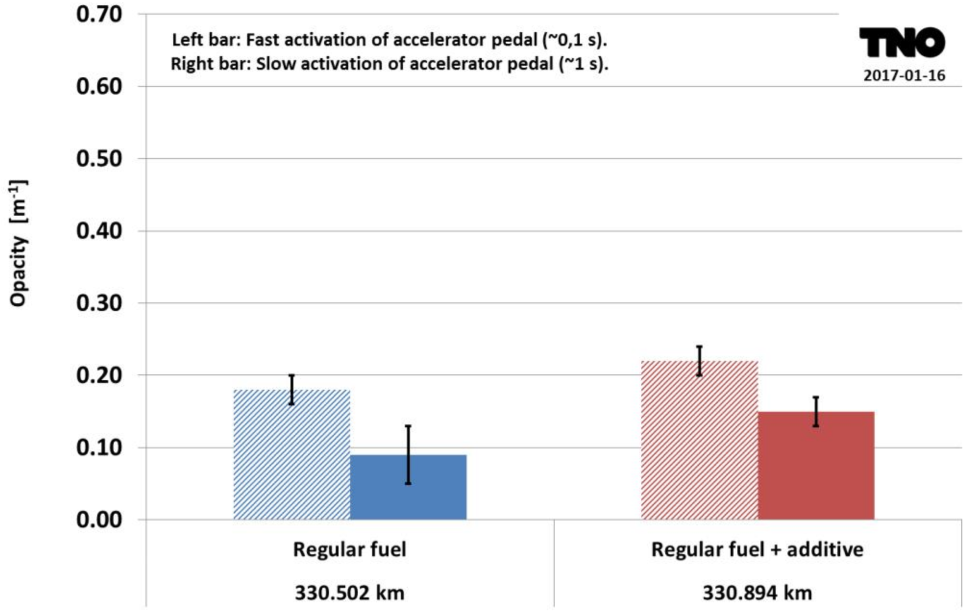


Figure 16: Smoke emission free acceleration test results (Mode B) of a Seat Ibiza Euro 3 diesel @ 330,000 km without and with fuel additive.

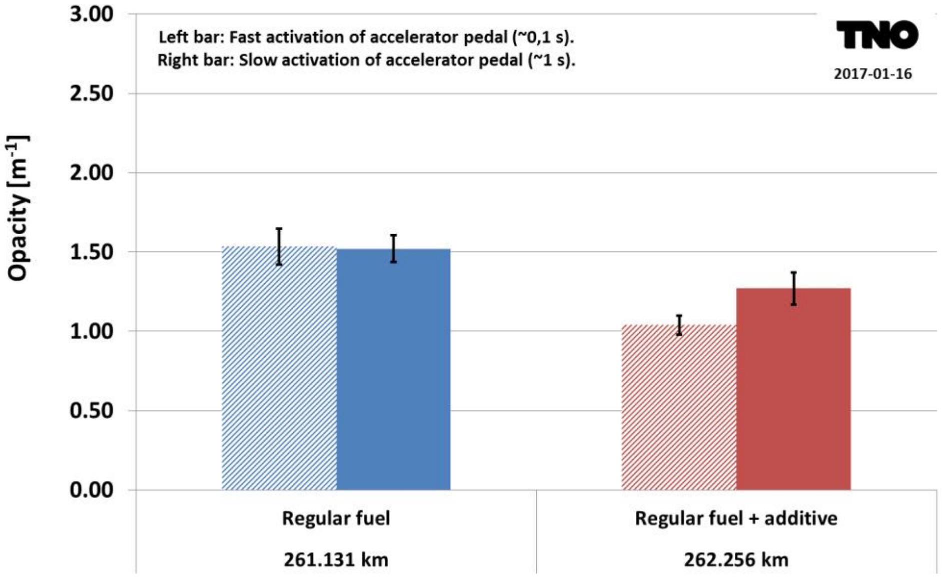


Figure 17: Smoke emission free acceleration test results (Mode B) of a Peugeot 307 Euro 3 diesel @ 261.000 km without and with fuel additive.

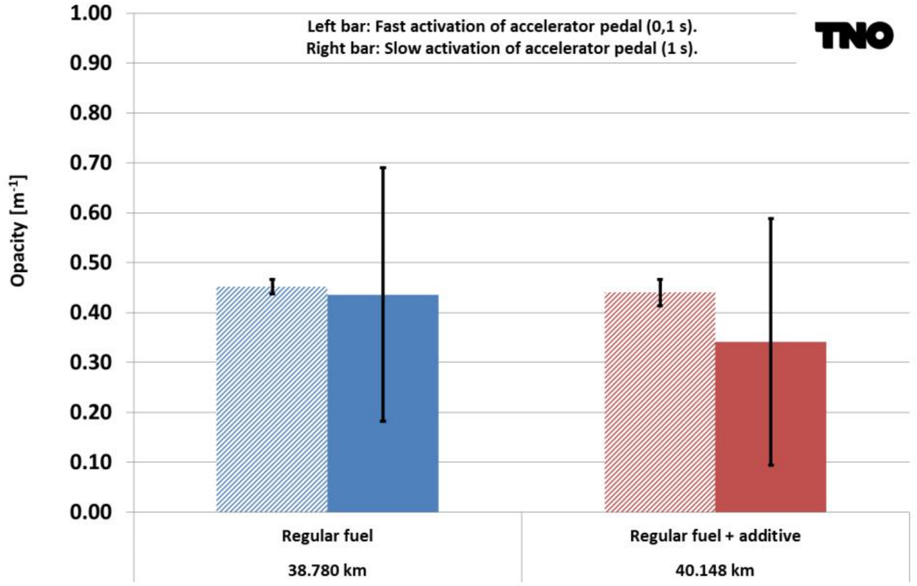


Figure 18: Smoke emission free acceleration test results (Mode B) of a Ford Focus Euro 5b diesel (with DPF failure) @ 39.000 km without and with fuel additive.

The robustness of free acceleration smoke emission tests is poor because the condition of an engine determines the test result. Carbon deposits on the fuel injector tips and in the combustion chambers heavily influence smoke emissions; Deposits are created with the use of low quality fuels (with relative high amount of heavy fractions) and long term low load operation of the engine. In three vehicles the use of premium or Gas-To-Liquid diesel fuel or certain fuel additives resulted in a 30-50% reduction of the smoke emission. The application of a fuel additive in a fourth vehicle with an initial relatively low smoke emission (k = 0.09 m^{-1}) resulted in slightly increased smoke emission (k = 0.15 m^{-1}).

3.7 Discussion and technical conclusions

Smoke opacity test procedure

The introduction of UNECE R24 in 1958 regulated the smoke emissions of diesel engines in two ways. At full load static conditions and in a dynamic free acceleration test the smoke emissions are measured with an opacimeter with a measuring scale of 0 to 10 m^{-1} .
From a technical point of view the current opacimeter is not optimal because the dynamic measuring signal must be suppressed (filtered) to create reproducible results in all different opacimeters. Furthermore the engine conditions at full load and in the dynamic speed ramp do not represent daily engine operation.
The introduction of particulate filters completely vanished the traditional smoke emission.

Execution of a free acceleration test is complicated. The opacimeter and engine must be warmed up and engine speed and oil temperature sensors must be installed. Installation of the measuring probe and execution of at least three free acceleration tests is relatively complex.

During testing the noise emission in workshops is excessive and exhaust gas must be removed in a safe manner. These facts do not create a common sense of acceptance of the PTI smoke emission test.

The reproducibility and repeatability of the current smoke emission test is not good because the activation of the accelerator within 1 second cannot be checked. Practically there is no simple solution to activate the accelerator in a more defined way.

Long term engine use, fuel quality, fuel additives and the execution of the free acceleration test may result in deviations of the results of the PTI smoke emission test. It can be concluded that the free acceleration test procedure is not covering all relevant items.

Smoke emissions of engines with DPF are mostly below 0.05 m^{-1} and from Euro 3 vehicles these are near 0.30 m^{-1}. The smoke emission limit value of 0.70 which will be introduced in 2018 doesn't match the emission level of current diesel vehicles. Even new proposed limit values of 0.20 or 0.30 are not useful because some engines without DPF already perform at this level.

From these findings it can be stated that the current free acceleration smoke emission test is not suitable for diesel vehicles with DPF.
For detection of particulate filters with a certain leakage a more sensitive test for the periodic technical inspection is needed which yields information about the condition of the particulate filter. With improvements on test equipment, test procedure in combination with a stringent limit value it may become suitable, but many practical disadvantages remain.

In Chapter 4 the relationship of smoke, PM and PN emissions is investigated.

4 Investigations of new PTI emission test methods

New exhaust after treatment technologies of vehicles need a dedicated PTI approach because the emission levels are relatively low and specific technologies have a specific behaviour. In Chapter 3 the free acceleration smoke emission test is assessed and it is clear that diesel vehicles with a DPF cannot be judged by measuring smoke emission. In this Chapter existing and new measuring technologies (PM & PN) and test methods (EOBD) for PTI purposes are investigated.

For the development of a new PTI emission test four different items must be taken into account, these are:

1. The applied engine, fuel and after treatment technology.
2. The type of test (i.e. low or high idle or free acceleration test).
3. The type of emission tester (EOBD, smoke, PM or PN).
4. The applied emission limit value.

4.1 Assessment of regulated PM and PN test methods

- Particulate Mass (PM): In 1990 a more refined mass based type approval test method for light duty vehicles was introduced. This PM measuring technology was added to the existing test equipment of a chassis dynamometer. In an emission test (i.e. 1180 seconds of a NEDC test) from a defined partial diluted exhaust gas flow small sample filters are loaded with particulates. The (un)loaded filters are weighed before and after the emission test. In Figure 19 an example of a loaded PM sampling filter is shown. The PM emission is expressed in mg/km. This test result is a good representation of the real world PM emissions but this test method with dilution tunnel and Constant Volume Sampler cannot be applied in PTI's because it is too expensive.

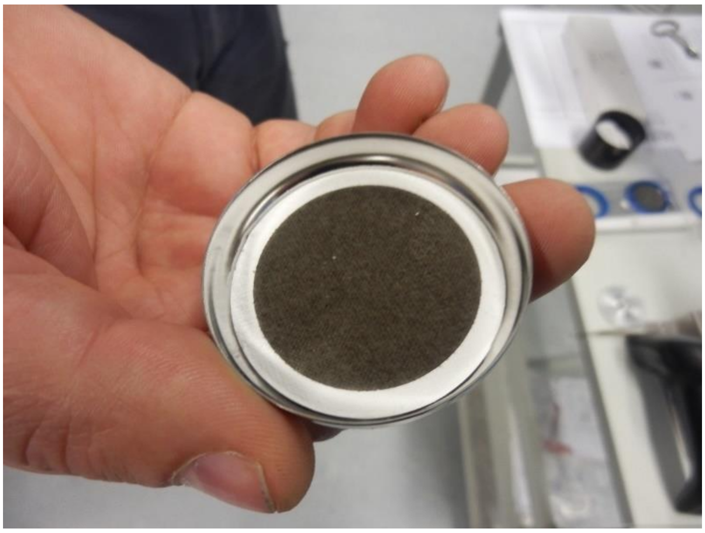


Figure 19: Particulate Mass sample filters.

- Particulate Number (PN): From 2007 onwards diesel LD-vehicles have been equipped with Diesel Particulate Filters (DPF). Due to very high efficiencies of DPF's (> 99%) and the corresponding very low PM emissions a more sensitive test method was needed. This new test method was developed in the Particulate Measurement Programme (PMP) and it is a type approval test method for engines and vehicles. In addition to the existing dilution tunnel (CVS-system with PM sampling system) a PN counter counts solid particles in a size range of 23 – 1000 nm. In order to be able to measure repeatable volatile particles must be removed and certain preparation of the sample is needed. An example of PM&PN measuring devices is shown in Figure 20. The sample gas is again diluted and the volatile fraction is evaporated in an evaporation tube. Finally the solid particles with a size range of 23-1000 nm are counted in a PN-counter. The PN emission is expressed in particles per kilometre (#/km). This test result yields a good indication of the quality of a specific DPF and real world PN emissions but again this test method with the CVS cannot be applied in PTI's, it is too expensive and too complicated. In this project new PTI test methods with several PN-testers are investigated.

Figure 20: PM & PN type approval test equipment according to PMP-protocol.

Current PM&PN PMP test protocols are not suitable for the daily PTI test practice because they are too complicated and too expensive.

4.2 EOBD test methods

An EOBD system monitors the condition of the hardware (sensors and actuators) of a vehicle as well as the electrical connections and in certain cases emission levels. In case of a malfunction specific (emission related) failure codes are stored in a memory and the Malfunction Indication Light (MIL) can be activated on the dashboard. The driver will be warned and can take action, mostly the vehicle must be offered to a service shop for investigation of the technical problem.
Electronic On Board Diagnosis systems are already implemented in vehicles and must meet certain legal criteria. The legislator defines general minimum EOBD requirements which are assessed for specific vehicles in type approval test procedures. On the other side a manufacturer wants to avoid irrelevant failure codes because users might lose confidence in their vehicle.
Currently no low cost PM/PN sensors are available which can be mounted in exhaust systems of LD-vehicles; Consequently monitoring of the performance of Diesel Particulate Filters with current EOBD systems is not possible.

Future EOBD systems might be able to monitor PM/PN/NOx emissions but this requires a very detailed assessment of the quality. EOBD systems are very complicated and its software consists of thousands of pages with software codes and scripts. Practically it is not feasible to assess the quality of these EOBD systems because one needs very specific detailed technical knowledge, testing capabilities and a defined legal framework. Given this complexity it is recommended to focus on a certain PTI test procedure with appropriate limit value.

Current EOBD systems are not able to detect DPF failures because the systems are not equipped with PM or PN sensors. Furthermore EOBD systems are manipulated when DPF’s are removed.

4.3 Potential PN test equipment for the PTI

In the Particulate Measurement Program (PMP) of last decades one has defined the conditions and requirements for measuring of PM and PN emissions. The type approval test protocol consists of requirements for sample dilution, treatment and conditioning as well as a definition of a particle which must be measured.

4.3.1 Different types of PTI PN counters.

Based on this measuring technology in last years manufacturers of PN test equipment has developed mobile PN counters for PTI purposes. Currently the Testo PEPA is available as prototype and the TSI 3795 (NPET) is for sale. Both PN testers are based on the PMP protocol. First the exhaust gas is diluted, than the volatile fraction is removed (not by evaporation but with a catalytic stripper) and particles with a size of 23-1000 nm are counted.
Both PN-counters as well as two other handheld PN counters (TSI 3007 and TSI 8525) were applied in this research test program. The handheld PN counters measure solid as well as volatile particles in different particle size ranges.
In general they measure higher PN numbers than the TSI 3795 and Testo PEPA. More detailed specifications of all four PN-counters are described in section 2.2.

4.3.2 *A first investigation of the PN emissions of a DPF-equipped diesel engine at low idle speed with four different PN counters (1st measuring campaign).*

In a first test with an Euro 6 diesel vehicle with DPF all four PN-counters were applied at the same time and they sampled during 7 minutes ambient air, 7 minutes exhaust gas at low idle speed and finally 7 minutes exhaust gas at high idle speed. In Figure 21 the test results are reported. In ambient air the four PN-numbers air different because the PN-testers count particles with different sizes. The two handheld testers (3007 and 8525) also count smaller and volatile particles, hence higher particle numbers can be expected.
In the next step of this test exhaust gas of the hot engine at low idle speed is offered to all PN-counters. All readings of the four PN-counters decrease to zero (or near zero) particles per cm^3.
Even at high idle speed all PN-counters measure an extremely low PN emission.
It can be concluded that diesel vehicles with well functioning DPF reduce the particle concentration of ambient air at idle speeds. This test result supports the visual and swipe test results of DPF equipped vehicles which can have an extremely clean tail pipe.
Given this filtration behaviour of DPF's one might possibly define a PTI idle test because a certain leakage of the DPF will probably result in some PN emission. This potential PTI test will be like the UNECE R83 Type II test for petrol vehicles in which at low idle speed the CO emission is measured in the tailpipe.

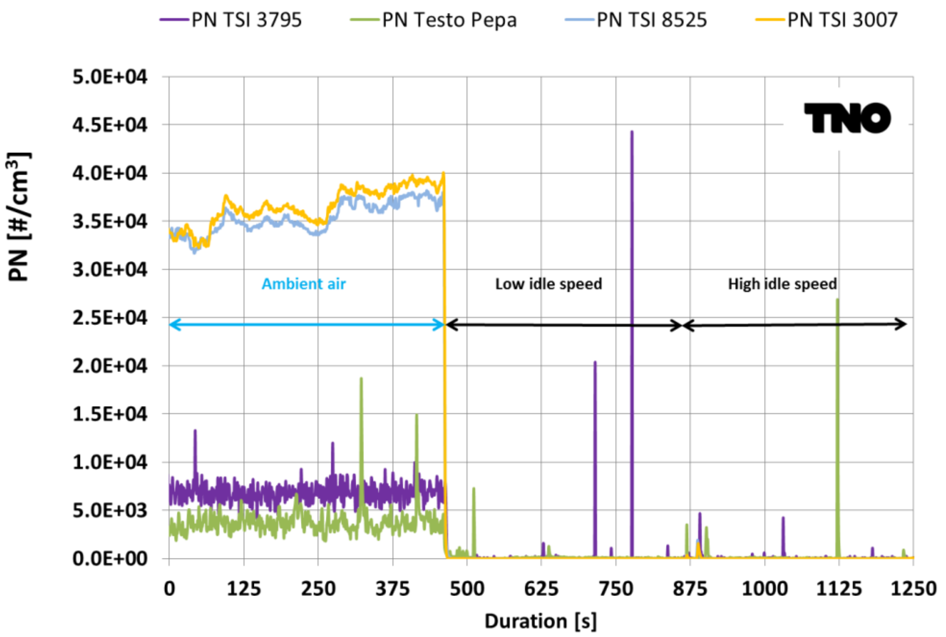


Figure 21: PN emissions measured with four different mobile PN-testers of ambient air and at different idle speeds of a Peugeot 308 diesel Euro 6b with DPF @ 104,755 km.

A PN emission test is a good candidate for the PTI; At low idle speed a hot DPF cleans ambient air because the volatile and solid PN emission at idle speed is reduced to zero #/cm^3. Consequently a fully clean tail pipe with a visible steel structure and a lack of soot is visible.

4.3.3 A second investigation of the PN emissions of a DPF-equipped diesel engine with variable DPF bypass flow at low idle speed with the four PN-counters (1st measuring campaign)

All 4 PN-counters were subjected to exhaust gas with different PN concentrations. For this experiment an adjustable bypass of the DPF was created in a Peugeot Partner Euro 6. In order to simulate DPF leakages at low idle speed the bypass was adjusted to create certain PN-levels and all four measuring signals were logged.
At a regular basis the handheld testers were temporarily removed from the sample flow because these testers are not developed for measuring wet exhaust gas.
In Figure 22 and Figure 23 all PN counters follow the PN trend if they measure in their operating range.
The handheld testers (3007 and 8525) measure higher PN concentrations because they measure also volatile fractions and smaller particles.
The Testo PEPA and TSI 3795 follow the same trend up to 300,000 #/cm^3. Above this reading there is a significant difference between these two devices.
In order to get touch with this deviation the test results and PN-testers were checked by the suppliers and further investigations were carried out in a second measuring campaign.

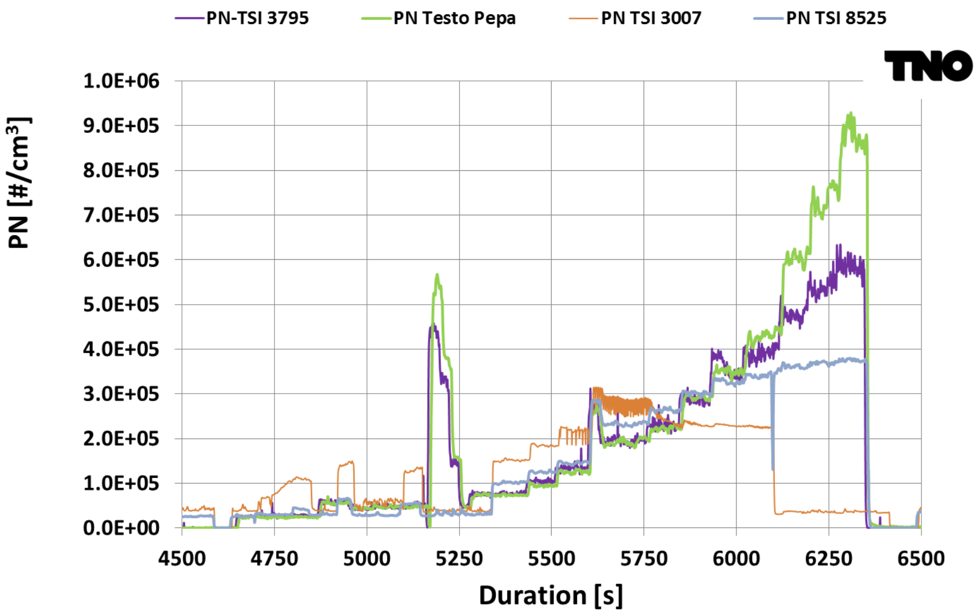


Figure 22: PN emissions measured with four different mobile PN-testers at low idle speed of a Peugeot Partner diesel Euro 6b with different DPF bypass exhaust flows (1st measuring campaign).

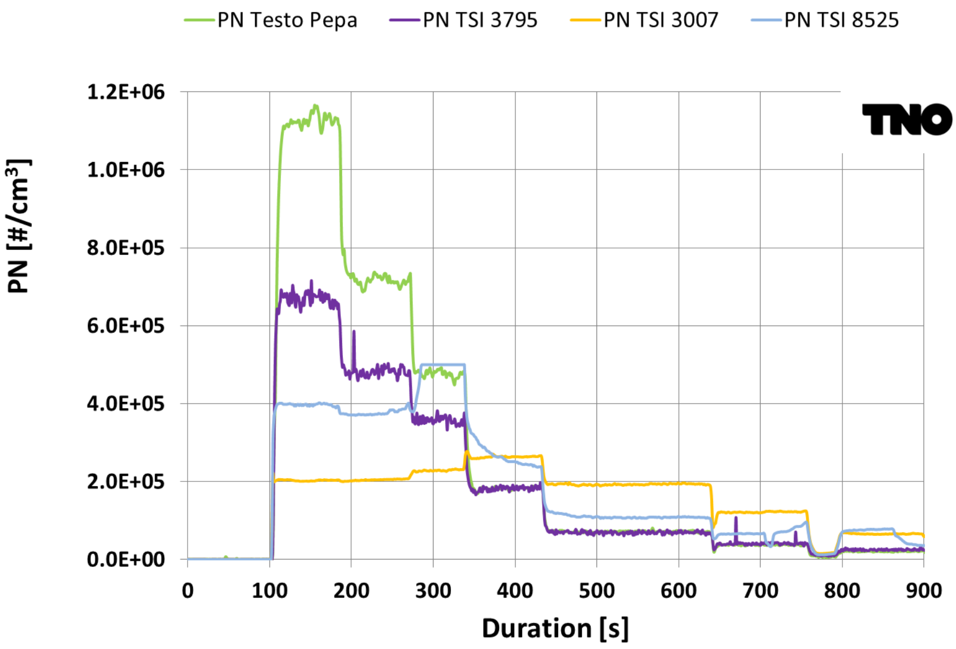


Figure 23: PN emissions measured with four different mobile PN-testers at low idle speed of a Peugeot Partner diesel Euro 6b with different DPF bypass exhaust flows (1st measuring campaign).

The PN emission at low idle speed is clearly related to the leakage rate of the DPF.

4.3.4 *A third investigation of the PN emissions of a DPF-equipped diesel engine with variable DPF bypass flow at low idle speed with the four PN-counters (2nd measuring campaign)*

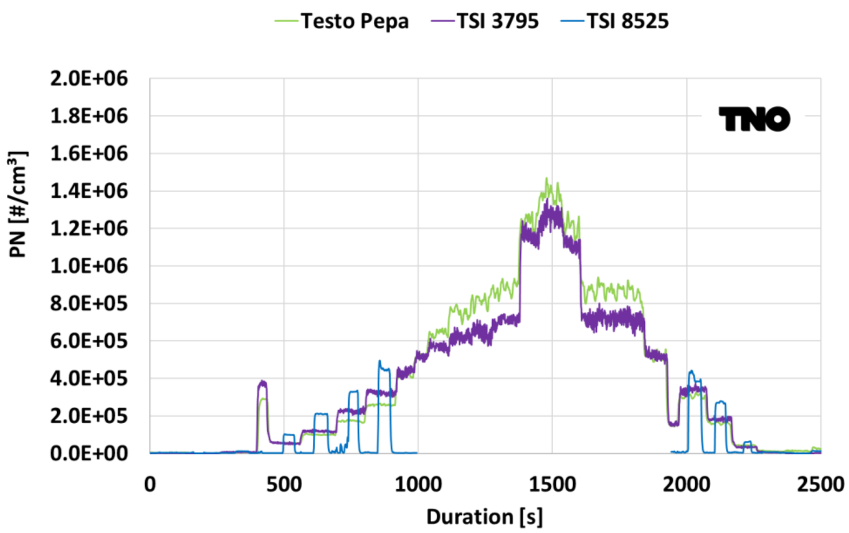


Figure 24: PN emissions measured with three different mobile PN-testers at low idle speed of a Peugeot Partner diesel Euro 6b with different DPF bypass exhaust flows (2nd measuring campaign).

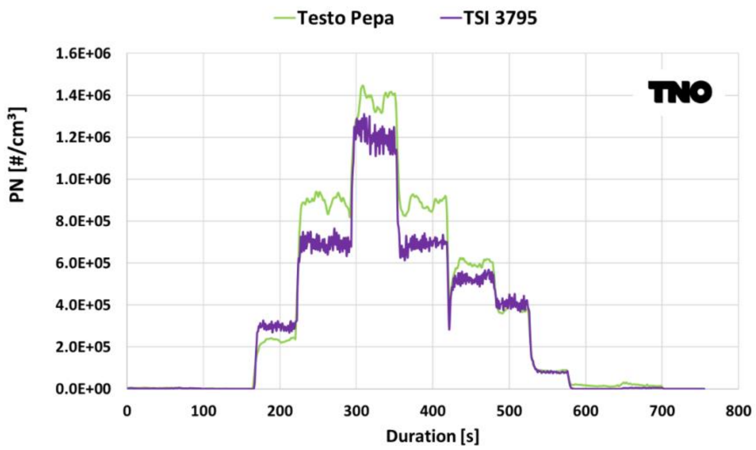


Figure 25: PN emissions measured with two different mobile PN-testers at low idle speed of a Peugeot Partner diesel Euro 6b with different DPF bypass exhaust flows (2nd measuring campaign).

The measured PN emissions at low idle speed differ per PN tester.
The differences are probably related to the measuring principle (CPC or ECD) and the different applied particle size ranges.

4.3.5 Comparison of PN test results of the TSI 8525 and the PMP test method.

A test was done to compare the official PN equipment (connected to the full flow dilution tunnel) with the portable TSI 3795 directly connected to the exhaust pipe (including 100-1 dilution). The results at low idle and the NEDC test are respectively shown in Figure 26 and 27.

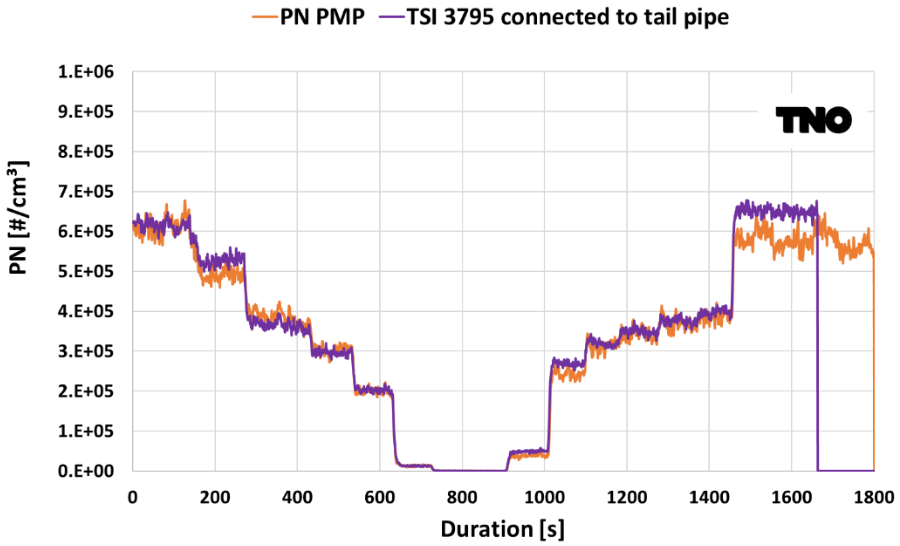


Figure 26: PN emissions at low idle speed of a Peugeot Partner diesel Euro 6b with different DPF bypass exhaust flows (2nd measuring campaign).

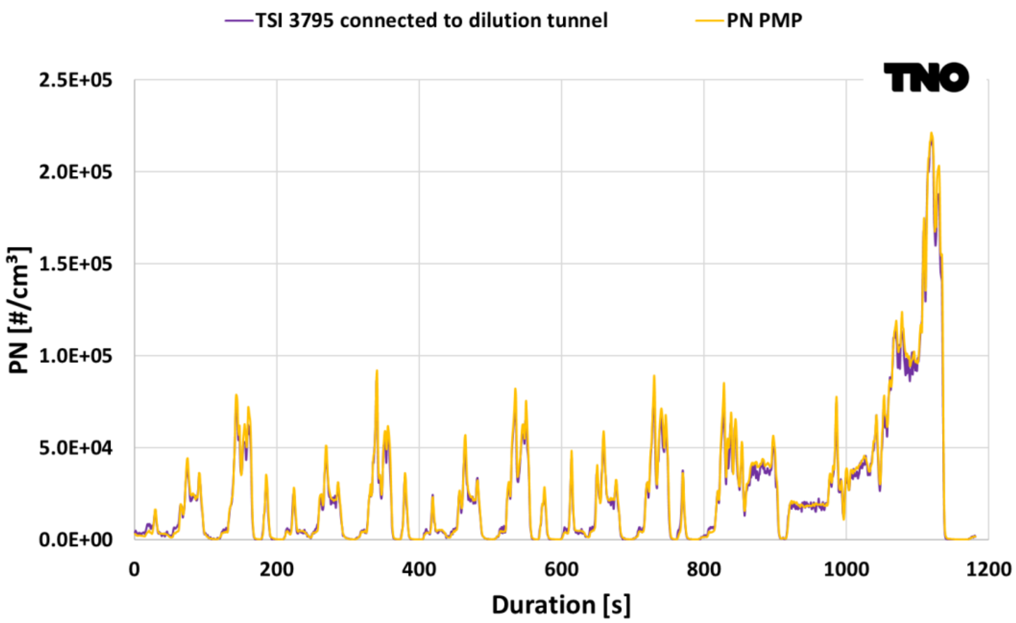


Figure 27: PN emissions measured in a NEDC with hot start according to PMP protocol and with TSI 3795 mobile PN tester of a Peugeot Partner diesel Euro 6b with a certain DPF bypass exhaust flow (2nd measuring campaign).

In an NEDC test the PTI PN tester (CPC type with catalytic stripper) correlate very well with the official PMP-PN tester (CPC type with evaporation tube).

4.4 Potential PN test methods for diesel vehicles in the PTI

In order to get view on PN emissions at PTI conditions several PN emission tests were carried out. The results of this investigation are reported in this section.

4.4.1 PN emission investigations in different PTI tests of a diesel vehicle with proper functioning DPF

In Figure 28 the results of low and high idle speed tests as well as free accelerations tests of a Peugeot Partner Euro 6b with good working DPF are shown. In the first 100 seconds of this test ambient air was sampled and this contains 3000-4000 #/cm^3. After installation of the PN sample probe in the tail pipe the PN emission reduced to zero and in the next 2000 seconds this emission was stable and very low at all idle speeds. Than free acceleration tests were performed and in the first trial the PN emission was not stabilised, probably the sampling system contained condensed matter which was released during the first free acceleration tests. In the second set of free acceleration tests the PN emission was 500 – 2000 #/cm^3.

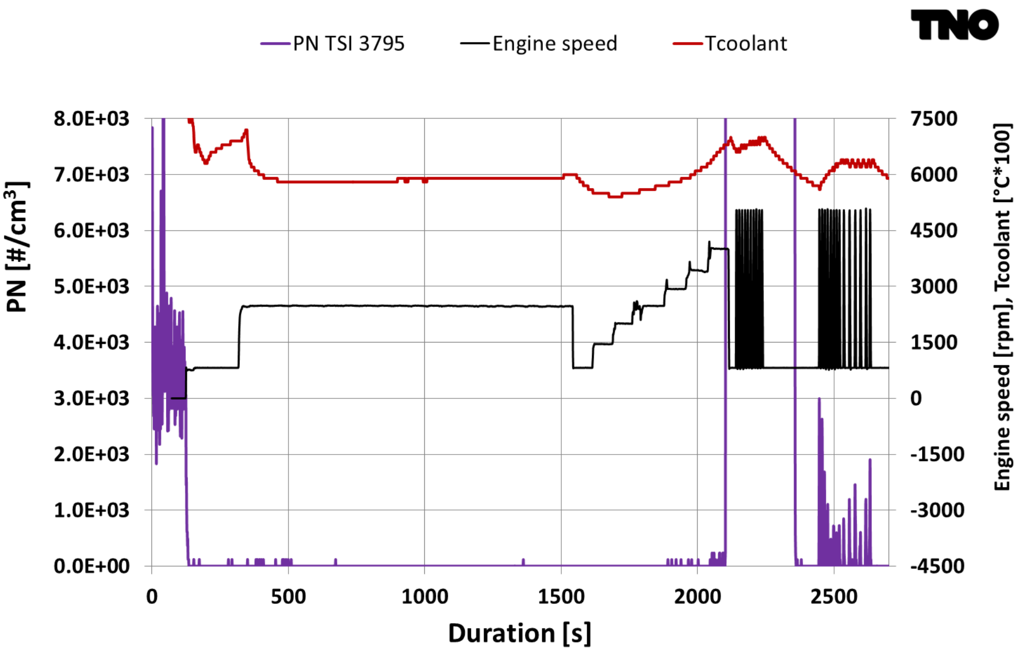


Figure 28: PN emissions at different idle speeds and free acceleration test of a Peugeot Partner diesel Euro 6b @ 21,000 km.

PN emissions of a diesel vehicle with a proper functioning DPF at low idle speed are very stable (near zero #/cm^3). This is a basis for a PTI PN-test.

4.4.2 *PN emissions in free acceleration tests of a diesel vehicle with a proper functioning DPF*

In Figure 29 a more detailed view of the PN emission in free acceleration test is shown. Again this PN emission is lower than the PN concentration of ambient air and it is proved that a DPF is extremely effective.

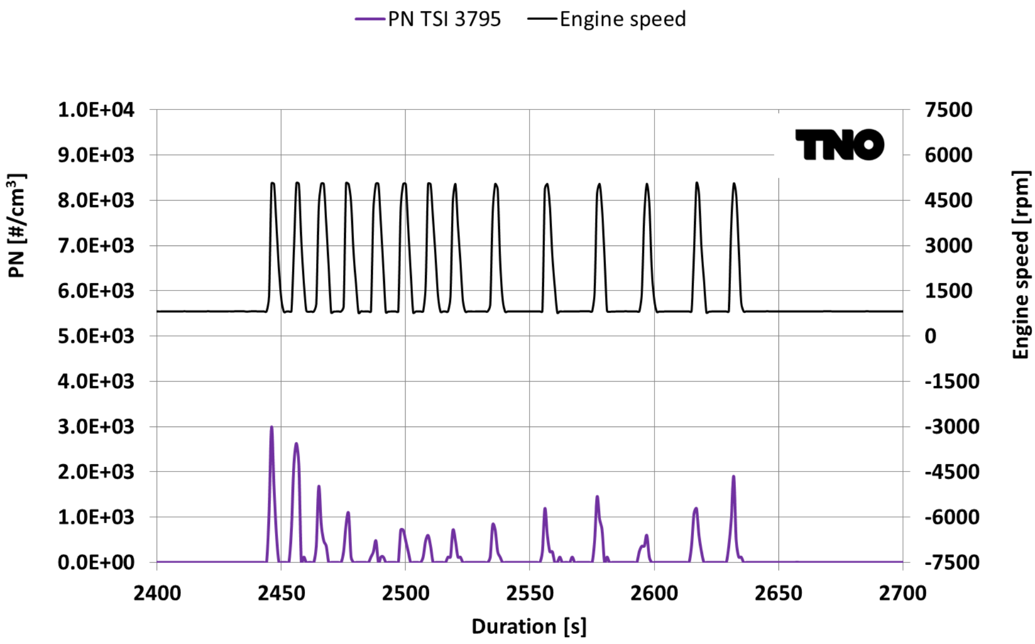


Figure 29: PN emissions in free acceleration tests of a Peugeot Partner diesel Euro 6b (DPF is in good condition).

PN emissions in free acceleration tests of a diesel vehicle with well functioning DPF are very low (< 3000 #/cm³). This proves the high filtration efficiency of a DPF.

4.4.3 *PN and smoke emissions in free acceleration tests with different DPF leakages*

In Figure 30 the test results of free acceleration tests of the Peugeot Partner with adjustable DPF bypass are reported. Initially the bypass is adjusted at low idle speed and the PN emission is set at a certain value. Than free acceleration tests are executed and smoke and PN emissions are registered. After these tests the bypass flow is set at the next value and free acceleration tests are executed again. From these test results it is clear that smoke emission in free acceleration tests is relatively low (0.00 to 0.08 m^{-1}) and hardly detectable but the PN emission is in the range of 0 to 10,000,000 #/cm3. From these tests it is shown that PN readings have more screening capacity and are more sensitive than smoke emission readings. Even very small DPF leakages are detectable with a PN counter which are not recognised by the opacimeter.
These PN test results show a fairly constant ratio between PN emission at low idle speed and the peak PN value in a free acceleration tests, it is around 20.

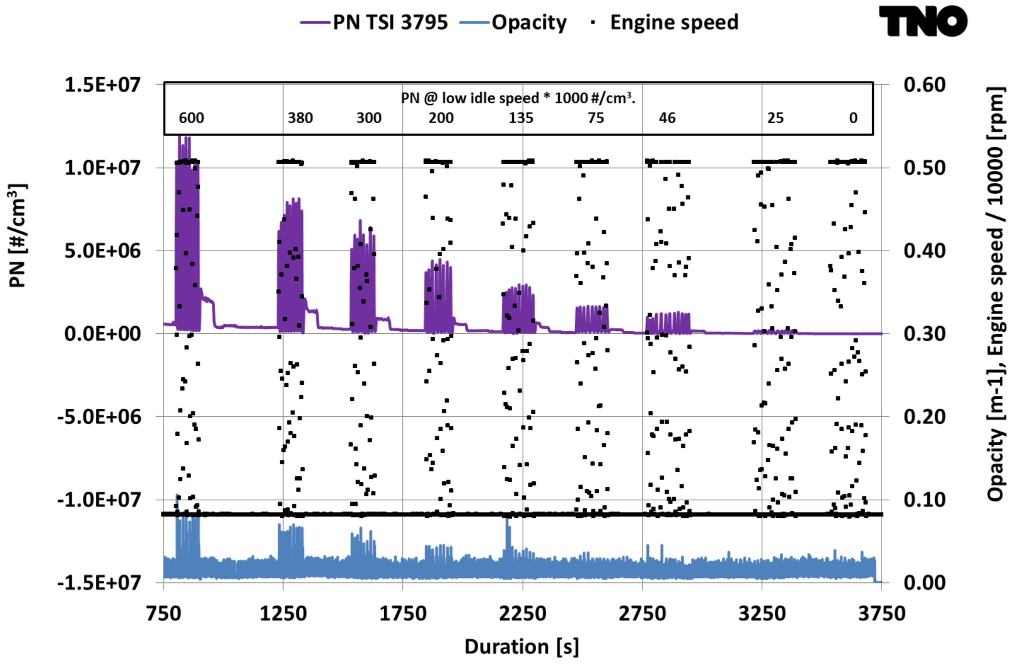


Figure 30: PN emissions and smoke emissions in free acceleration tests of a Peugeot Partner diesel Euro 6b with different DPF bypass exhaust flows.

> In free acceleration tests of a diesel vehicle with DPF with a substantial leakage the smoke emissions are very low (< 0.10 m^{-1}). The corresponding PN emission at low idle speed is in the range of 0 to 600,000 #/cm^3 and has a good resolution,

4.4.4 PN investigations at low idle speed pre and post DPF during warming up of a Ford Fiesta Euro 6 diesel with a small DPF leakage

In Figure 31 an example of PN emissions during warming up at low idle speed is shown. The DPF of this Euro 6 Ford Fiesta has a small leakage. In two test runs the PN emission is measured pre and post DPF and based on these results the efficiency of the DPF is calculated.
The PN emission pre DPF starts around 14,000,000 #/cm^3 and in the course of one hour it is reduced to 4,000,000 – 6,000,000 #/cm^3. The same trend is measured post DPF and the final PN emission with a hot engine is around 300,000 #/cm^3. This post DPF PN reducing emission trend needs to be investigated for potential new PTI test procedures.
This test proves that engine behaviour can strongly influence the PN emission. Probably the EGR rate has an effect on the PN emission.

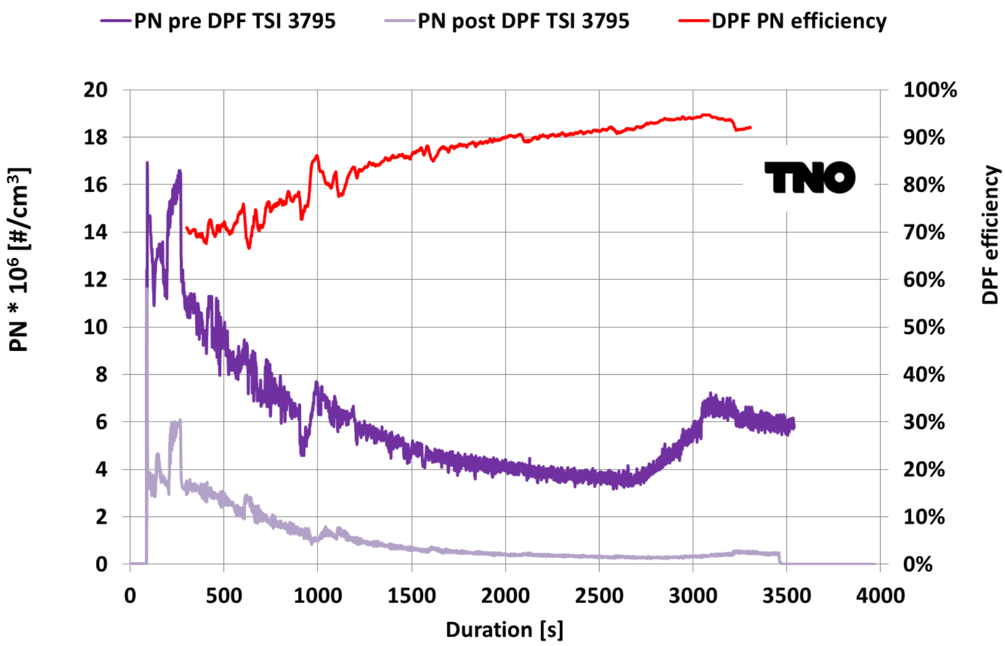


Figure 31: PN emission pre and post DPF warming up of a Ford Fiesta Euro 6 diesel engine with small DPF leakage, at low idle speed.

4.4.5 PN investigations at low idle speed pre DPF of a Ford Fiesta and Peugeot Partner Euro 6 diesel with different EGR rates

In Figure 32 an even more clear picture of the same Ford Fiesta is shown. Here the PN emission pre DPF is very related to the oxygen content in the exhaust gas and this is probably caused by the (de)activation of the EGR system. If EGR is added to the intake air less oxygen is available for the combustion and PN/PM emission increases. In general the PN emission of this engine is stable at the different specific PN levels.
After 500 seconds the engine is restarted and the PN emission returns to far higher level than before the engine was shut off. From this figure it is clear that time and event related control strategies are applied.

In Figure 33 the pre DPF PN emission at low idle speed varies between 7 and 18 million #/cm^3. Due to the relative slow variations it is expected that variations are caused by the control strategies of the engine management.

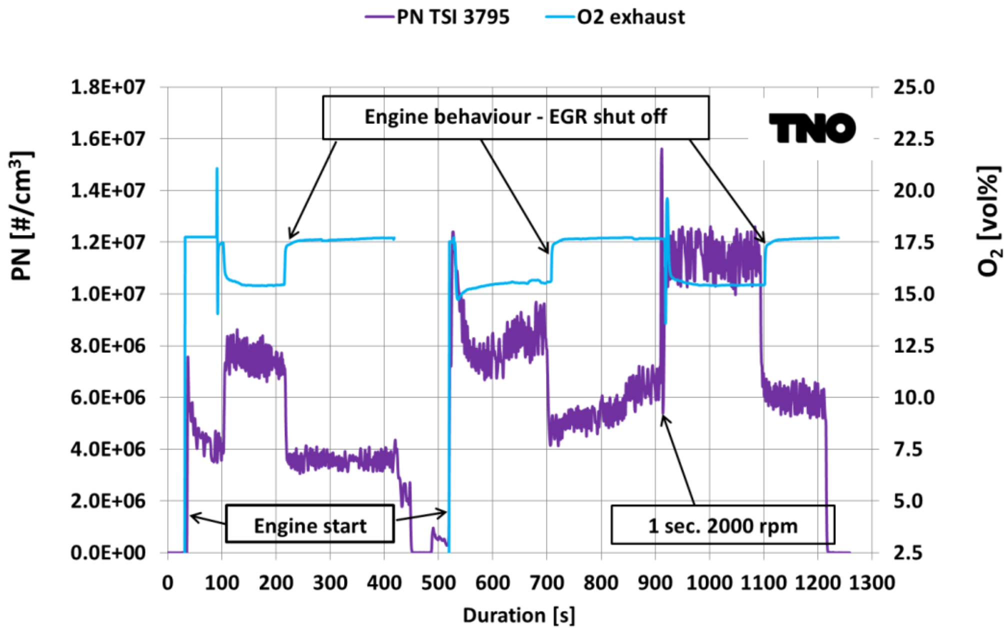


Figure 32: PN and O_2 emission pre DPF after two engine starts of a Ford Fiesta Euro 6 diesel engine with small DPF leakage at low idle speed.

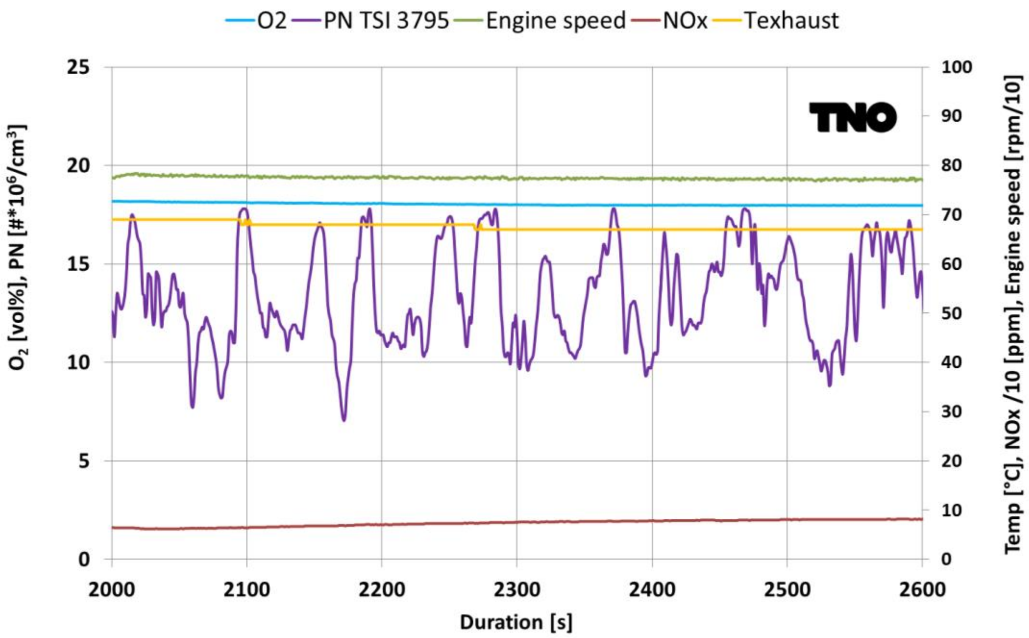


Figure 33: PN emission pre DPF of a Peugeot Partner Euro 6 diesel engine at low idle speed.

The application of EGR has substantial effect on the PN emission of an engine at low idle speed. Low EGR rates generate a low PN emission. With respect to a new PTI-PN test at low idle speed the PN emission of the engine should be taken into account.

In Figure 34 PN emissions pre and post DPF of a Ford Focus with DPF leakage are shown. In this test the sample probe of the PN tester was moved during the test between sample locations pre and post DPF. Again it is shown that the PN emission pre DPF may vary substantially (from 5,000,000 to 11,000,000 #/cm^3) which is probably caused by engine control settings. However the PN emission can also be very stable (around 5 million #/cm$^{3)}$ which also results in a stable PN emission post DPF (nearly 2 million #/cm^3).

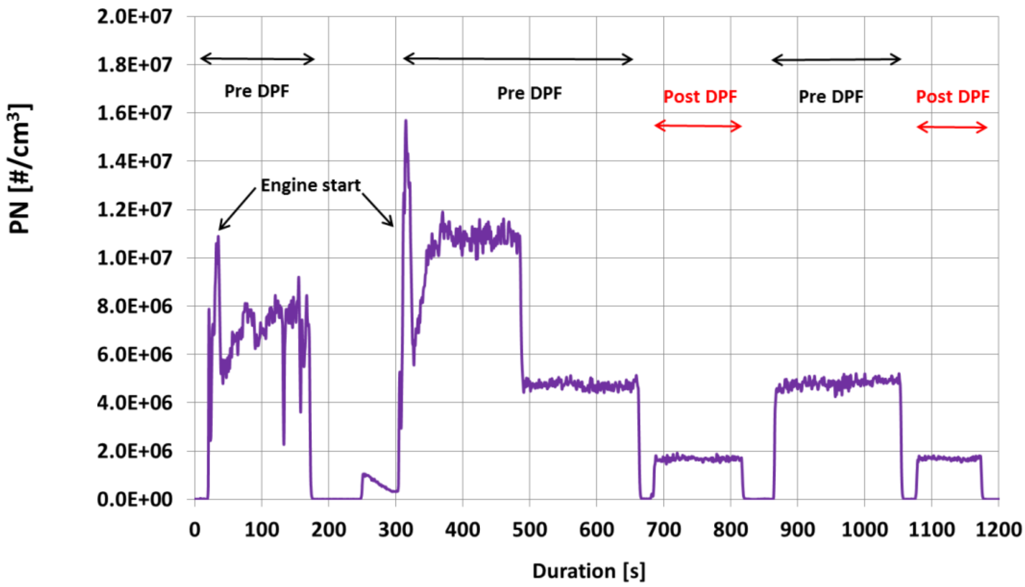


Figure 34: PN emission pre and post DPF of a Ford Focus Euro 5b diesel engine with DPF failure at low idle speed. After 180s idling the pre DPF PN emission reduces more than 50%.

In Figure 35 the PN emission post DPF at low idle speed of the Ford Focus (with DPF with crack) is 2,000,000 #/cm^3 and at high idle speed it reaches a level of more than 6,000,000 #/cm^3. This DPF has a certain leakage and the fluctuating PN emission of the engine can be detected in the tail pipe.

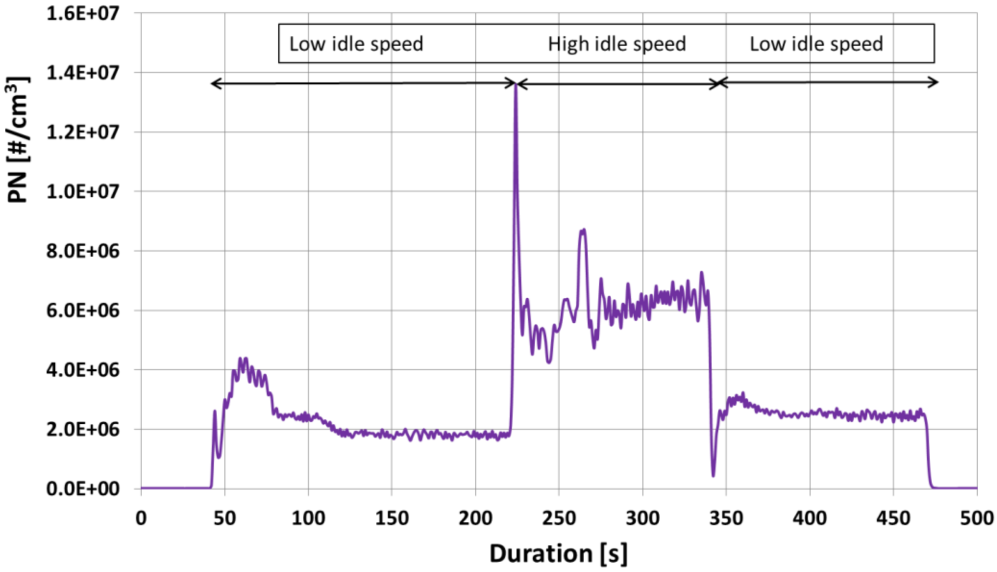


Figure 35: PN emission post DPF of a Ford Focus Euro 5b diesel engine with DPF failure at low idle speed.

The PN emission of an engine is the lowest at low idle speed and related to the air fuel ratio (and/or EGR%??). In the view of the measuring range of future PTI PN testers it is most feasible to design a PTI test at low idle speed.

4.4.6 *PN emissions in NEDC tests with cold and hot start*

In Figure 36 and Figure 37 the PN traces of NEDC tests with cold and hot start are shown. In the test with cold start the PN emission decreases in time. Obviously the filtration efficiency increases with increasing temperature of the DPF.
In the additional NEDC test with a hot start the common PN level is the lowest.

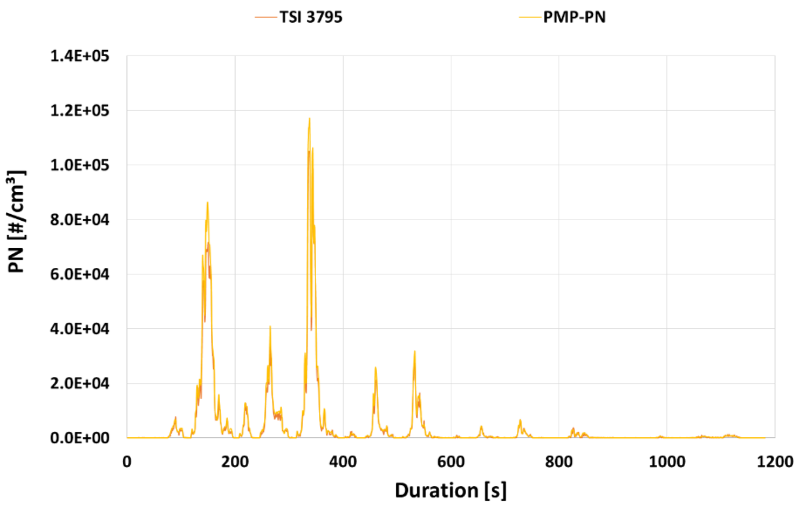


Figure 36: Comparison of PN emissions of the PMP reference method and a mobile TSI 3795 PN tester in an NEDC test with <u>cold</u> start of a Peugeot Partner Euro 6 diesel (with closed DPF-bypass).

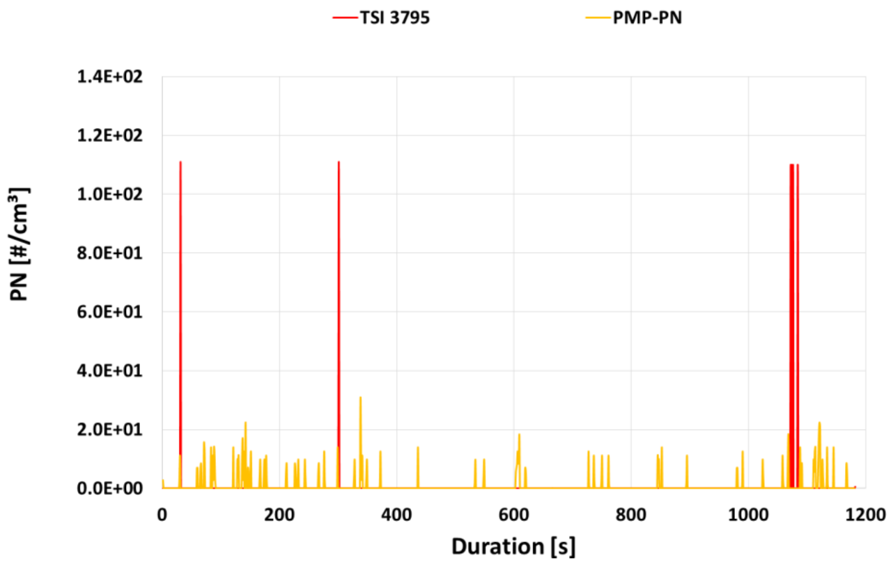


Figure 37: Comparison of PN emissions of the PMP reference method and a mobile TSI 3795 PN tester in an NEDC test with <u>hot</u> start of a Peugeot Partner Euro 6 diesel (with closed DPF-bypass).

4.5 Relations of different PTI and chassis dynamometer tests

Before alternative test procedures for PTI emission test are introduced some results are presented of different diesel vehicles with DPF.
In Figure 38 the PM results of NEDC tests and free acceleration smoke emission test results of four different vehicles are shown. The four different vehicles have in certain tests equal PM emissions (around 4-5 mg/km) but their smoke emission varies from 0.06 to 0.46 m^{-1}. From these results no clear relationship between smoke and PM emissions can be derived.

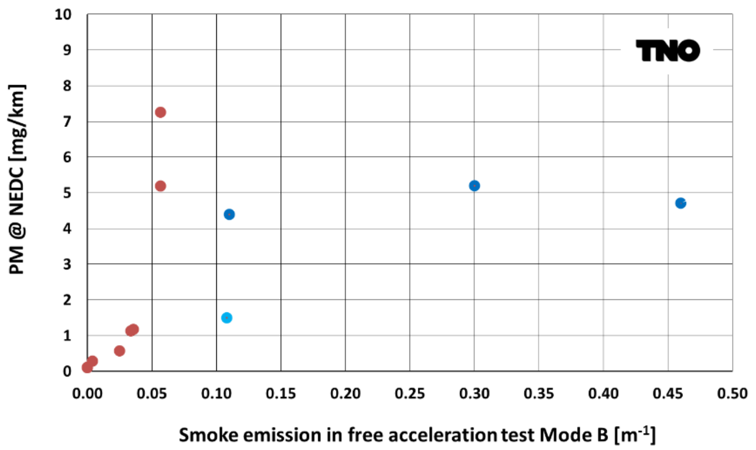


Figure 38: Smoke emissions in free acceleration tests and NEDC PM emissions of four different diesel vehicles with (cracked) DPF or variable bypass (red dots).

In Figure 39 the PM results of NEDC tests and PN results of low idle speed tests of three different vehicles are shown. For the higher emission levels there is no clear relationship between the PM emissions and PN emissions at low idle speed.

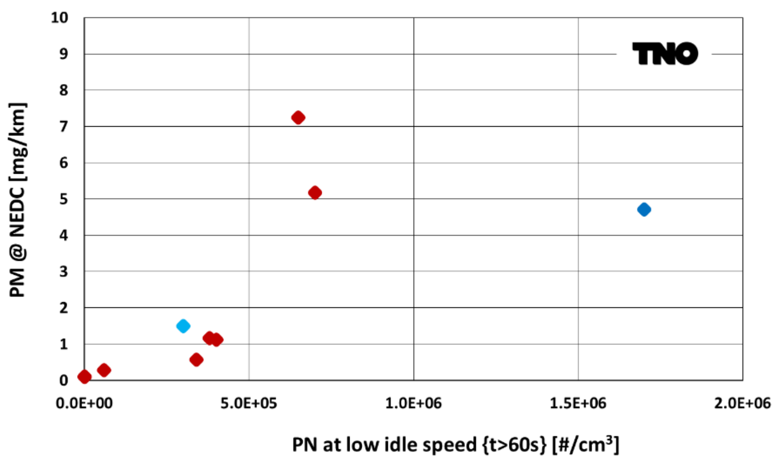


Figure 39: PN emissions in low idle speed tests and NEDC PM emissions of three different diesel vehicles with (cracked) DPF or variable bypass (red dots).

In Figure 40 the PN results of NEDC tests and PN results of low idle speed tests of three different vehicles are shown. It must be noted that the PN emission at low idle speed of these vehicles is decreasing in time. After 60 seconds idling the emission levels are relatively stable and the lowest because the EGR of the engine is deactivated. A quite good linear relationship between PN emissions in the NEDC tests and at low idle speed tests is available and this seems a good basis for a new PTI PN-test.

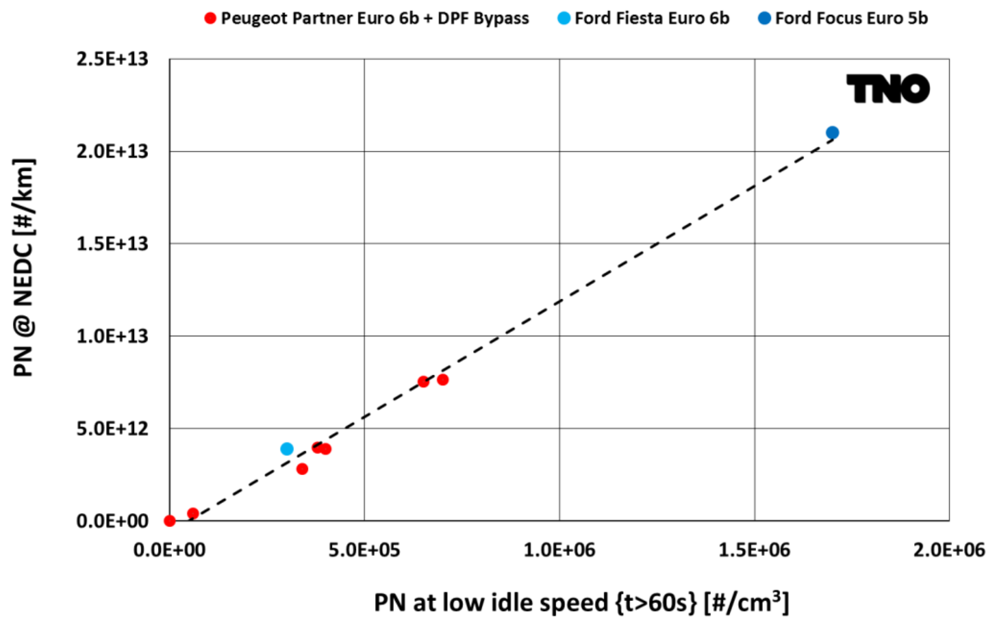


Figure 40: PN emissions in low idle speed tests and NEDC PN emissions of 3 different diesel vehicles with (cracked) DPF or variable bypass.

Smoke emissions of free acceleration tests have a weak correlation with PM emissions in NEDC tests. Results of PN emissions in low idle speed tests and PM emissions in NEDC tests show a moderate correlation. The PN emissions at low idle speed (without EGR) of diesel vehicles with DPF have a strong correlation with PN emissions in NEDC tests. This low idle speed test is very similar to the current UNECE R83 type II type approval test for petrol vehicles and can be easily implemented in current legislation.

4.6 Potential PN limit values for the PTI of diesel vehicles with DPF

PTI PN limit values must be less stringent than the In Service Conformity limit values because a vehicle which passes the ISC procedure may not fail in the PTI test.

4.6.1 In Service Conformity

In Service Conformity is a means to check the emission performance of a vehicle family. It consists of a testing regime on the chassis dynamometer in which the emission performance of in-use vehicles must be checked. All tested vehicles must comply with their type approval emission limit values. In general the ISC limit values are more strict than PTI limit values. Consequently a certain vehicle can pass the PTI-test but it fails in an ISC test procedure. For new PTI test procedures the limit values must be related to ISC limit values,

How is ISC organized today?
Vehicle manufacturers must perform In Service Conformity (ISC) test programs in which PM&PN emissions on the chassis dynamometer are measured. Current regulation for passenger cars requires a procedure of at least three different vehicles in immaculate state to be tested for in service conformity (ISC). The vehicles must have an use-and-maintenance record which excludes all cases of arrears in repair or abuse of the vehicle. For the NEDC not more than 40% of these vehicles may be faulty. For heavy-duty engines a stricter criterion of less than 20% of the engine faulty during its lifetime. Currently, a more strict protocol is discussed, bring the maximal number of faulty vehicles and their exceedances in the emissions at a failure down to reasonable number.
Now it requires the testing of four vehicles which will all fail the NEDC test, to reach a decision of incompliance with the in-service-conformity demands. With 7 vehicles at least 6 must be exceed the NEDC emission limits, to reach the same decision.

Hence in service conformity sets a very strict demand on the number of faulty vehicles from which it can be decided a vehicle family does not comply. To our knowledge, a fail decision has never been reached, based on current legislation. In the case of detection of inferior quality, which may lead to failures which go undetected in the normal maintenance according to the manufacturer's recommendations, the manufacturer will point to their compliance according to the official regulation 83 Annex 8. With this reference, they argue then they are below the maximum of 40% faulty vehicles, for vehicles with proper maintenance and usage records. In principle, manufacturers have very limited liability for such problems, and given the fact that manufacturers set the maintenance standard, it will be difficult to hold an owner to a higher standard in the PTI than the in service conformity limit.

4.6.2 *Proposals for PTI PN limit values*

Euro 5b and Euro 6 diesel vehicles should meet in a type approval test (NEDC) a PM limit value of 4.5 mg/km and a PN limit value of 6 * 10^{11} #/km. Once a PTI-PN limit value is introduced this may not be more stringent than the PN limit value of the type approval test. The PN relationship of Figure 41 seems a good basis for determination of a PTI-PN limit value. For Euro 5b/6 diesel vehicles at low idle speed the limit value might be 250,000 #/cm^3. In the more stressed Figure 42 it is shown that a PTI PN limit value of 250,000 #/cm^3 is relatively easy because the PN emission of such a vehicle in the NEDC test is around 2,5 * 10^{12} #/km (CF=4.2).

In the type approval test of Euro 5a vehicles only a PM limit value is applied. In practice this Euro 5a PM limit value is less stringent than the PN limit values of Euro 5b/6 vehicles. Therefore a higher PTI-PN limit value might be chosen for Euro 5a vehicles. On the basis of a few emission tests a PTI-PN limit value for Euro 5a diesel vehicles at low idle speed might be set at 1,000,000 to 1,500,000 #/cm^3. This PTI-PN limit value might also be applied for Euro 3 and Euro 4 vehicles with a DPF. Further PM/PN investigations of Euro 5a vehicles are needed to build a reliable PN limit value for a PTI test.

When a PTI-PN test is applied as a Type II test of UNECE R83 there is no need to continue the smoke emission tests of UNECE R24 and 72/306/EC.

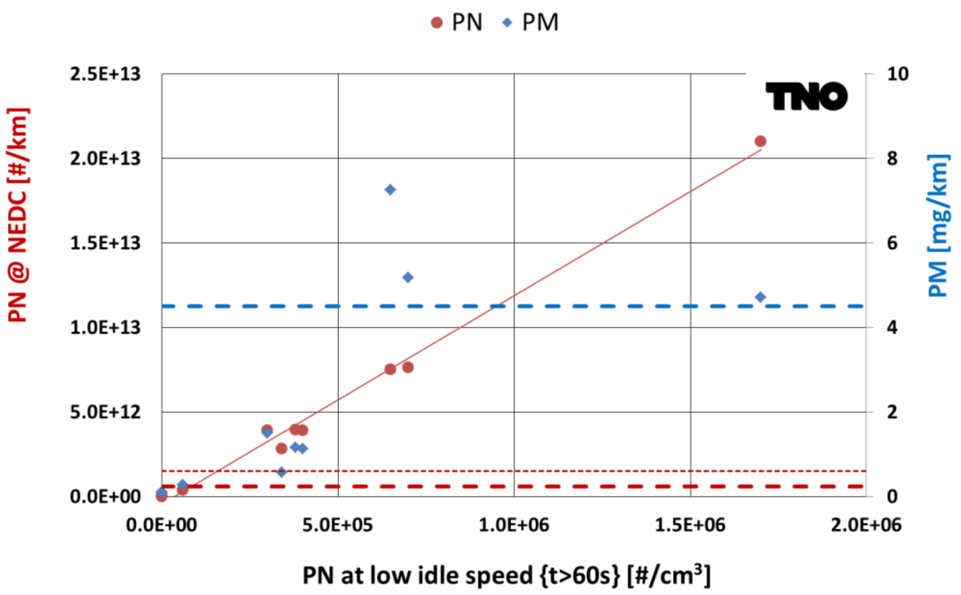


Figure 41: PN emissions in low idle speed tests and NEDC PM&PN emissions of 3 different diesel vehicles with (cracked) DPF or variable bypass.

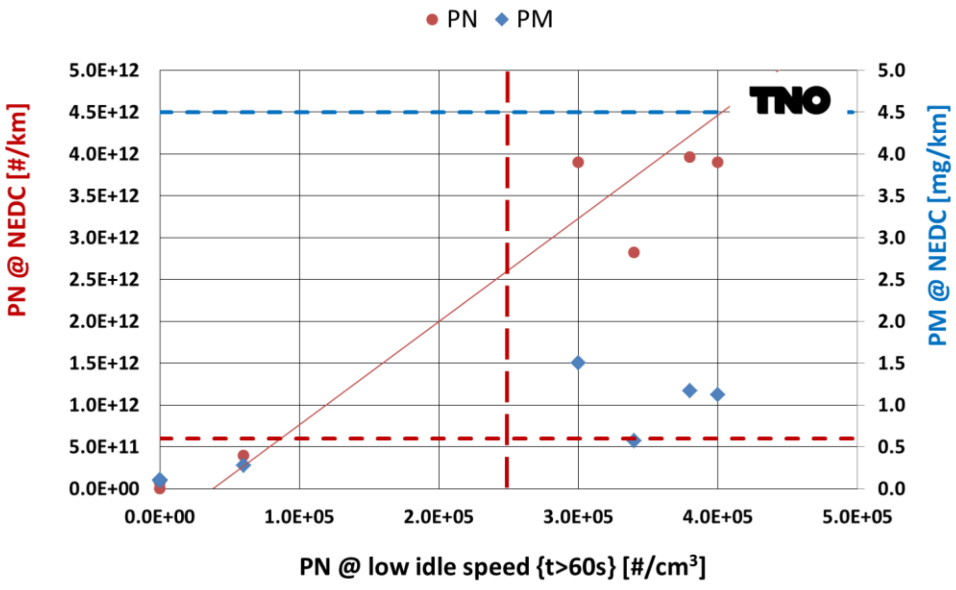


Figure 42: PN emissions in low idle speed tests and NEDC PM&PN emissions of 3 different diesel vehicles with (cracked) DPF or variable bypass and a proposal for a PTI PN limit value of 250,000 #/cm^3.

In a first test program of three vehicles a quite correlation of the PTI-PN emission and the PN emission in NEDC tests is determined. The PN limit value of a new PTI-PN emission test must be less stringent than the PN limit values of the type approval emission test. It is proposed to set a PTI-PN limit value in a low idle speed test of 250,000 #/cm^3 for Euro 5b/6 diesel vehicles and 1,000,000 to 1,500,000 #/cm^3 for Euro 5a vehicles. This limit value might also be used for Euro 3 and Euro 4 vehicles with a DPF. A more profound validation test program is needed to set final PTI-PN limit values.

4.7 PN emissions of petrol vehicles

Following the discussion of PN emissions a short investigation of different vehicles with a petrol engine was carried out. Simple tests at low and high idle speed of IDI and DI engines are executed and the results are plotted in the next figures.
These results show clearly that the PN emission behaviour of petrol vehicles deviates from diesel vehicles with DPF. If a PTI-PN test for petrol vehicles is needed a new research program is needed which is dedicated to the development of a PN-tester for exhaust gas with a high moisture share.

In Figure 43 the PN emission of an IDI petrol engine with more than 200,000 km at high and low idle speed is plotted. At high idle speed the PN emission is below 10,000 #/cm³ and at low idle speed it varies between 20,000 and 50,000 #/cm³, both can be marked as low.

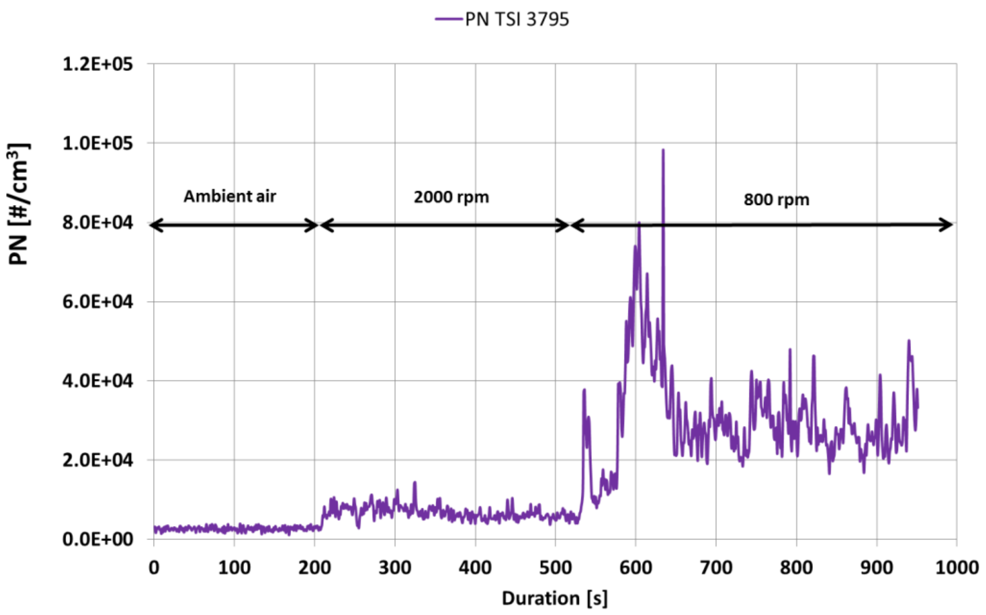


Figure 43: PN emissions of a Citroen C8 2.0 ltr IDI Euro 3 petrol vehicle @ 201,000 km.

In Figure 44 the PN emission of an IDI petrol engine with 91,000 km at high and low idle speed is plotted. Initially at low idle speed the PN emission is very low (< 20,000 #/cm³). At high idle speed in the first part of the warming up of the engine the PN emission is still 20,000 #/cm³ and in the course of time it grows and has peaks (misfiring). At low idle speed the PN emission varies between 20,000 and 50,000 #/cm³.

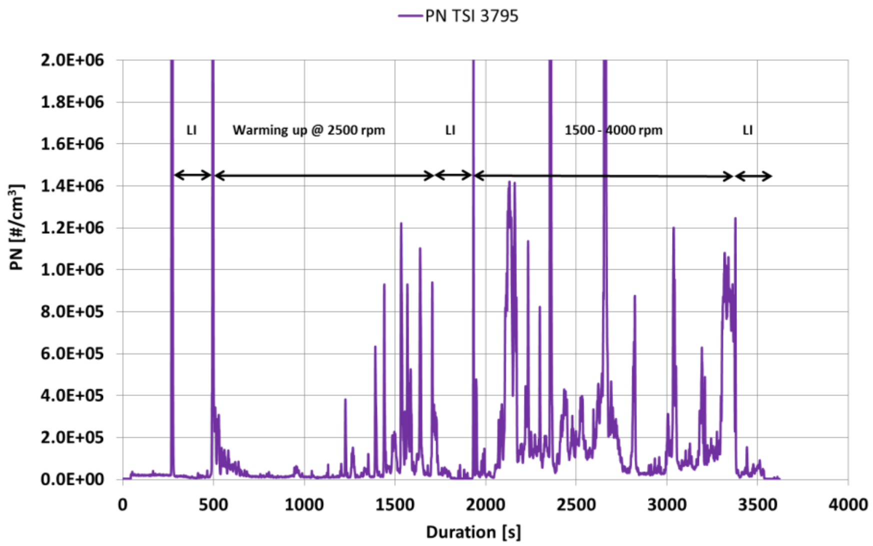


Figure 44: PN emissions of a Fiat Punto 1.2 ltr IDI Euro 4 petrol vehicle @ 91,000 km.

In Figure 45 and Figure 46 the PN emissions of a Peugeot 1.6 ltr DI petrol engine are plotted. After the first cold start in the first 15 seconds, this is the open loop part with an lambda value less than 1, the PN emission is around 8 million #/cm^3 and decreases relatively fast to less than 2 million #/cm^3. Probably the lambda control is activated after 15 seconds because the lambda sensor becomes operational.
At constant engine speeds the PN emission is stable and the PN level is dependent on engine speed. Higher engine speeds create more particles per unit of volume. When moving from one engine speed to a next speed PN emissions become instable. This is probably caused by the poor formation of a air-fuel mixture.
At low idle speed (see Figure 46) with a cold engine the PN emission is around 400,000 #/cm^3 and after warming up this is reduced to 100,000 #/cm^3. During the warming up of the engine @ 2500 rpm the PN emission is around 1 million #/cm^3 which is about 100 times higher than this emission of an IDI engine (see Figure 43).

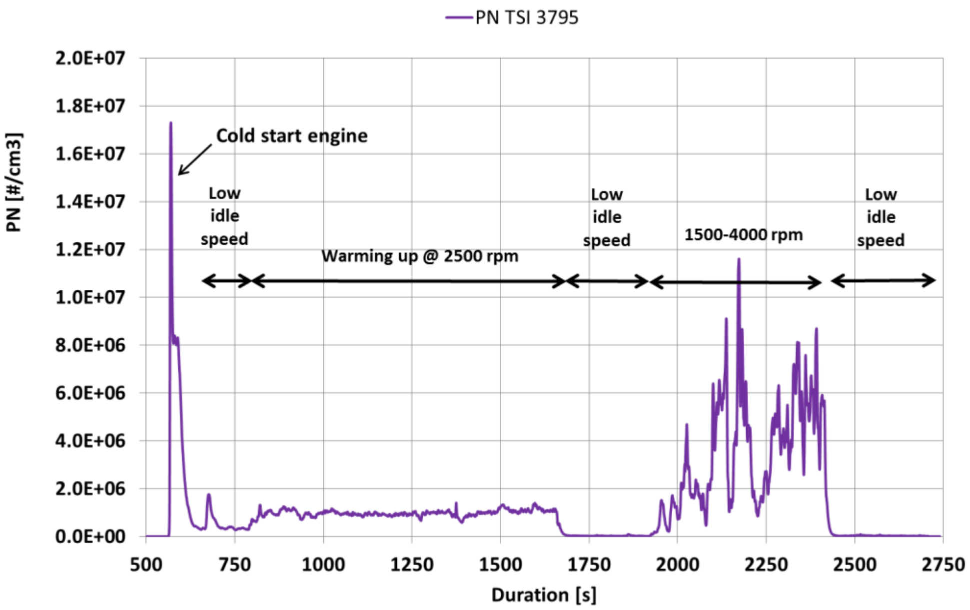


Figure 45: PN emissions of a Peugeot 5008 1.6 ltr DI Euro 5 petrol vehicle @ 110,252 km (1).

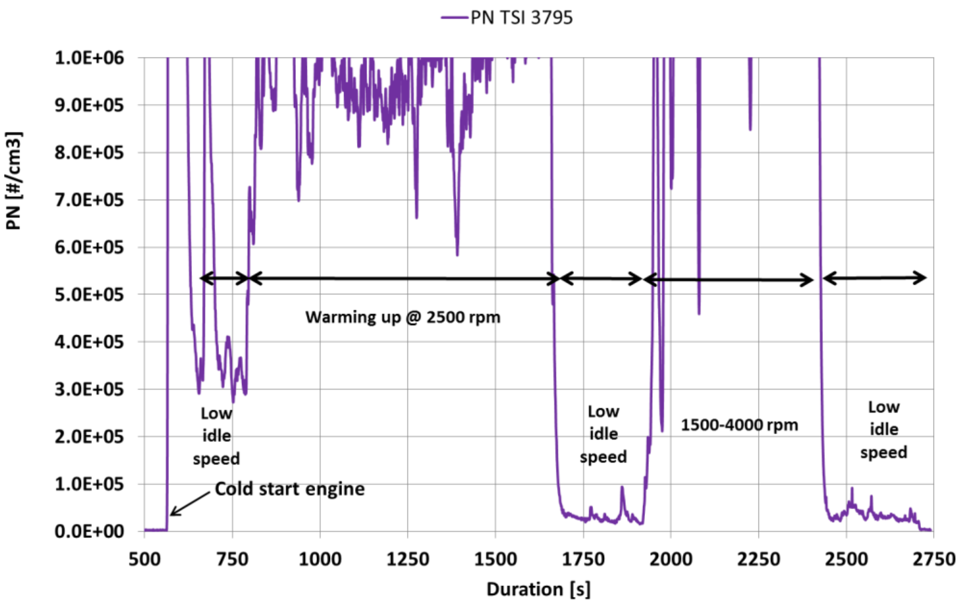


Figure 46: PN emissions of a Peugeot 5008 1.6 ltr DI Euro 5 petrol vehicle @ 110,252 km (2).

In Figure 47 and Figure 48 the PN emission of a Ford Focus 1.6 DI Euro 5 petrol engine is plotted. After the cold start the PN emission peaks at 17 million #/cm3 and decreases over a period of 1800 seconds to around 55,000 #/cm3. Below a PN emission of 200,000 #/cm3 the two handheld testers (3007 and 8525) follow this decreasing trend because these PN concentrations are in their measuring range.. At high idle speed the PN emission is around 100,000 to 150,000 #/cm3.

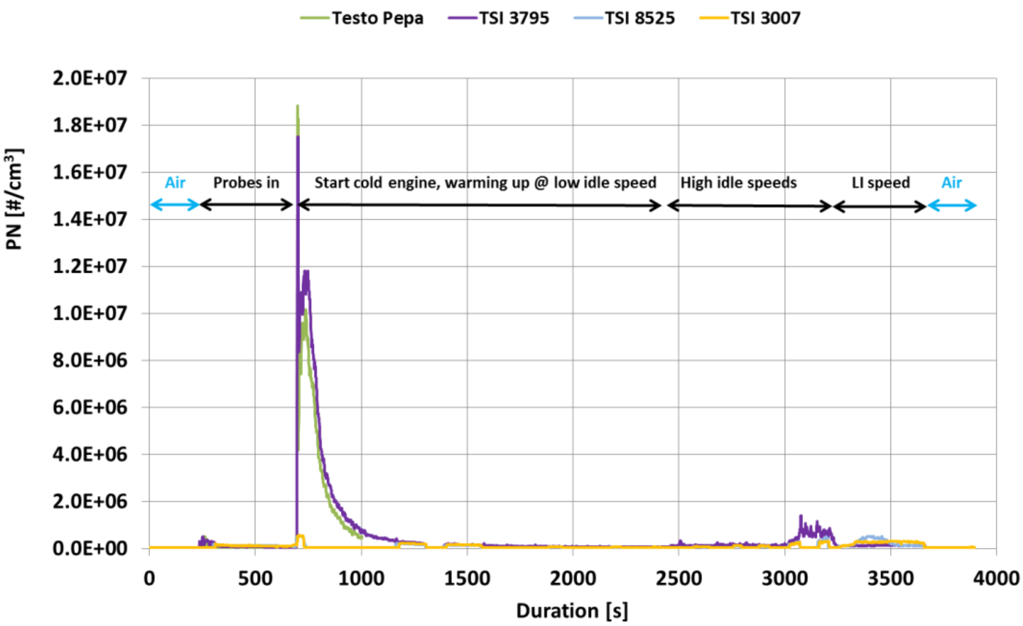


Figure 47: PN emissions of a Ford Focus 1.6 ltr DI Euro 5 petrol vehicle @ 139,592 km (1).

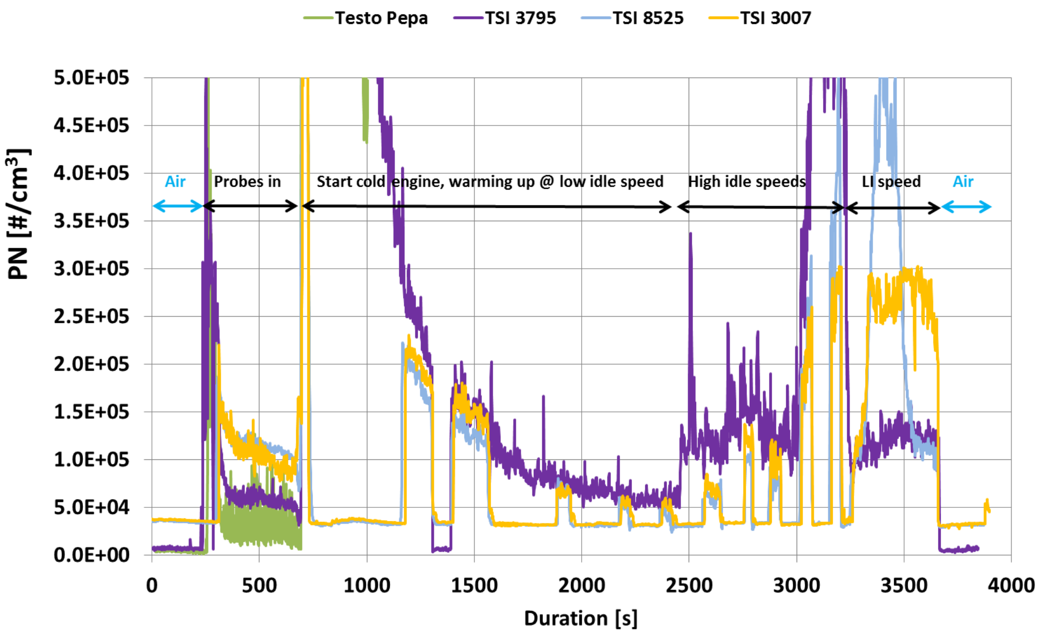


Figure 48: PN emissions of a Ford Focus 1.6 ltr DI Euro 5 petrol vehicle @ 139,592 km (2).

4.8 Discussion and technical conclusions

4.8.1 EOBD systems

Current PTI emission tests of diesel vehicles use EOBD systems and smoke meters but they are not suitable to detect DPF failures. At the long term it is expected that vehicles will be equipped with sensors which monitor the PM/PN and NOx emissions of vehicles. In case of a malfunction the EOBD system will warn the driver or will apply a certain derating. However current EOBD systems are not able to detect DPF failures because the systems are not equipped with PM or PN sensors.

4.8.2 PTI procedure

Different PTI test procedures were investigated in order to detect cracked and/or removed particulate filters.

The application of the free acceleration test with stringent limit value appeared to be not very suitable, due to the following reasons:

- Insufficient sensitivity of the standard opacity meters
- Easy to manipulate the test by actuation time of the accelerator pedal and the frequency setting
- Poor correlation with mg/km and #/km emissions in the NEDC test.
- Excessive noise and pollution in the workshop

The PN measurement at low idle with portable PN equipment scores much better on all these criteria. Reason why this is proposed as future test method.

4.8.3 General requirements of a new PTI test procedure

In order to be able to judge DPF's in a PTI test a new test procedure is needed.
In this research program the main characteristics of this new PTI emission test for diesel vehicles with DPF are investigated, these are:

- A low idle speed test with a hot DPF
- A simplified PTI-PN tester
- PTI-PN limit values of 250,000 – 1,500,000 #/cm^3 (for detection of cracked particulate filters).
- For detection of removed particulate filters a higher limit value can be applied

This new PTI emission test procedure can be implemented in the type II test of UNECE R83.
In order to determine the limit value more test are recommended with cracked and/or removed particulate filter

4.8.4 Simplified PN-testers for the PTI

Current mobile PN-testers for automotive purpose, for example the certified testers that are used to check Swiss diesel machinery that are used for the construction of tunnels, are very close to the PMP-PN specifications and are too expensive for PTI test centers. In order to reduce the costs of a PTI PN-tester simplified specifications are needed.

Based on the results of this measuring campaign and the characteristics of hot DPF's in low idle speed tests the next modifications are proposed:

1. Removal of the catalytic stripper. In this measuring campaign the volatile and solid PN emission of a hot DPF is near zero #/cm³. The volatile particles have been oxidized by the oxidation catalyst of the vehicle and the solid particles remain in the DPF.
2. Simplification of the particle definition. If only particles with a size of 70 nm are counted (this particle size is typical for diesel combustion) the calibration of a PN-tester becomes easier and cheaper.
3. On the basis of a particle size of 70 nm and the need to screen the PN emission of Euro 5a vehicles a certain dilution is proposed (factor 10). A measuring range of 0 – 5,000,000 #/cm³ seems convenient.

The verification of new simple PTI-PN testers and comparison with the PMP-PN method must be part of a next development step.

4.8.5 Potential manipulations of the PTI-PN test

PN emissions might be manipulated with foam in the tail pipe.
In case of a presumption of manipulation the new test procedure should contain possibilities for further technical inspections.

This can be done in three ways:

- Execution of an engine speed ramp (free acceleration) as a preconditioning,
- visual inspection of the exhaust,
- an alternative PN sampling point post DPF (i.e. after removal of a sensor).

5 Conclusions

In order to develop an improved PTI smoke emission test procedure for diesel vehicles with a diesel particulate filter, the smoke, PM and PN emissions of different in-use light-duty diesel vehicles with a DPF were investigated by means of two different test methods: (1) a smoke emission test using an improved opacity meter and (2) a particulate number (PN) measurement using four different particulate number testers. The two opacity meters were used in free acceleration tests; the PN test with the four PN-testers was used in low and high idle speed tests as well as some free acceleration tests.

What can be reported about the current smoke emission test procedure?
The current PTI smoke emission test was developed in the fifties of last century and with current vehicles with DPF the quality of the test result is poor. Generally diesel smoke emissions don't correlate with real world PM&PN emissions.
Current measuring signals of the opacimeter are mandatory filtered and insensitive. Furthermore the accuracy of current PTI smoke meters is +/- 0.3 m^{-1} which results in poor readings below a measuring value of 0.3 m^{-1}. Moreover the reproducibility of a smoke emission test is not well defined because for every free acceleration test the accelerator should be pressed to the bottom in 1 second (which is not monitored). Smoke emissions are very dependent on this activation time of the accelerator.
Finally the smoke emission test can be manipulated if high quality fuels are applied. I.e. GTL diesel fuel consists mainly of paraffin's which yield less smoke than a regular EN590 trade fuel.

What are the general requirements for a new PTI test?
Alternative PTI emission test should be based on:

- A reasonable relation with the particulate emission of the chassis dyno test.
- Easy to carry out in a workshop.
- Relatively low cost equipment.
- Little or no possibilities for manipulation.
- Engine and aftertreatment technology and fuel type.
- The type of emission test.
- The type of measurement.
- The emission limit value.

What is the potential of EOBD technology in the PTI?
Current EOBD technology is not suitable for judgements of DPF's in PTI tests because vehicles are not equipped with PM or PN sensors.

Which alternative test is suitable for the PTI?
A PN emission test at low idle speed with a hot DPF is suitable for PTI purposes. This PN emission correlates well with the PN emission in an NEDC test on the chassis dynamometer, the correlation with PM is less good.

Which PN-tester is suitable for the PTI?
Current mobile PN-testers are accurate but too expensive for most PTI workshops. An expert group of scientists and equipment manufacturers has designed new specifications for a PTI-PN-tester. These new PTI-PN-testers can be engineered, built and validated.

Which PN limit values must be applied in the PTI?
This is dependent on the objective of the test. If you want to disapprove vehicles with DPF with one or more cracks a low limit value of 250,000 #cm3 can be applied. If you just want to disapprove vehicles with a removed DPF and much higher limit value can be applied

The different type approval PM and PN limit values of Euro 5a and 5b/6 diesel vehicles require also different PN limit values in a new PTI-PN-test. A suitable PTI-PN limit value for Euro 5b/6 vehicles might be 250,000 #/cm3 and the limit value of Euro 5a vehicles might be in the range of 1,000,000 – 1,500,000 #/cm3. This limit value might also be used for Euro 3 and Euro 4 vehicles with an DPF. A new PTI-PN-test procedure can easily be implemented in the current UNECE R83 type II test because this low idle speed test for petrol engines is already in use in the PTI. Additionally the deletion of the smoke emission tests of UNECE R24 and 72/306/EC might be considered.

Can this new PTI-PN test procedure be applied in petrol vehicles?
The exhaust gas composition of petrol engines deviates strongly from diesel exhaust gas and a new simplified PN-tester for diesel vehicles cannot be applied in petrol vehicles.

6 Recommendations

In this project a new PTI emission test with a mobile Particulate Number test equipment has been developed. Based on these results a very simple PN-tester for PTI purposes has been specified. It is recommended to validate dedicated PN meters for PTI purposes on different vehicles with different DPF leakages. In order to be able to measure higher PN concentrations, sample dilution with a factor 10 is advised. More tests are also needed for determination of a final limit value or final limit values.

Currently PTI emission tests are derived from tests of UNECE R83 or UNECE R24. The final new PTI-PN test might be implemented in UNECE R83 or 2014/45/EU.

Due to the restricted measuring range of this new PN-tester it is recommended to stick on the current free acceleration test with opacimeter for vehicles without DPF.

7 Abbreviations

CVS	Constant Volume Sampler
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EOBD	Electronic On Board Diagnosis
EUDC	Extra Urban Driving Cycle
GDI	Gasoline Direct Injection
GPF	Gasoline Particulate Filter
GTL	Gas-To-Liquids
HD	Heavy Duty
IDI	InDirect Injection
ISC	In Service Conformity
LD	Light Duty
LNT	Lean NOx Trap
MIL	Malfunction Indication Light
NEDC	New European Driving Cycle
NO_x	Nitrogen Oxides ($NO + NO_2$)
PM	Particulate Matter
PMP	Particulate Measurement Programme
PN	Particulate Number
PTI	Periodic Technical Inspection
SCR	Selective Catalytic Reduction
TWC	Three Way Catalyst

8 References

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9 Signature

The Hague, 1 May 2017

TNO

P.J. van der Mark
Projectleader

G. Kadijk
Author

A Test vehicle specifications

Trade Mark	[-]	Ford
Type	[-]	Focus
Body	[-]	Stationwagon
Vehicle Category	[-]	M1
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Engine Code	[-]	T3DB
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Max. Power	[kW]	110
Euro Class	[-]	Euro 5b
Type Approval Authority	[-]	Luxembourg
Type Approval Number	[-]	e13*2007/46*1138*05
Vehicle Empty Mass	[kg]	1358
Declared CO_2 emission	[g/km]	137
Vehicle Identification Number	[-]	?
Odometer	[km]	139,592
Registration Date	[dd-mm-yy]	27-04-12

B Table test results

Overview chassis dyno test results

					Chassis dyno test				
					NEDC				
			Euro class	Odometer	CO2		NOx	PM	PN
				[km]	[g/km]		[mg/km]		[#/km]
					Declared	Measured			
1	Ford	Focus	5a	155082	109	119	165	4.4	1.5E+13
2	Ford	Focus	5a	160200	115	122	195	5.2	1.9E+13
3	Ford	Focus	5b	39400	109	115	169	4.7	2.1E+13
4	Ford	Fiesta	6b	29000	82	99	53	1.5	3.9E+12
5	Volvo	V40	5b	92315	-	-	-	-	-
6	Peugeot	Partner	6b	21000	110	125	58	0.1	6.7E+10
7	Seat	Ibiza	3	333000	-	-	-	-	-
8	Peugeot	307 SW	3	261000	-	-	-	-	-
9	Peugeot	308	6	104755	-	-	-	-	-
10	VW	Passat	3	425000	-	-	-	-	-
11	Citroen	C8	3	201000	-	-	-	-	-
12	Peugeot	5008	5	110252	-	-	-	-	-
13	Fiat	Punto	4	91000	-	-	-	-	-
14	Ford	Focus	5	139592	-	-	-	-	-
6	Peugeot	Partner	6b	25000	110	118.7	119.7	0.1	1.3E+07
6	Peugeot	Partner	6b	25000	110	120.0	72.3	0.3	3.9E+11
6	Peugeot	Partner	6b	25000	110	119.4	89.3	0.6	2.8E+12
6	Peugeot	Partner	6b	25000	110	120.1	93.6	1.2	4.0E+12
6	Peugeot	Partner	6b	25000	110	120.0	100.7	1.1	3.9E+12
6	Peugeot	Partner	6b	25000	110	121.1	85.9	5.2	7.6E+12
6	Peugeot	Partner	6b	25000	110	118.6	73.9	7.3	7.5E+12

Overview PM & PN & Opacity test results

					PTI											
					Free acceleration				Low idle							
			Euro	Odometer	Opacity		PN	PN	PN							
			class				TSI 3795	Testo-Pepa	TSI 3795	TSI 3795	TSI 3795	TSI 3795	Testo-Pepa	Testo Pepa	TSI 8525	TSI 3007
				[km]	[1/m]		[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]	[#/cm^3]
					Mode A	Mode B	post DPF	post DPF	pre DPF	pre DPF	post DPF	post DPF	pre DPF	post DPF	post DPF	post DPF
									without EGR	with EGR	without EGR	with EGR				
1	Ford	Focus	5a	155082	0.32	0.11	-	-	-				-	-	-	2.6E+05
2	Ford	Focus	5a	160200	0.52	0.30	-	-	-				-	-	-	>540000
3	Ford	Focus	5b	39400	2.28	0.46	-	-	3.2E+06	1.4E+07	1.7E+06	6.0E+06	-	-	-	>540000
4	Ford	Fiesta	6b	29000	0.40	0.11	>4E09	-	2.0E+06	1.6E+07	3.0E+05	4.0E+06	-	-	-	3.4E+05
5	Volvo	V40	5b	92315	0.07	0.03	8.0E+06	6.0E+06	-	-	1.1E+05		-	-	-	-
6	Peugeot	Partner	6b	21000	0.00	0.00	6.0E+03	2.5E+03	2.0E+06	1.5E+07	0.0E+00	0.0E+00	-	9	-	0
7	Seat	Ibiza	3	333000	0.83	0.20	>4E09	1.8E+09	-	9.0E+06		9.0E+06	8.3E+06	8.3E+06	-	-
8	Peugeot	307 SW	3	261000	3.29	1.46	-	-	-	-			-	-	-	-
9	Peugeot	308	6	104755	0.00	0.00	1.0E+03	1.6E+04	-	-	0.0E+00	0.0E+00	-	100	0	0
10	VW	Passat	3	425000	2.24	0.59	>4E09	-	-	-		1.3E+07	-	-	-	-
11	Citroen	C8	3	201000			-	-	-	-		6.0E+03	-	4.0E+03	-	1.4E+04
12	Peugeot	5008	5	110252			-	-	-	-		2.8E+05	-	-	-	-
13	Fiat	Punto	4	91000			-	-	-	-		5.0E+03	-	-	-	-
14	Ford	Focus	5	139592			-	-	-	-		6.0E+04	-	-	5.3E+04	5.3E+04
6	Peugeot	Partner	6b	25000	-	0.000	1.1E+02	-	2.0E+06	1.5E+07	0.0E+00	0.0E+00	-	-	-	-
6	Peugeot	Partner	6b	25000	-	0.004	5.0E+05	-	2.0E+06	1.5E+07	6.0E+04	1.2E+05	-	-	-	-
6	Peugeot	Partner	6b	25000	-	0.025	5.0E+06	-	2.0E+06	1.5E+07	3.4E+05	3.1E+05	-	-	-	-
6	Peugeot	Partner	6b	25000	-	0.036	5.0E+06	-	2.0E+06	1.5E+07	3.8E+05	4.7E+05	-	-	-	-
6	Peugeot	Partner	6b	25000	-	0.034	5.0E+06	-	2.0E+06	1.5E+07	4.0E+05	-	-	-	-	-
6	Peugeot	Partner	6b	25000	-	0.057	1.1E+07	-	2.0E+06	1.5E+07	7.0E+05	1.6E+06	-	-	-	-
6	Peugeot	Partner	6b	25000	-	0.057	1.0E+07	-	2.0E+06	1.5E+07	6.5E+05	1.5E+06	-	-	-	-