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TNO report

TNO 2016 R10735v2

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

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Copy no	2016-TL-RAP-0100297306
Number of pages	63 (incl. appendices)
Number of appendices	
Sponsor	Dutch Ministry of Infrastructure and the Environment PO Box 20901 2500 EX THE HAGUE The Netherlands
Project name	In use compliance program for light-duty vehicles
Project number	060.14432

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 en Euro 6 normen hebben 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 onderzoek van TNO en de RDW blijkt dat bij circa 5 tot 7% van de dieselpersonenauto's met een affabriek 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 On-Board-Diagnostics-systeem (OBD). 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 OBD-controle niet opgemerkt.

Als bij de OBD-uitlezing foutcodes worden aangetroffen, moet 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 verwijderde 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 daarom een verkennend onderzoek uitgevoerd naar de wijze waarop in de toekomst in de APK kan worden gecontroleerd of een goed werkend roetfilter aanwezig is. In het onderzoek is niet alleen gekeken naar aanpassingen van de nu gebruikte methode, de roetmeting, maar is ook onderzoek gedaan naar nieuwe meetmethoden en limietwaarden.

Aanpak
TNO heeft in het verkennend onderzoek vier meetmethodes onderzocht:

1 Als indicatieve test een **veegtest** voorafgaand aan elke meting, om een indruk te krijgen van de zwarting in de uitlaat;

2 De nu bestaande conventionele **roet- of opaciteitsmeting** bij vrije acceleratie van de bedrijfswarme motor, uitgevoerd met:
   a. een **conventionele of 'standaard' roet- of opaciteitsmeter**, én;
   b. 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;

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

4 als indicatieve test een **doekjestest** bij voertuigen die daar op basis van de voorgaande metingen aanleiding toe gaven, om te beoordelen of een voertuig bij 3 minuten stationair draaien op een papieren tissue zwarting veroorzaakt.

In totaal zijn gedurende het onderzoek 213 Euro 5 en Euro 6 dieselvoertuigen gemeten. De voertuigen zijn beschikbaar gesteld door diverse lease- en garagebedrijven in Nederland.

Conclusies
Op basis van de metingen aan de 213 dieselvoertuigen, concludeert TNO per type meting als volgt:

1 de **veegtest is niet geschikt** om in de APK vast te stellen of het roetfilter aanwezig is of goed functioneert. Hoewel een schone uitlaat een goede indicatie is voor een goed werkend roetfilter, kan van een zwarte, vervuilde uitlaat niet met zekerheid worden gesteld dat het filter niet goed functioneert of afwezig is. Dit komt met name omdat niet bekend is over welk tijdsspanne de vervuiling in de uitlaat is afgezet. Ook kan de vervuiling, in plaats van door roetemissies uit de motor, andere oorzaken hebben, zoals bijvoorbeeld olielekkage. Bovendien kan deze test makkelijk worden gemanipuleerd door voor de APK de uitlaat schoon te maken.

2 de **opaciteitsmeting** bij vrije acceleratie, uitgevoerd met:

   a. **de standaard opaciteitsmeter is niet geschikt** om in de APK vast te stellen of het roetfilter aanwezig is of goed functioneert. Deze apparatuur is te onnauwkeurig en te ongevoelig om de lage roetemissies van moderne Euro 5 en Euro 6 dieselwagens te meten;

   b. **de verbeterde opaciteitsmeter is een van de opties** om in de APK vast te stellen of een roetfilter aanwezig is of goed functioneert.

Voordelen
Met zijn hogere nauwkeurigheid dan de standaard opaciteitsmeter is de moderne opaciteitsmeter beter in staat ook bij de lage roetemissies van moderne diesels onderscheid te maken tussen een auto met goed functionerend roetfilter en een auto met een defect of verwijderd roetfilter. Daarbij moet worden opgemerkt dat ook bij de verbeterde rookmeter nog altijd onderin het bereik wordt gemeten, waardoor het discriminerend vermogen van deze meter ten opzichte van de deeltjesteller kleiner is. De prijs van opaciteitsmeters is echter wel lager dan de huidige prijs van deeltjestellers.

Nadelen / verder onderzoek
Metingen met opaciteitsmeter vinden plaats in een vrije acceleratietest. Deze test veroorzaakt veel geluidsoverlast en is relatief lastig uit te voeren. Voor het vaststellen van een adequate grens-rookwaarde is aanvullend onderzoek nodig naar de correlatie tussen rookwaardes in de APK en de emissielimieten voor fijnstof gesteld in de typegoedkeuring. Verder is er op dit moment onvoldoende inzicht in de filtering van de electronische meetsignalen van rookmeters.Toepassen van filtering leidt tot een reductie van de meetwaarden met een factor 2 a 3. Het is op dit moment onvoldoende duidelijk waarop deze filtering is gebaseerd. TNO baseert zich in dit onderzoek op de *ongefilterde* meetsignalen van de geteste opaciteitsmeter, mede vanwege het feit dat de leverancier TNO heeft geadviseerd ongefilterde waarden te meten om een goede vergelijking met de deeltjesteller mogelijk te maken;

3 de **meting van het aantal deeltjes in uitlaatgas met behulp van een deeltjesteller bij stationair toerental is een van de opties** om in de APK vast te stellen of het roetfilter aanwezig is en goed functioneert.

Voordelen
De deeltjesteller levert de beste resultaten. Dit type meter heeft een significant beter onderscheidend vermogen dan de verbeterde rookmeter. Bovendien kan een meting met een deeltjesteller bij stationair toerental worden uitgevoerd. De monsternameslang van de deeltjesteller wordt gedurende korte tijd in de uitlaat van de auto gehouden. De methode is hierdoor zeer snel. Doordat de meting van het aantal deeltjes niet bij vrije acceleratie van de motor hoeft te worden uitgevoerd, is deze methode minder belastend voor de auto en de keurmeester. Uit technisch en arbotechnisch oogpunt heeft de meting met een deeltjesteller dan ook de voorkeur boven de verbeterde opaciteitsmeter. Een ander voordeel is dat deze meting minder eenvoudig te manipuleren is dan de opaciteitsmeting.

Nadelen / verder onderzoek
De gebruikte apparatuur is niet specifiek ontwikkeld voor toepassing in de APK en is nog relatief duur.

4 de **doekjestest is niet geschikt** om in de APK vast te stellen of het roetfilter aanwezig is of goed functioneert. Niet in alle gevallen laten auto’s waarvan het doekje grijs of zwart kleurt ook een hoge opaciteitswaarde en hoge deeltjesaantallen zien. Auto’s met een schone tot licht verkleurde doek laten daarentegen in 21 van de 63 gevallen verhoogde deeltjesaantallen zien en in 7 van de 63 wagens een verhoogde opaciteit.

Aanbevelingen

Ten aanzien van de twee hierboven genoemde opties om in de APK vast te stellen of een roetfilter aanwezig is en goed functioneert, doet TNO de volgende aanbevelingen:

- Voor beide testmethodes, de deeltjes- en de opaciteitsmeting, is in het rapport voor drie verschillende grenswaarden aangegeven welk percentage voertuigen van de geteste vloot in de APK zou worden goedgekeurd. Voor het daadwerkelijk toepassen in de APK verdient het aanbeveling onderzoek te doen naar de correlatie tussen enerzijds deeltjesaantallen (PN) in [#/cm^3] zoals gemeten met de deeltjesteller en opaciteit gemeten in [m^{-1}] én anderzijds de deeltjesmassa (PM) in [g/km] en deeltjesaantallen (PN) in [#/km] zoals gemeten in de typegoedkeuringstest.
- Voor beide meetmethodes moeten de mogelijkheden voor doorontwikkeling en prijs in nauwe samenwerking met onder meer de RDW en leveranciers van de meetapparatuur verder worden onderzocht. Daarbij is het van belang te zorgen voor goede kalibratiemethoden, om de apparatuur bij de garagebedrijven te kunnen ijken.
- Voor goede toepassing van de opaciteitsmeting moet de wijze van filtering van de rookwaardes verder worden onderzocht. Er dienen criteria voor de filtering van de meetsignalen te worden onderzocht en gedefinieerd.
- Verwacht wordt dat de deeltjesteller niet kan worden ingezet bij een APK-test van dieselvoertuigen zonder roetfilter. Voor deze voertuigen wordt aanbevolen om gebruik te blijven maken van de huidige APK testprocedure voor roetmeting.
- Welke meetmethode hiervoor zal worden toegepast, hangt voor een belangrijk deel af van de kosten voor garagebedrijven en keuringsstations. In dit rapport is een beknopte berekening uitgevoerd waaruit blijkt dat de kosten van een APK-test met een deeltjesteller bij een groot aantal testen per jaar vergelijkbaar zijn met een APK-test met een opaciteitsmeting; om een afgewogen besluit te kunnen nemen over invoering dient dit nader te worden onderzocht.
- Het is een gebruikelijke praktijk om bij oudere dieselauto's zonder filter de APK-rooktest te manipuleren door speciale additieven of benzine aan de diesel toe te voegen. Tegenwoordig is er ook fischer tropsch diesel zoals GTL beschikbaar waarmee de rookemissie kan worden teruggebracht. Verder onderzoek is nodig naar het effect van deze (manipulatie-)mogelijkheden op de meetresulaten van de verbeterde rookmeter en de deeltjesteller.

Extended 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}. This indicates that the DPF's of these vehicles were either damaged or removed. The collection of measuring data was performed by many stakeholders in different workshops with different smoke meters, this yields a certain inaccuracy in the test results. Consequently, on basis of the collected data, an accurate determination of a smoke emission limit value for a PTI test is not possible. Therefore an additional test program was required.

Aim and approach

The Ministry of Infrastructure and the Environment asked TNO to investigate test methods and to obtain more reliable smoke emission data as a basis for determination of a smoke emission limit value for periodic technical inspections (PTI) and to start new research regarding PN measurements of diesel vehicles with a DPF. In this report the results of this project are described.

Within this project 213 light-duty vehicles with diesel particulate filters were tested by TNO using different smoke test procedures. The vehicles were mostly Euro 5 class vehicles. All tests were performed by a fixed team of TNO employees to assure the same type of handling procedures during all measurements and with a defined set of instruments. The tests occurred in different vehicle maintenance workshops and storage sites of lease companies in the Netherlands.

Apart from providing insight into the number of vehicles with increased PM and PN emissions, the test results were also used to design and propose a new roadworthiness smoke emission test procedure able to identify vehicles with a malfunctioning or removed DPF. A new test procedure is required because generally, the current roadworthiness test procedure is not able to identify such failures.

All 213 light-duty vehicles were subjected to four different tests:

1 A tailpipe swipe test;
2 Free acceleration and high idle smoke emission test with two opacity meters;
3 Low idle speed emission test with a particulate number meter;
4 Tissue filter test at low idle speed.

On the measurement of the number of particles in exhaust gases
Different methods exist to measure the number of particles in exhaust gas. In the type approval test of vehicles, the particulate numbers are determined by means of the official Particulate Measurement Programme (PMP) method, which quickly dilutes and heats the exhaust gas, and strips it of the organic components. The remaining solid particulates are limited to a size of 23 nanometer minimally. As of Euro 5b, diesel passenger cars may not exceed the PN emission limit of 6,0*E11 per kilometer in the PMP test.

The handheld condensation particle counter (CPC) used in this project does not remove volatile particles and it measures particles with a size down to 10 nanometer. The number of particles measured in this project is therefore likely to be higher than the values encountered during type approval testing.

Conclusions
The results of the above tests lead to the following conclusions for roadworthiness testing of diesel vehicles with diesel particulate filters (DPF):

- Tailpipe Swipe Tests (TST) are not suited as an official PTI test because the test result is not related to the actual condition of the DPF. The TST result can, however, support the judgement of a DPF condition.
- In very conditioned roadworthiness tests with 213 (mainly ex business use) Euro 5 and 6 diesel vehicles, at least 12 vehicles (5.6%) showed elevated smoke emissions (opacity value $k > 0.10\ m^{-1}$). This indicates that the Diesel Particulate Filters of these vehicles are either damaged or removed. If a smoke emission limit value of $0.30\ m^{-1}$ is applied only 3.3% of the vehicles fail. This result is not in line with former failure rates of 6% of random selected vehicles. Possibly the relatively low failure rate is caused by the relatively young and well maintained test vehicles in this project. From the 5% highest emitting vehicles, most vehicles are older than 48 months. This indicates that deterioration of diesel particulate filters is related to DPF-age, supporting the need for DPF testing in PTI's.
- In former research projects it was found that the current smoke emission test procedure with an improved opacity meter was the best option because no better alternative for PTI-purposes was available. However, after detailed research in this project it must be stated that the current PTI test procedure is not very accurate and can be manipulated. This is mainly caused by the poor definition of the execution of the PTI emission test, the characteristics of the dynamic test procedure, the undefined dynamic sample flow characteristics of sample lines and the measurement techniques applied in (improved) opacity testing. Moreover, with a measuring range of 0 to $10\ m^{-1}$, the screening performance of improved opacity meters is unsufficient. Most vehicles with DPF have opacity results that are significantly lower than $0.10\ m^{-1}$ while reasonable limit values are in the range of $0.10 - 0.20\ m^{-1}$.
  Furthermore, the execution of free acceleration tests is not very comfortable and tester friendly and evokes sometimes resistance with vehicle owners because they think the engine is being overloaded during the test.
- It is therefore concluded that opacity tests using improved smoke meters are not preferred for detection of DPF failures. An opacity meter measures black smoke by the principle of light absorption but particulates are not always black. As a result, other particulates cannot be detected by an opacity meter. Due to

the relatively low smoke emissions of a modern diesel engine itself (0.30 – 0.50 m^{-1}) and the very high filtration efficiency of a DPF, small DPF leakages can hardly be detected by an opacity meter.

- Within this project, alternative DPF tests were carried out with a handheld Particulate Number (PN) tester at low idle engine speed with a hot engine. This PN test procedure is relatively easy and one measurement takes only 15 seconds. It has a good screening performance and yields very robust test results. Due to the clear and simple definition of the static test and the speedy and accurate performance of the PN tester, manipulation is not very likely.
  In low idle speed tests with a hot engine and a particulate number limit value of 250,000 particles per cm^3, 8.5% of the vehicles failed.
  Futher improvement of the PN tester may be realized by use of a water separator and sample dilution system.
- Figure 1 shows the PTI failure percentages of this fleet-under-test for the smoke test using the standard and the improved opacity meters and for the test using the PN counter.
  From the test results with a standard opacity meter (blue bars) and a limit value of 0.10 m^{-1} 3,3% of the vehicles fail. This percentage increases to 5.6% with an improved opacity meter (blue/white bars). Due to the very low opacity limit value of 0.10 m^{-1} (1% of the full scale), the sensitivity, accuracy and stability of the equipment around this value of 0.10 become very important. Furthermore, a shortcoming is that these characteristics cannot be evaluated in the current standard static calibration procedures of the smoke opacity meter. Seen from this perspective, the reliability of the smoke emission test result is poor.
  PN-tests (brown bars) allow a higher screening performance (because PN limit values can be set from 50,000 – 250,000 #/cm^3.

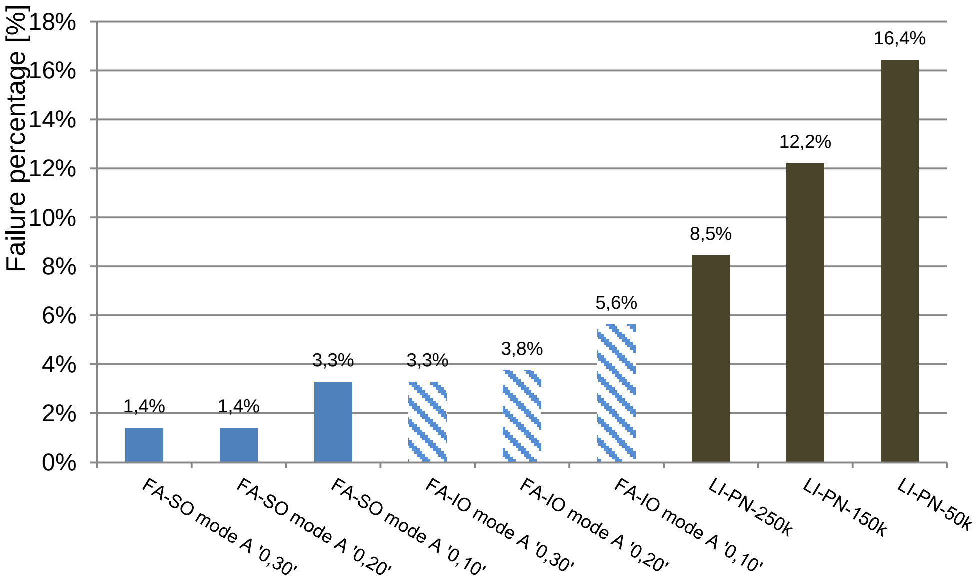

Figure 1: Percentages of DPF failures based on different test procedures and limit values

The costs of the measurement per PTI depend on the price and economic life time of test equipment, yearly maintenance and calibration costs as well as labour time per PTI test and the number of PTI's executed per year. For an improved smoke meter of € 4000,- and a life time of five years and on the basis of 100-1000 PTI's per year, the estimated price per test is in the range of € 3.30 - €15.00. For a PN-meter of € 10.000,- and a life time of 5 years and 100-1000 PTI's per year the estimated price per test is in the range of € 3.30 - € 28.50.

Table 1 an overview and assessment of parameters of three different test methods is shown.

Table 1: Overview assessment of parameters of three different test methods

Parameter	Free Acceleration	Free Acceleration	Low idle
	Standard Opacity	Improved Opacity	PN
Comment	Current method	Improved 1 'CITA'	Improved 2
Representativeness	+/-	+/-	++
Sensitivity, threshold	--	+/-	++
Accuracy	-	+	++
Reliability	+/-	+	++
Screening performance	--	-	++
Reproducability	-	-	++
Repeatability	+/-	+/-	++
Executibility	+/-	+/-	++
Costs	+	+	+/-
Costs [€/test]	3.30 – 15.00	3.30 – 15.00	3.30 – 28.50
Test duration	+/-	+/-	++
Comfort for tester	-	-	+
Acceptance vehicle owner	+/-	+/-	++
Maturity	++	+	+
Limit values	--	+	++
Limit values	0.7 m^{-1}	0.10 m^{-1}	250,000 $\#/cm^3$

Recommendations
In this project, smoke emission tests were performed with opacity meters as well as with Particulate Number measurement equipment as a basis for the determination of a(n) (smoke) emission limit value for periodic technical inspections (PTI). On basis of the results, it is recommended to develop dedicated PN-meters for PTI purposes because the results of the PN-test at low idle engine speed are very robust and reflect the condition of the DPF. In order to avoid too high measured PN concentrations sample dilution with a factor 10 is advised. With respect to the measurement equipment, a cost saving can probably be reached by not implementing a catalytic stripper which removes volatile fractions from the sample. Furthermore it is recommended to develop a calibration procedure for PN-meters that can be executed in a simple way by service personnel in the workshop.

It is expected that a new PN-meter cannot be applied for PTI's of diesel engines without DPF. For these vehicles it is recommended to stick with the current PTI smoke emission test procedure.

In the past, PTI smoke emission tests were manipulated by adding special liquids or petrol to the diesel tank to reduce smoke emission levels. In general currently it is very hard to detect malfunctioning or removal of a DPF because smoke emissions of modern engines are very low. In addition new fuels, like BTL and GTL, even reduce smoke emissions with more than 50%. Therefore it is recommended to investigate the effects of such manipulation practices on the measurement results of the improved smoke opacity meter and the PN-counter.

Contents

1 Introduction

1.1 Background

In order to decrease their particulate matter (PM) emissions, modern diesel passenger cars are fitted with a Diesel Particulate Filter, or DPF. DPF's are a very effective means of reducing PM emissions: when functioning well, DPF's are found to be capable of reducing the PM emissions to practically zero. Since 2011, a PN limit value for DPF-equipped vehicles is also applied (Euro 5b). The exact determination of PM and PN emissions is however only possible on a chassis dynamometer with a dilution tunnel. This sophisticated, expensive technique is not available for everyday roadworthiness checks in service shops.

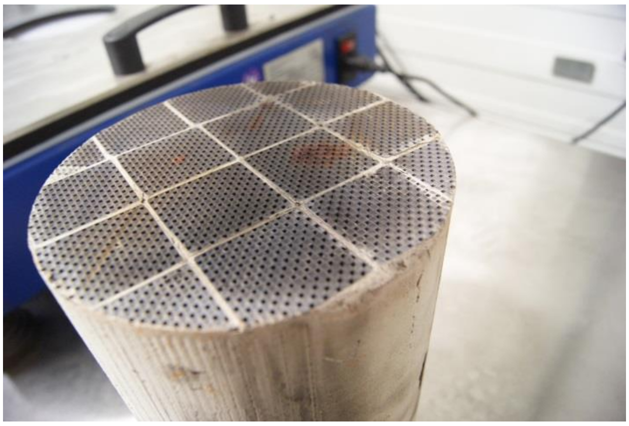

Figure 2 A deinstalled DPF, in this case originating from a Citroen C4 (left). Whereas DPF's vary in size and shape, the height of this DPF is approximately 20 cm; its radius is about 10 cm. A DPF is installed in the exhaust pipe of the vehicle. The zoom-in at the right clearly shows the channels designed to trap the particles.

In order to verify the smoke emission of vehicles in roadworthiness tests, a free acceleration test was developed in which the peak smoke emission or opacity is determined. In general, no correlation between PM/PN emissions and smoke emission exists. Table 2 shows an overview of emission limit values.

Table 2 PM and PN emission limit values of light-duty diesel passenger cars.

		Type approval	
Emission class	Entry into force	Particle Mass limit value (PM)	Particle Number limit value (PN)
		[mg/km]	[#/km]
Euro 1	1993	140	-
Euro 2	1996	80	-
Euro 3	2000	50	-
Euro 4	2005	25	-
Euro 5a	2009	5	-
Euro 5b	2011	4,5	$6 * 10^{11}$
Euro 6b	2014	4,5	$6 * 10^{11}$
Euro 6c	2017	4,5	$6 * 10^{11}$

In type approval and roadworthiness free acceleration tests, the smoke emissions of diesel vehicles are determined with opacity meters 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 0.4 m^{-1} will be registered with a plate value of 0.9 m^{-1}. In roadworthiness tests the plate value of this vehicle is valid and the measured smoke emission may not exceed a value of 0.9.
The maximum allowed smoke emission limit plate values are reported in Table 2.

Table 3 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}. Consequently test equipment and test procedures that are currently used in PTI[1] testing are not capable of adequately assessing 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.

From an air quality perspective, it is important that the presence and proper functioning of a vehicle's DPF is adequately established during the car's life. Therefore, the Ministry of Infrastructure and the Environment asked TNO to collect information on the performance of DPF's in the Dutch car park and, based on this information, to design a PTI test procedure that enables PTI inspectors to reliably determine whether a DPF is present and functioning well.

In the past several research projects and field tests for the development of new roadworthiness emission tests [1], [2], [3], [4], [5] were performed. Most of these experiments were carried out with opacity meters 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 opacity meter. CITA [5] proposes a pass/fail limit k-value of 0.20 m^{-1}.
In these projects the collection of measuring data was performed by many stakeholders in different countries with different smoke meters. This yields a certain inaccuracy in the test results. Consequently, the determination of a limit value is not

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

very accurate. Moreover, if the limit value is set near 0.10 or 0.20 m^{-1}, the accuracy of the test method and the quality of the measuring data become even more important. In order to determine an appropriate and reliable (smoke) emission limit value more controlled conditions of experiments are needed. In addition to former research projects, a new Particulate Number (PN) test procedure is investigated in this research and development project.

1.2 Objectives and approach

The objectives of the research presented here are:
1 to gather information on the particulate matter emissions of a large number of in-use Euro 5 and Euro 6 diesel passenger cars, and, subsequently;
2 to advise on a new PTI procedure capable of detecting cars with a removed or faulty DPF.

To this end, TNO performed opacity measurements using two types of opacity meters or smoke meters. To get indicative results on the particulate number emissions of the cars, tailpipe tests were performed using a handheld Condensation Particle Counter. Additionally, a tailpipe swipe test was performed on all cars. Cars that indicated poor results during the aforementioned tests were tested by means of tailpipe tissue filter test.

All measurement equipment and supporting materials were placed in a van, thus creating a mobile laboratory capable of performing measurements throughout the Netherlands.

The tests were performed on a total of 215 diesel cars (24 trade marks). Test cars were kindly made available by four large Dutch car lease companies and three car shops. The measurements were carried out on the premises of these companies.

Figure 3 The measurements were carried out on-site at various lease companies and car shops using a ‘mobile laboratory’.

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

1.3 Project partners

As stated above, several lease companies and car shops were of great help in this project. The cooperating companies gratuitously provided test cars and their facilities. TNO thanks Arval BV, ALD Automotive, Business Lease Nederland B.V., Athlon, Vakgarage Van ‘t Hoog, Bovag Autobedrijf Alewijn Ott and Digicar Engineering.

Apart from the participating companies, several others offered assistance as well. TNO values very much the response of Autobedrijf Bloemberg B.V., Delsink Auto’s, MAK Auto & Techniek, Herwersgroep, Automobielbedrijf Hooijer B.V., Autobedrijf Bloemberg B.V. and other companies.

Additionally, TNO thanks the Dutch Association of Car Leasing Companies VNA and BOVAG for reaching out to their members on behalf of TNO.

Finally, measurement equipment and assistance was kindly made available by TEN Automotive Equipment and TSI / j.j. bos b.v..

1.4 Structure of this report

The test programme is described in chapter 2, after which chapter 3 presents the test results. The results are further analysed in chapter 4. Cost estimates for two different PTI test methods are given in chapter 5 and an overview and assessment of test methods is presented in chapter 6. Conclusions and recommendations are given in chapters 7 and 8.

2 Test programme

2.1 Tested vehicles

As stated in the introduction, several car lease companies and car shops made test cars available. Test cars provided by lease companies were ex-lease diesel passenger cars, i.e. cars of which the lease term finished, and were offered for sale. The test cars made available by car shops were used cars, also offered for sale.

As Table 4 shows, a total of 215 diesel cars were tested. The majority of the tested cars were Euro 5 diesel passenger cars.

Table 4 The tested diesel vehicles, categorized by euro class and vehicle type.

Euro Class	Passenger cars	Light Commercial Vehicles	Total
4	0	2	2
R*	6	0	6
5	196	7	203
6	4	0	4
Total	**206**	**9**	**215**
***** Euro 4 cars fitted with a DPF			

In this report, the two Euro 4 LCV's are not taken into account as they are not fitted with a DPF. Cars designated 'Euro R' by the Netherlands Vehicle Authority ("RDW") are Euro 4 cars fitted with a DPF to fulfil the Euro 5a particle emission limit of 5 mg/km. DPF's at that time were not yet obligatory, but in anticipation of the Euro 5a legislation car manufacturers introduced this technology about halfway the Euro 4 era. As the DPF technology in these 'Euro R' cars is identical to the DPF's Euro 5 and 6 cars are equipped with, the passenger cars of 'Euro R' were included in this project. All investigations of the test results are therefore based on 213 vehicles, which are all equipped with a closed DPF.

Table 5 shows the odometer readings of the tested cars, categorized into six odometer ranges.

Table 5 Odometer readings of the tested vehicles, excluding the Euro 4 LCV's of Table 4.

Odometer [km]	Passenger cars	Light Commercial Vehicles	Total
0 – 50,000	7	0	7
50,001 – 100,000	45	2	47
100,001 – 150,000	70	2	72
150,001 – 200,000	58	2	60
200,000 – 250,000	18	1	19
250,000 – 300,000	5	0	5
Unknown	3	0	3
Total	**206**	**7**	**213**

2.2 Test equipment

TNO performed opacity measurements in free acceleration tests using two types of opacity meters or smoke meters, the TEN EDA2 and the TEN LPA (Figure 4). The particle number (PN) measurements were performed at idle engine speed using the TSI 3007, a handheld Condensation Particle Counter (CPC, Figure 5, Figure 6)

Figure 4 Opacity was measured using two types of opacity or smoke meters. The conventional EDA2 (right), and the modern, more accurate LPA (left). Both smoke meters are manufactured by TEN Automotive Equipment. As the picture shows, the in-line opacity meters were inserted into the exhaust pipe simultaneously.

Figure 5 The particle number (PN) measurements were performed using the TSI 3007, a handheld Condensation Particle Counter (CPC). A sample hose, connected to the 3007, was kept in the exhaust flow with the engine running at idle engine speed.

Figure 6 The sample hose was kept in the exhaust pipe until the read-out stabilized.

Table 6 gives an overview of the technical specifications of the test equipment.

Table 6 Specifications of TEN EDA2 and LPA smoke meters and the TSI 3007 Condensation Particle Counter used in this project.

Tester	**TEN**	**TEN**	**TSI**
Name	EDA2	LPA	3007
Principle	Opacity (k)	Opacity (k)	PN counter
Measuring unit	[m^{-1}]	[m^{-1}]	[#/cm^3]
Measuring range	0 - 10	0 - 10	0 - 100,000
Maximum reading	10	10	100,000*
Resolution	0.01	0.001	1
Minimum measurement value	0.01	0.001	1
Size range [nm]	n/a	n/a	10 – 1,000
Applied measurement frequency [Hz]	5	5	1
Accuracy [m^{-1}, %]	+/- 0.3	+/- 0.01	+/-20%
Response time T95 [s]	n/a	n/a	9
Sampling line	Non heated	Non heated	No
Sample pump	No	No	Yes
Sample flow [cm^3/min]	-	-	700

* The measuring cell of the TSI PN meter is able to reliably detect up to 100,000 particles per cm^3. PN readings above 100,000 particles per cm^3 are likely to underrepresent the actual number of particles as the measuring cell can no longer distinguish all separate particles.

The EDA2 opacity meter has been on the market for several years now, and has a limited resolution of 0,01 m^{-1}. It is currently used in PTItests to measure smoke emissions of older diesel vehicles, and was therefore included in this project.

The LPA opacity meter is a newly developed opacity meter, with a much higher resolution than that of the EDA2: 0,001 m^{-1}. Based on this resolution, it is thought the LPA might enable reliable opacity measurements on modern diesel cars and that it might be able to identify cars with a missing or faulty DPF.

In order to prevent noise in the opacity measurements, opacity signals in periodic technical inspections (PTI) are filtered. In a filtered mode, the opacity meters yield less peaky and more stable readings. In the unfiltered mode, the opacity meters respond more quickly and produce more accurate test results.

One of the sub goals of this project is to investigate if a correlation between PN measurements and opacity measurements can be found. The PN meters are quite fast and accurate meters. Given this fact and in consultation with the manufacturer of the opacity meters, the opacity measurements in this project were carried out in the unfiltered mode. This allows for a better comparison of particle emissions and opacity. The data analysis in this project is mainly based on the test results of the new, accurate LPA, data of which is referred to as “improved opacity” or “improved opacity values”, and the TSI 3007 PN counter.

The measuring cell of the TSI PN meter is able to reliably detect up to 100,000 particles per cm^3. As the number of particles exceeds 100,000 per cm^3, the measuring cell is no longer able to ‘perceive’ all particles due to the fact that particles start to cover other particles. This means that PN readings above 100,000 particles per cm^3 are likely to show values that are lower than the actual PN emissions. For example, when the PN meter reports 500,000 particles per cm^3, the real-world PN emissions are likely to be higher than 500,000 cm^3. Although there is no exact data available on the deviation between reported PN emissions and actual PN emissions, this deviation grows with increasing numbers of particles. As a further example: if car A has an emission of for example 250,000 particles per cm^3, and another car (B) has an emission of 400,000 particles per cm^3, it is safe to say that car B emits more than car A – although no exact emission level can be given.

The smoke meters were connected to a laptop and data was logged using dedicated software. The TSI 3007 logs data internally, and test data was retrieved from the device by connecting it to a laptop at the end of a measurement day.

Figure 7 The smoke meters were connected to a laptop and data was logged using dedicated software. The TSI 3007 logs data internally, and test data was retrieved from the device by connecting it to a laptop at the end of a measurement day.

Additionally, a Tailpipe Swipe Test (TST) was performed on all cars. The tailpipe swipe test was performed by swiping the end of exhaust pipe with a clean finger. Cars that indicated poor results during the aforementioned tests were tested by means of Tissue Filter Test (TFT). For this test, normal napkins were used.

2.3 Test Protocol

Whenever possible, participating car lease companies and car shops beforehand shared the license plate numbers of the cars available for testing. Based on this, TNO checked the Euro class and type fuel for these cars to establish the set of vehicles to be tested. On the day of testing, the cars were localized and then underwent the following test sequence:

1. Registration and check of the vehicle
2. Tailpipe Swipe Test (TST)
3. Engine warm-up
4. Free Acceleration tests (FA)
5. High Idle speed test (HI)
6. Low Idle speed test (LI)
7. Tissue Filter Test (TFT)

Using this well-defined test protocol for each vehicle allows for reliable test results to be obtained.

2.3.1 Registration and check of the vehicle

Cars to be tested were photographed and their main characteristics were registered. Cars were checked for damage and error codes on the dashboard. In case a car signalled error codes relevant to functioning of the DPF or the car showed abnormal engine operation, the car was rejected for the test.

2.3.2 *Tailpipe Swipe Test (TST)*

The tailpipe swipe test is a very simple test, yielding a first impression of the vehicle's PM emission. The test allows the tailpipe to be checked for soot by simply swiping it with a finger. The finger touches the inner tailpipe and swipes over a small surface. In case of loose layers a finger or tissue will collect deposits, which in most cases can be recognised as black soot.

The results were categorized into four groups or scores: clean or no darkening (0), grey (1), black (2) and deep black (3). Clean tailpipes generally show no soot at all and leave fingers absolutely clean, indicating a well-functioning DPF. In case of heavily soiled tailpipes, a black, sticky and greasy layer of soot can be found. This black soot may indicate a malfunctioning or removed DPF.

Figure 8 Example of two tailpipe swipe tests resulting in a deep black finger, scoring 3.

2.3.3 *Engine warm-up*

In order to prevent engine damage, free acceleration tests must be performed with a hot engine. After having performed the tailpipe swipe test, the engine of the test cars was therefore properly warmed up. As due to insurance matters the test cars were not allowed to be driven off the companies' premises and free space was limited, the engines of the test cars were warmed up by letting them idle. Idling time was at least 30 minutes and on average, cars had idled for almost 2 hours before the tests were performed. In order to load the engines, the airconditioning and lights were switched on to let the engine warm faster.

2.3.4 *Free Acceleration test (FA)*

In a free acceleration test, the accelerator pedal is depressed quickly (< 1 s) to speed up the engine. Most engines emit measurable black smoke during a free acceleration test, but, as the DPF almost completely filters smoke emissions, opacity meters in use today normally measure a zero emission on modern diesel vehicles with a DPF.

In the free accerelation test, the probes of both smoke meters were inserted into the tailpipe, in line with the exhaust flow (Figure 9). It is assumed that both meters are charged with equal exhaust gas mixture.

Figure 9 The probes of the LPA and EDA2 opacity meters were both inserted into the tailpipe during the free acceleration test and the high idle speed test. This way, both smoke meters measured simultaneously. Also see Figure 4.

Figure 10 shows an example of an LPA opacity measurement on a *high-emission* Euro 5 vehicle, with the LPA in the unfiltered mode. Its pattern is typical for an opacity measurement: first, one or more high(er) peaks occur, which can be associated with lubricating oil, soot or other substances still present in the exhaust. Usually, during the first couple of free accelerations these remaining substances are removed from the tailpipe, after which a more or less stable opacity value is found. In this project, whenever possible, the final opacity value for a car was the average smoke value of three stable opacity readings. In the example of Figure 10, the first two peaks of 0,9 m^{-1} and 0,65 m^{-1} are associated with remaining pollution in the exhaust pipe; the signal in the end stabilizes at three opacity readings of 0,4 m^{-1}. Compared to most other Euro 5 vehicles measured, this car showed elevated opacity.

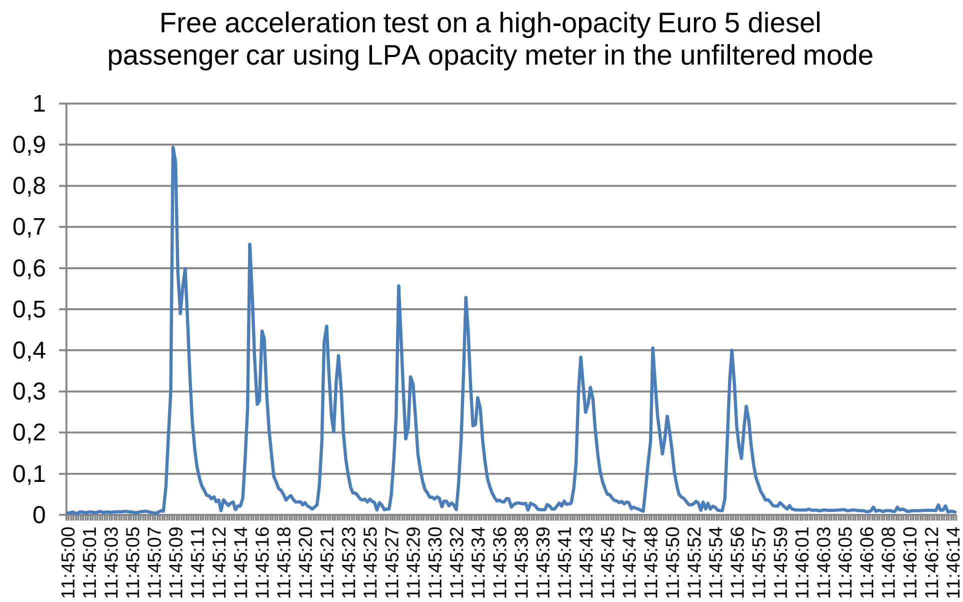

Figure 10 Example of opacity measurement of a Euro 5 diesel passenger car, measured during a Free Acceleration test using the LPA opacity meter. This car shows elevated opacity compared to most Euro 5 vehicles measured.

Figure 11 shows the results of a free acceleration test on a *low-emission* Euro 5 passenger car. This kind of low smoke values were frequently encountered for Euro 5 and Euro 6 cars during the measurement series. 52 of the tested cars had average opacity values not exceeding 0,005 m^{-1}. In case of the vehicle in Figure 11, opacity during the three accelerator operations even reached a value of 0.000 m^{-1}, as the figure shows. With clean cars, the free acceleration tests cannot always be easily discerned from the opacity measured in between free acceleration tests. Therefore, opacity values were written down during testing. After performing the experiments, opacity profiles were looked back to verify the results.

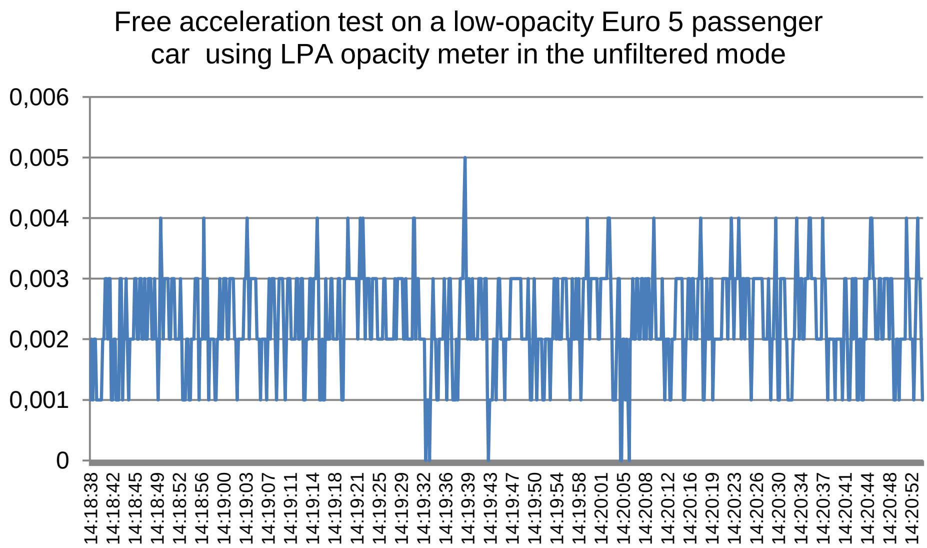

Figure 11 Example of opacity measurement of a Euro 5 diesel passenger car, measured during a Free Acceleration test using the LPA opacity meter. This car shows low opacity values, comparable to many of the tested Euro 5 and 6 vehicles.

2.3.5 High Idle speed test (HI)

After the free acceleration test, the engine speed was kept at high idle speed of 2500 rpm for approximately 10 seconds and the smoke emissions were registered by both smoke meters.

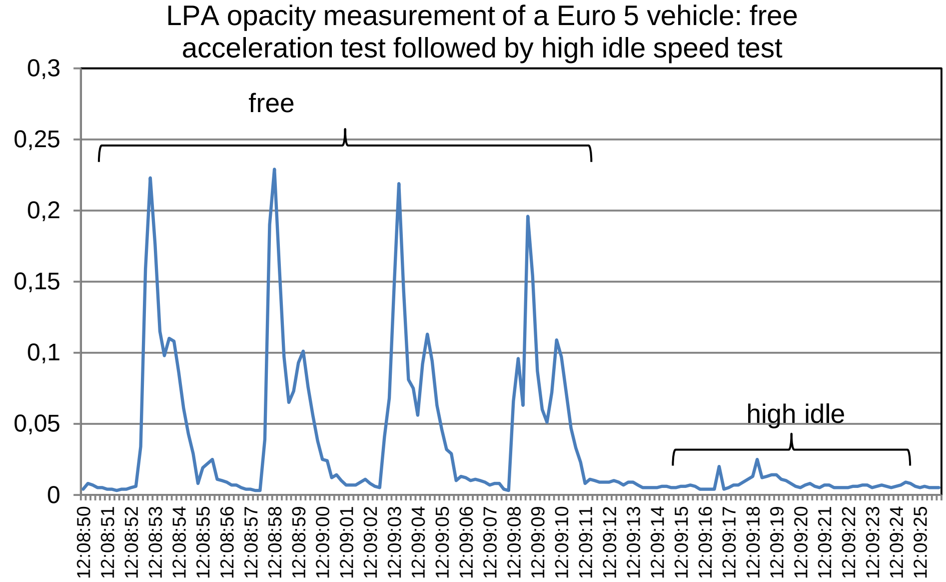

Figure 12 High idle speed test on a Euro 5 vehicle, directly following a free acceleration test on the same vehicle. In a high idle speed test, engine speed was kept at approximately 2500 rpm for 10 seconds.

Smoke emissions during high idle speed tests are generally lower than peak emissions during free acceleration tests, as Figure 12 clearly shows. For the vehicle at hand, smoke emissions during high idle testing are approximately 0,005 – 0,007 m^{-1}; two peaks occur at 0,02 and 0,025 m^{-1} (Figure 13).

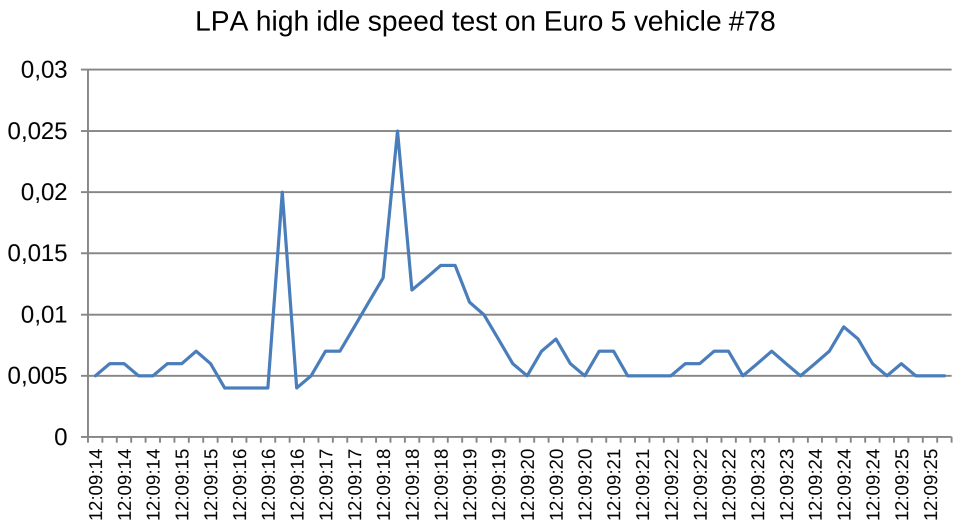

Figure 13 Zoom-in on the high idle test of Figure 12, showing emissions of approximately 0,005 – 0,007 with two peaks of 0,02 and 0,025 m^{-1}.

2.3.6 Low Idle speed test (LI)

After the high idle speed emission test, the smoke meter probes were removed from the tailpipe. Subsequently the low idle speed test was performed: the Particulate Number emission in the undiluted exhaust gas was measured by means of the TSI Condensation Particle Counter with the engine running at low idle speed (Figure 5 and Figure 6). Most of the PN measurements were executed twice or three times to check the repeatability of the test result and the average values of two stabilized measurements were reported whenever available.

Figure 14 and Figure 15 show the results of PN measurements on a car with high particulate emissions and on a car with low particulate emissions respectively.

Both graphs show the phenomenon of background concentration: the ambient air itself contains many different particulates or particulate matter. Partly, this particulate matter originates from natural sources. Sea salt and sand are examples of this. Another part of particulate matter originates from human activities. For example, the use of vehicles causes particulate emissions by the burning of fossil fuels and brake and tyre wear, and particulate emissions arise in many industrial activities, using a fireplace at home, etc.

The background concentration varies from location to location. In a heavy-industrial area and associated transport activities, generally higher background concentrations are found than on the country side, far away from pollutant highways and industrial plants. Also, weather conditions have an effect on the number of particles in the air.

Figure 14 shows the PN measurement performed on a Euro 5 LCV. As can be seen in the figure, the background particulate matter concentration on the test location was around 25,000 particles per cm^3. Three tailpipe measurements were performed, represented by the three peaks at approximately 105,000, 76,000 and 75,000 particles per cm^3. For this vehicle, an average PN emission of a little over 86,000 particles per cm^3 was reported.

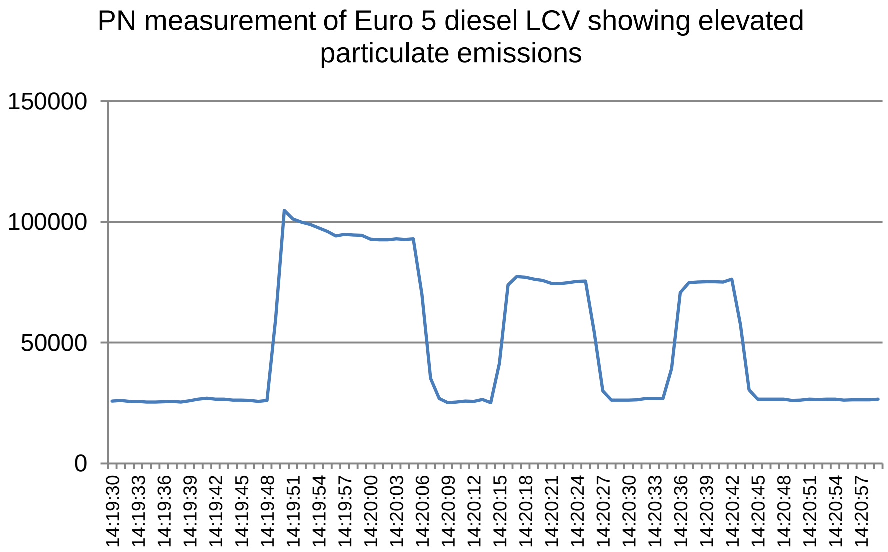

Figure 14 PN measurement on a Euro 5 LCV showing elevated particulate emissions. The measurement was performed three times to check for reproducibility.

Figure 15 is a typical example of a PN measurement on a low-emission vehicle. As can be seen in the figure, the PN counter first reports a background concentration of around 9,000 particles per cm^3. Upon insertion of the sample hose, the number of particles starts to drop significantly. As little as 6 to 8 particles per cm^3 were found.

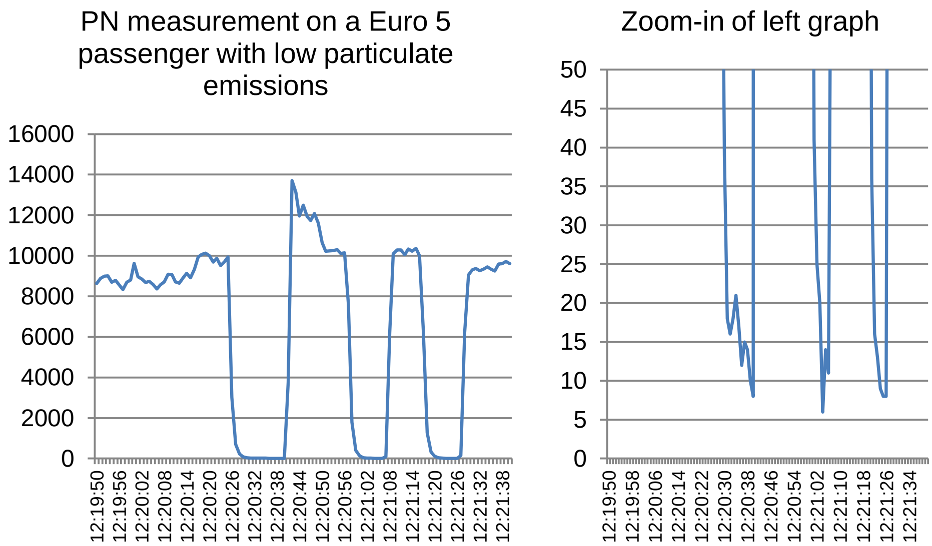

Figure 15 PN measurement on a Euro 5 car showing low particulate emissions. The graph shows that the ambient concentration was around 9,000 to 10,000 particles per cm^3. The three minima unmistakably represent the tailpipe measurements. Zooming in on the left picture shows the particulate emissions are as low as 6 to 8 particles per cm^3.

As the next chapter will show, this kind of results was found frequently during the measurement series. A modern diesel car equipped with a well-functioning diesel particulate filter is capable of reducing the particulate emissions to practically zero. The number of particles in the car’s exhaust in such cases is lower than the number of particles in the outside air.

2.3.7 *Tissue Filter Test (TFT)*

Vehicles scoring 3 on the tailpipe swipe test and showing high opacity values and/or high PN emissions were selected for a tissue filter test. A tissue was attached to the end of the exhaust pipe, as can be seen in Figure 16, after which the engine was let running at idle speed for three minutes.

Figure 16 In the tissue filter test, a tissue was attached to the end of the exhaust pipe after which the engine was let running at idle speed for three minutes. Cars showing elevated emissions in previous tests were selected for the TFT.

The tissue was then removed and the discoloration or blackening of the tissue was reviewed and scored in a way similar to the tailpipe swipe test scoring. All tissues were photographed. Figure 17 shows examples of results of tissue filter tests scoring 0, 1, 2 and 3. As with the Tailpipe Swipe Test, these scores were designated clean or no darkening, grey, black and deep black respectively.

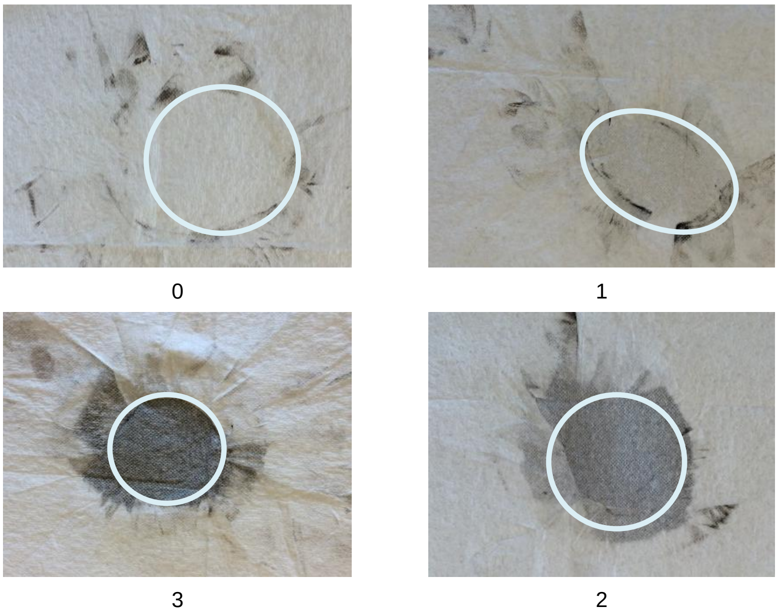

Figure 17 Examples of tissue filter test results with score 0 (no darkening or clean), 1 (grey), 2 (black) and 3 (deep black) - clockwise, starting in the top left corner. The shape of the exhaust pipe are indicated. In case of the upper figures, the black contaminations are the result of touching the outer tailpipe while placing the tissue and do not result from the idling of the engine

3 Test results

3.1 Vehicle ages and mileages

Figure 18 and Figure 19 show information on the odometer readings and age of the 213 tested vehicles. The group of tested vehicles covers a wide range of vehicle ages and mileages. 179 vehicles were ex-lease diesel cars or LCV's, i.e. cars that were mainly used for business use. Lease cars in general drive larger distances in shorter periods of time and are well-maintained. The test set therefore is not per se representative for the total Dutch diesel car fleet.

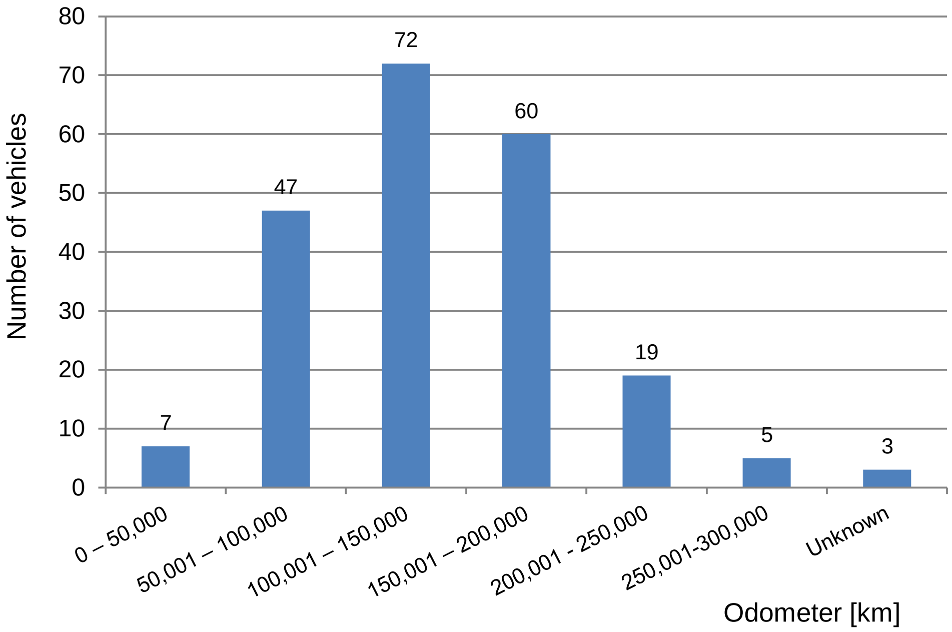

Figure 18 Odometer reading of the tested vehicles.

In Figure 19, the so-called 10% high-emitters are shown in red. Based on a Particulate Number (PN) emission of more than 250,000 #/cm^3, the 10% 'highest-PN vehicles' were identified. As can be seen, most of the vehicles with high PN numbers are 4 to 5 years old, with a mileage between 130,000 and 190,000 km.

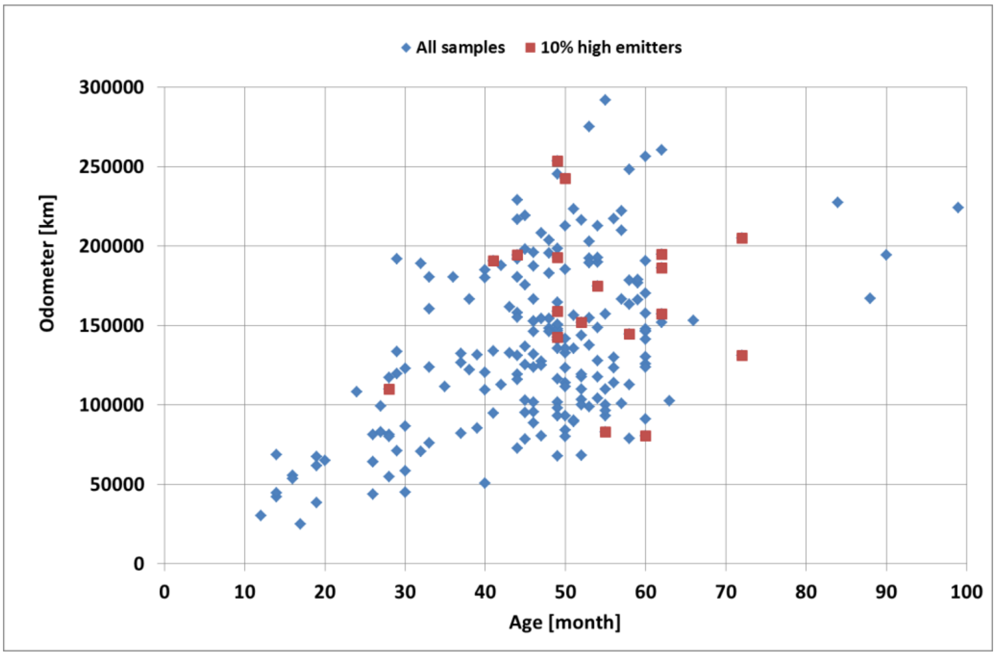

Figure 19 Age and odometer readings of the tested vehicles.

The results in Figure 19 show a relation of vehicle age and odometer readings. In case of increased smoke emissions most of the 10% highest emitting vehicles are older than 48 months.

3.2 Tailpipe Swipe Test results

The Tailpipe Swipe Test (TST, also refer to section 2.3.2) gives a first impression of the vehicle's PM emission. The tailpipes of all vehicles were swiped using a clean finger, yielding the test results depicted in Table 7 and Figure 20.

Table 7 Tailpipe Swipe Test results.

Results	**Color deposit**	**Score**	**Vehicles**	**Percentage**
Clean	No darkening	0	103	48%
Some deposits	Grey	1	67	31%
Moderate deposits	Black	2	27	13%
Heavy deposits	Deep black	3	16	8%
Total			**206**	**100%**

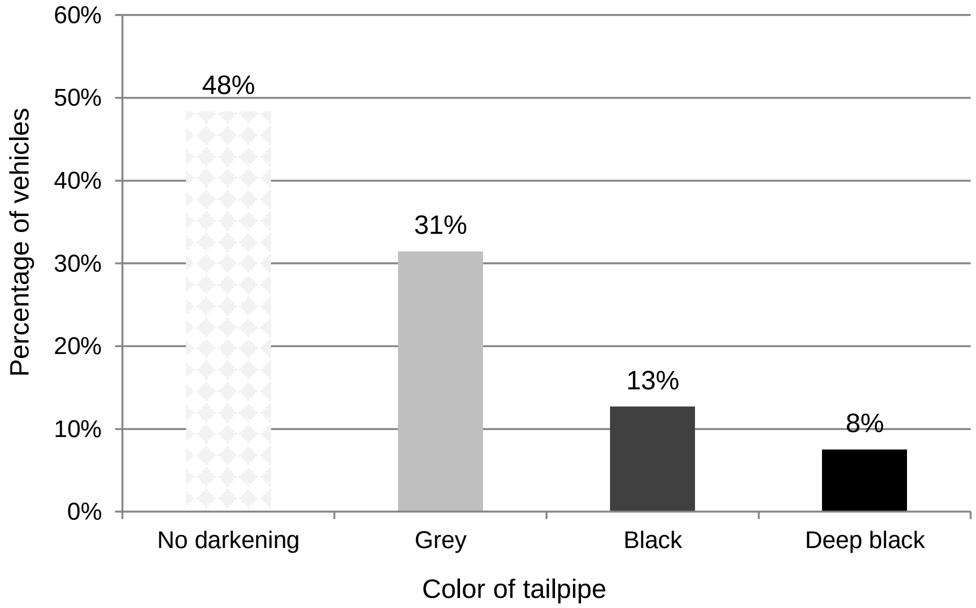

Figure 20 21% of the tested vehicles showed a noticeable darkening in the TST.

79% of the vehicles were found to have a clean exhaust pipe or showed some deposits (scoring 0 or 1). Most of these vehicles showed low smoke values and PN counts in the following tests. A total of 43 vehicles (21%) had tailpipes that were blackened or severely blackened, scoring 2 or 3.

3.3 Opacity results of free acceleration tests

Table 8 and Figure 21 show the test results of both opacity meters. Based on the standard opacity meter test results ("SO-EDA2" in the table), seven vehicles (3,3%) have an opacity of over 0,10 m^{-1}. Using the improved opacity meter, the opacity of twelve vehicles exceeds 0,10 m^{-1} (5,6%). In other words, based on these measurements 3,3 to 5,6% of tested vehicles have a malfunctioning or missing DPF; 94 to 96 percent of the tested vehicles has a well-functioning DPF.

Table 8 Opacity test results with a standard (SO) and an improved (IO) opacity meter.

Opacity meter	**SO-EDA2**		**IO-LPA**	
Filter mode	**Mode A (Low pass filter OFF)**		**Low pass filter OFF**	
Opacity [m^{-1}]	**# vehicles**	**percentage**	**# vehicles**	**percentage**
0,00 - 0,10	206	96.6%	201	94.3%
0,11 - 0,20	4	1.9%	4	1.9%
0,21 - 0,30	0	0.0%	1	0.5%
0,31 - 0,40	1	0.5%	1	0.5%
0,41 - 0,50	1	0.5%	1	0.5%
0,51 - 1,00	1	0.5%	2	0.9%
1,01 - 1,50	0	0.0%	2	0.9%
1,51 - 2,00	0	0.0%	1	0.5%
No reading	0	0.0%	0	0.0%
Total	**213**	**100.0%**	**213**	**100.0%**

In this project one of the tested cars was found to have a missing DPF, as stated by the vehicle owner. This car had an improved opacity of 0,44 m^{-1} and a standard opacity of 0,17 m^{-1}.

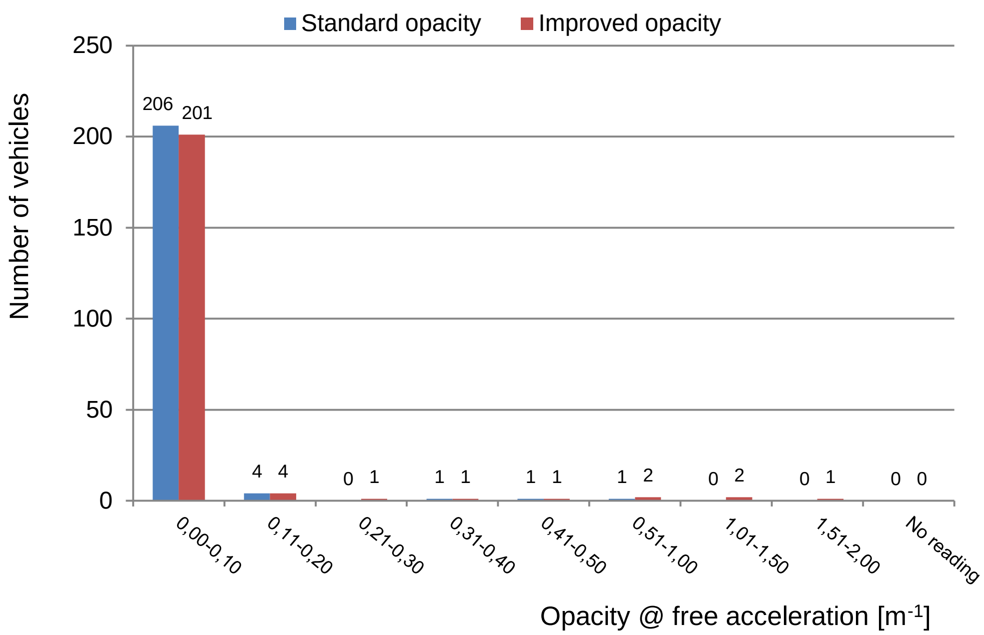

Figure 21 Standard and improved opacity test results.

Taking a closer look at the 201 vehicles with an opacity not exceeding 0,1 m^{-1} yields Figure 22. As this figure illustrates, 192 of those 201 vehicles have an opacity not exceeding 0,050 m^{-1}. These test results indicate that modern diesel vehicles are well capable of reaching opacity values below 0,050 m^{-1}. In the course of the measurements, 0,10 m^{-1} was considered to be a relative high opacity. All this provides a basis for defining an opacity limit of 0,10 m^{-1} in future smoke measurements if applicable.

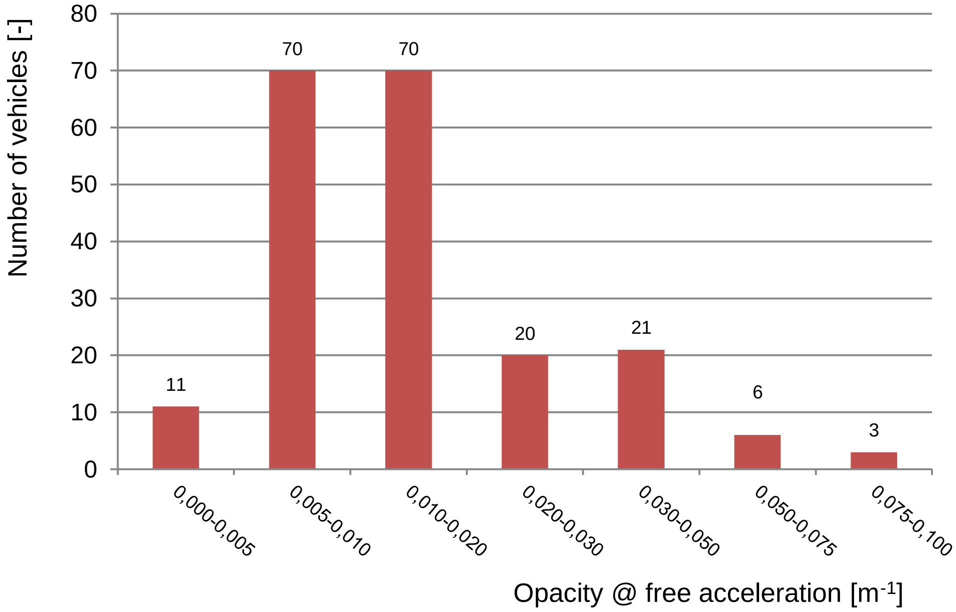

Figure 22 Further analysis of the 201 vehicles that do not exceed 0,10 m^{-1} using the improved opacity meter. 192 of those vehicles have an opacity not exceeding 0,005 m^{-1}, justifying a limit of 0,10 m^{-1}.

34 of the 201 vehicles shown in Figure 22 had a TST score of 2 or 3.

3.4 Opacity results of high idle speed tests

In general, it can be stated that opacity in high idle speed tests is low: based on the improved opacity meter, 202 cars showed smoke values equal to or smaller than 0,05 m^{-1}. What is more, 178 cars did not exceed 0,01 m^{-1} during the high idle speed test. Five cars showed opacities during high idle tests between 0,10 and 0,45 m^{-1}. Of those five cars, four had tailpipes that were blackened or severely blackened and all of them showed high PN emissions and their opacity in free acceleration tests varied between 0,021 and 1,481 m^{-1}. For six cars, no opacity results in high idle tests were obtained.

Figure 23 plots free acceleration versus high idle speed smoke test results. No clear correlation between these two test types exists.

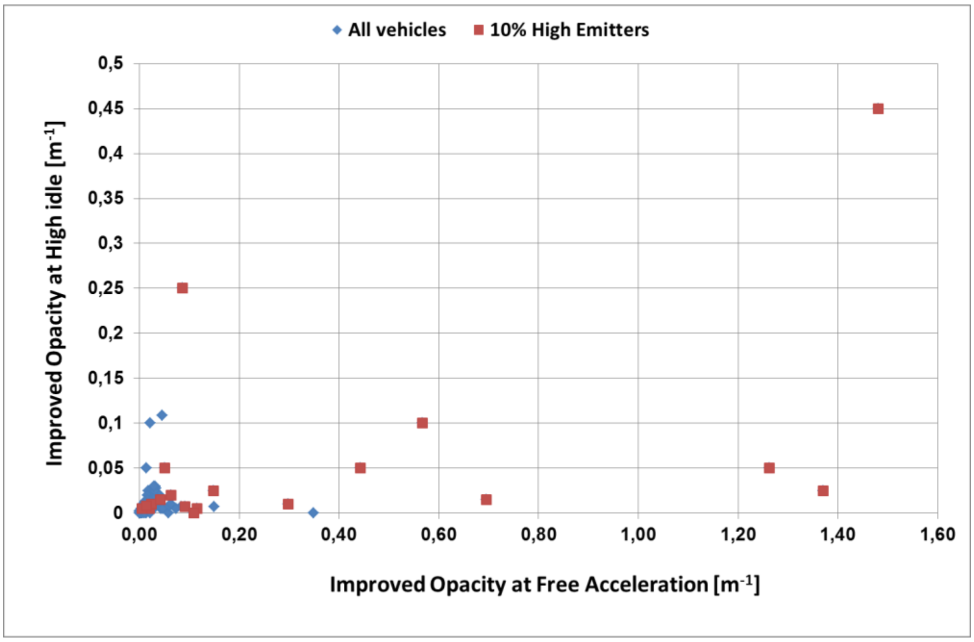

Figure 23 Improved opacity results in free acceleration and high idle speed tests.

3.5 Particulate number test results at low idle speed

Table 9 and Figure 24 show the results of the particle number measurements performed at low idle engine speed.

Table 9 Particulate Number test results at low idle speed.

	PN-TSI	**PN-TSI**
PN [#/cm^3]	**# vehicles**	**percentage**
0 - 1,000	142	66,7%
1,000 - 5,000	19	8,9%
5,000 - 50,000	17	8,0%
50,000 - 100,000	6	2,8%
100,000 - 250,000	10	4,7%
250,000 - 500,000	11	5,2%
500,000 - 750,000	8	3,8%
750,000 - 1,000,000	0	0,0%
Total	**213**	**100.0%**

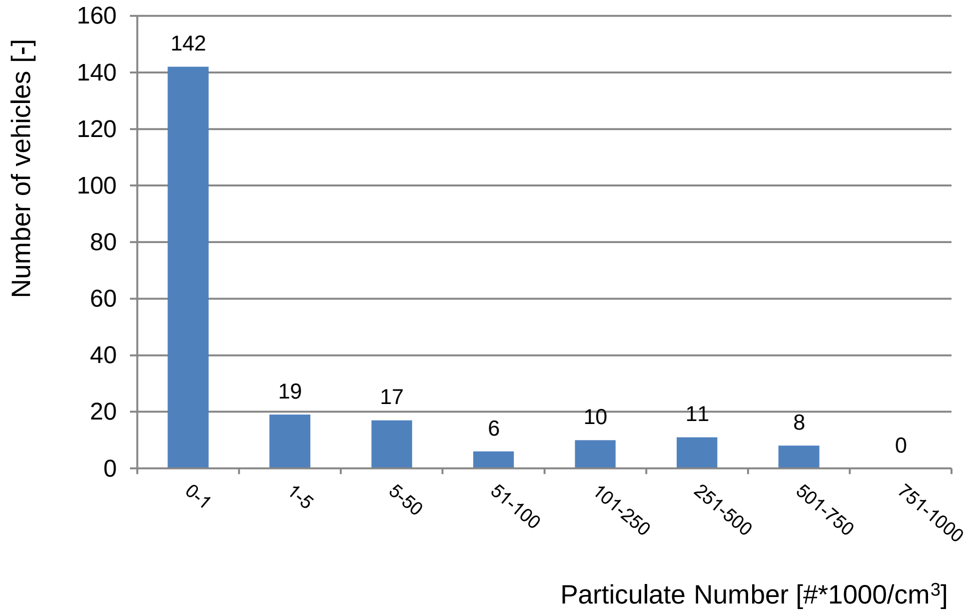

Figure 24 Particulate emission test results measured in low idle speed tests.

PN tests were performed on cars with a hot engine at low idle engine speed. Under such conditions, virtually all hydrocarbons are oxidized in the oxidation catalyst. This means a particle counter does not perceive hydrocarbons as particles.

Background particulate matter concentration measured on most testing days ranged between approximately 8,000 and 15,000 particles per cm^3. 142 of the 213 cars in the test had particulate emissions lower than 1,000 per cm^3. In other words: the exhaust gas of these cars contains significantly less particles than the ambient air. For 114 of the 142 aforementioned vehicles, particulate emissions were below 100 particles per cm^3. The particulate emissions of many tested cars even were close to zero particles per cm^3, an example of which was given in Figure 15. These results reconfirm the effectiveness of DPF's.

3.6 Tissue Filter Test results

As explained in section 2.3.7, vehicles with blackened tailpipes and high opacity and/or high PN emissions were subject to a tissue filter test. Results of the test are shown in Table 10; Figure 25 relates the TFT to opacity outcomes.

Table 10 Results of tissue filter tests.

Results	**Score**	**Vehicles**
No test	-	145
Clean	0	55
Some deposits	1	8
Moderate deposits	2	2
Heavy deposits	3	3
Total		**213**

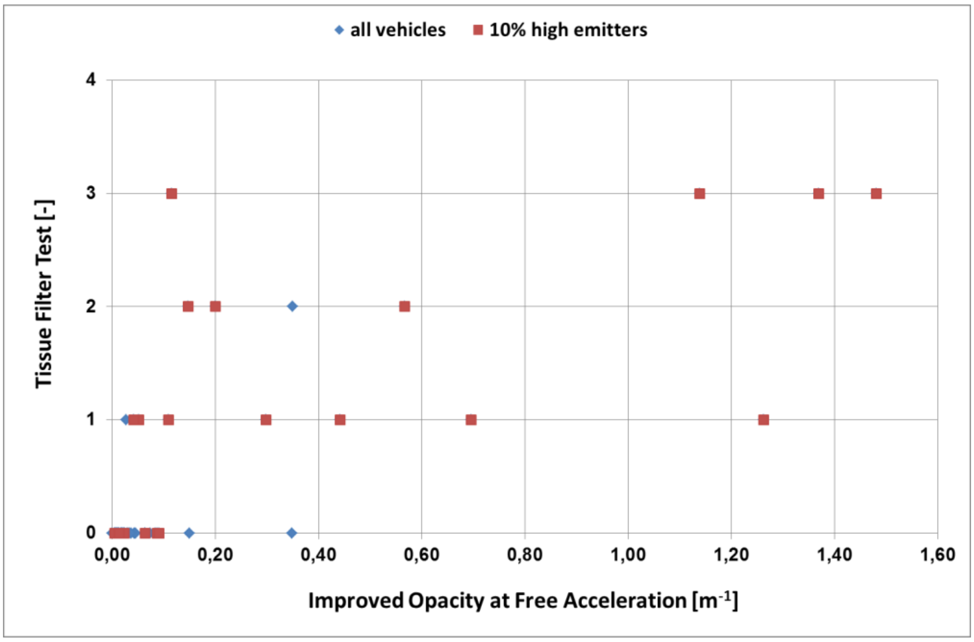

Figure 25 Improved opacity versus TFT results.

The five cars scoring 3 or 2 in the TFT, i.e. coloring the tissue black to deep black (Figure 17), have an opacity higher than 0,1 m^{-1}. What is more, those cars all had high PN emissions, ranging from 291,500 to 623,000 particles per cm^3. As an illustrative example, the score 3 tissue in Figure 17 is the result of a TFT on a Euro 5 passenger car scoring 3 on the tailpipe swipe test (TST), an average opacity of 1,481 m^{-1} and a PN reading of 623,000 particles per cm^3. This car almost certainly has a defective or missing DPF.

Opacity of the eight cars scoring 1 in the TFT ranged between 0,027 and 1,263 m^{-1}. Five of those vehicles had an opacity of over 0,10 m^{-1} in free acceleration. One car had PN emissions of 96,000 #/cm^3; the other seven cars had an average PN emission of a little over 423,000 particles per cm^3.

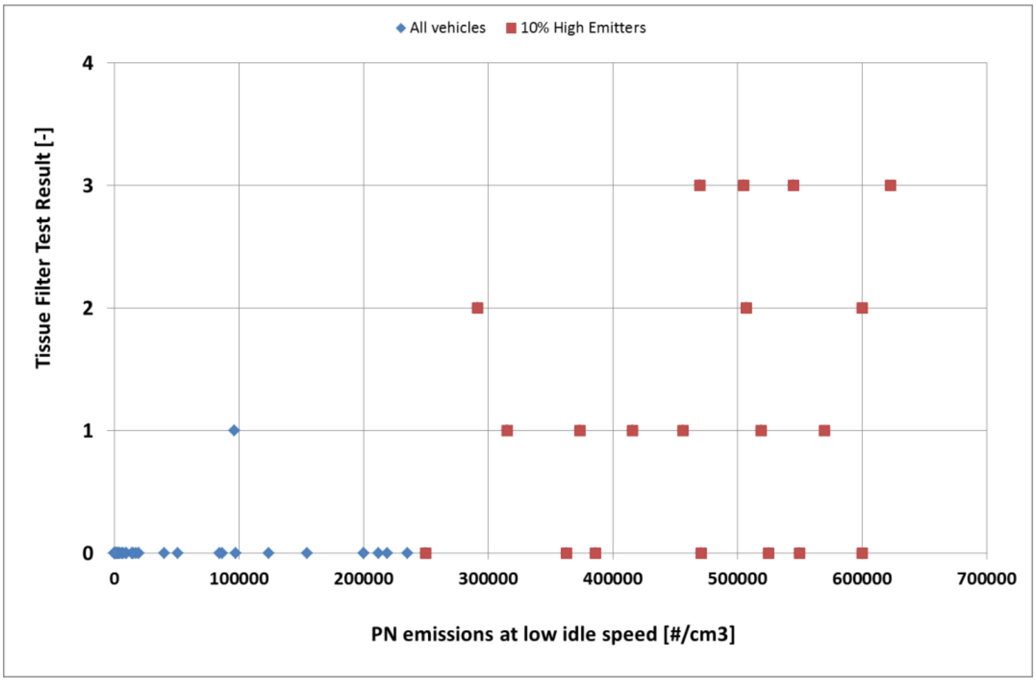

Figure 26 PN emissions versus TFT results.

Vehicles with a (high) score (1, 2 or 3) on the TFT have significant particulate emissions, i.e. there are no vehicles with a deep black tissue having low PN emissions. The reverse is not true however: vehicles with a clean TFT tissue can in fact have significant PN emissions. Whereas a vehicle showing a contaminated tissue almost certainly represents a DPF problem, a car's DPF having a clean TFT tissue is not necessarily performing well. The test could therefore be applied by car buyers to identify a car with a DPF problem (score 1, 2 or 3), but it has a serious shortcoming in that a clean TFT tissue does not mean a clean car per se.

4 Analysis of test results

4.1 Vehicle ages and test results of smoke and PN meters

The results in Figure 27, Figure 28 and Figure 29 show a relation between vehicle age and smoke or PN emissions. In case of increased smoke or PN emissions most vehicles are older than 48 months.

Figure 27 shows the PN emission of 213 vehicles at low idle speed. The PN test results vary between 0 and 623,000 #/cm^3 and have a relative good power of discernment variation over the measuring scale than opacity test results in a free acceleration test. It can be concluded that PN meters at low idle engine speed yield a relatively good screening performance.

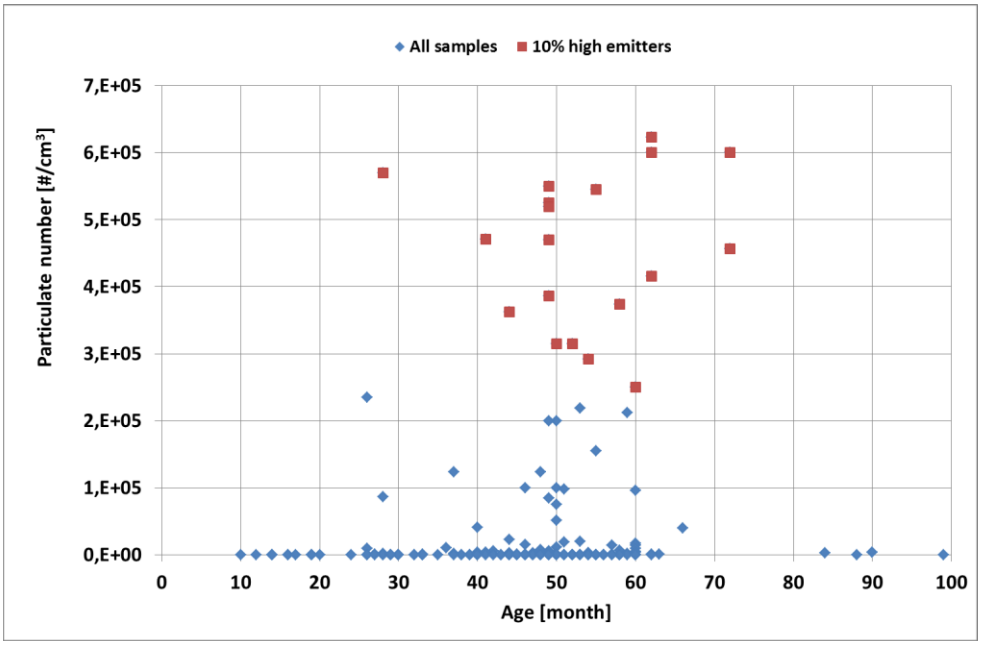

Figure 27: Particulate Number low idle speed test results of 213 vehicles.

In Figure 28 it is shown that the results of the improved opacity meter are less pronounced than the PN-results of Figure 27. This implies that PN-tests are more sensitive than smoke emission tests with an improved opacity meter and have a better screening performance.

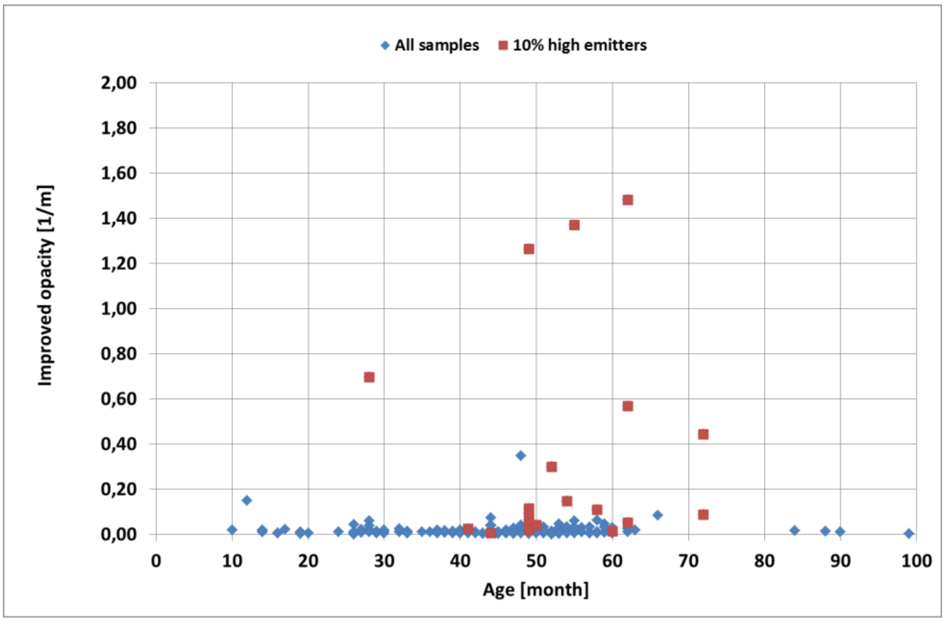

Figure 28: *Improved* opacity free acceleration test results of 213 vehicles.

In Figure 29 it is shown that the results of the standard opacity meter are lower than the results of the improved opacity meter of Figure 28. Furthermore the scatter of test results with the improved opacity meter are more detailed. These two meters are equipped with different light sources (emitters) and light sensors (receivers). The difference in opacity test results are probably caused by the different sensitivities of the two opacity meters. For DPF-equipped vehicles, the screening performance of opacity meters with a measuring range of 0-10 m^{-1} is very low as most vehicles have opacity values that are lower than 0,10 m^{-1}.

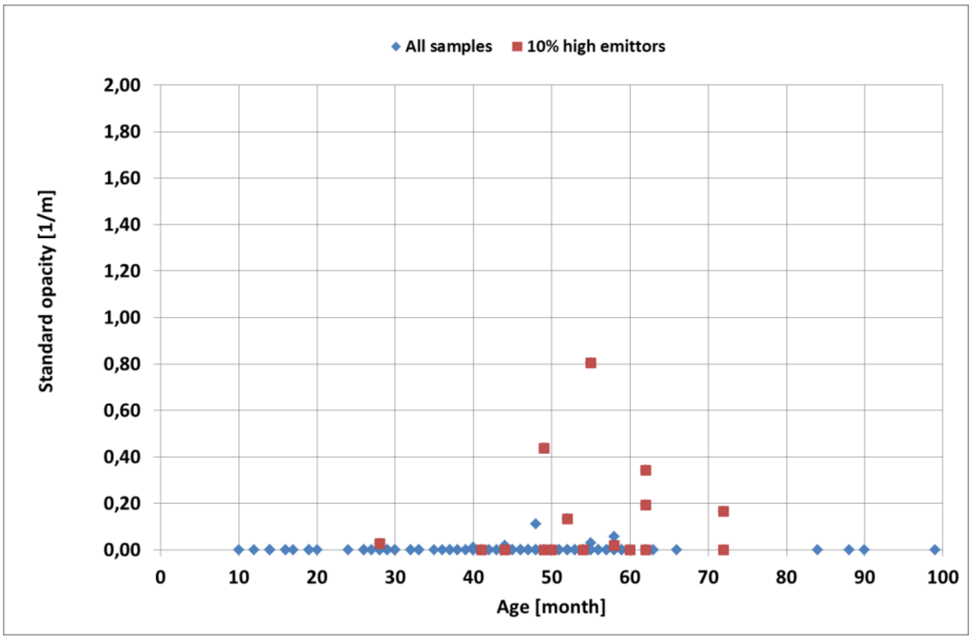

Figure 29: *Standard* opacity free acceleration test results of 213 vehicles.

4.2 Suitability of Tailpipe Swipe Test

Tailpipe Swipe Test results are a very good first indication of the DPF condition. The colour and intensity of the deposits in the tailpipe indicate a typical DPF leakage. However, it is generally not known over which period of time the contamination in the tailpipe has accumulated. Although a clean tailpipe in many cases seems to indicate that a DPF is installed and functioning well (see section 3.5), a black tailpipe does not necessarily mean the DPF is missing or malfunctioning. Therefore, the TST does not give accurate information on the present-day condition of the DPF and a car cannot be said to fail the PTI based on the TST. As such, the TST is not suited as an official PTI test.

4.3 Suitability of smoke emission tests with opacity meters

Are current smoke emission tests suitable?
The current free acceleration test is carried out with a hot engine and the gearbox in neutral and than the accelerator pedal must be pressed down fully within 1 second. Consequently, the engine speed increases from low idle speed to the maximum speed in approximately 2 to 3 seconds and the peak smoke emission is measured. It is well known that the speed of activation of the accelerator pedal influences the peak smoke emission.
In addition to this, engine smoke emissions can be reduced by adding dopes to the fuel or by applying a diesel fuel without heavy fractions (GTL or BTL). Because a fuel check is not part of a PTI, this enables possibilities for manipulation of black smoke emissions.
Due to the very poor definition of the activation of the accelerator pedal, which results in different executions of a free acceleration test, the current smoke emission test is not very robust and may cause very different smoke emissions.

Are current smoke emission opacity tests suitable for vehicles with a DPF?
For most used vehicles with DPF the opacity test results are 0,00 m^{-1}. This implies that a DPF is a very effective means to reduce PM emissions. Also, as most of the vehicles with higher smoke emissions are older than 48 months (section 4.1), it seems to function well over a long period of time. However, some vehicles show increased opacity test results.
The currently applied standard opacity meter with the filtered smoke measuring signal is not sensitive. Only 3,4% of the vehicles have a smoke emission that is higher than 0,10 m^{-1}, as Figure 29 showed. The improved opacity meter with non-filtered measuring signals yields 5,7% of the vehicles with smoke emission levels that are higher than 0,10 m^{-1} in the same tests (Figure 28).
In general the question raises if free acceleration tests with opacity meters are suitable for detection of DPF's with failures. The smoke emissions of diesel vehicles with DPF are nearly zero and moderate DPF leakages create in general very low smoke emissions. First it must be mentioned that current standard opacity meters with an accuracy of +/- 0,3 m^{-1} are not sufficiently sensitive to detect DPF failures. Improved opacity meters, with a measuring scale of 0 – 10 m^{-1} and higher accuracies of +/- 0,01 m^{-1} and more stable readings, seem to perform better, see Figure 30. However, a smoke emission limit value of 0,10 or 0,20 m^{-1} is very low and noise on measuring signals in service shops might disturb the smoke emission test. Furthermore, the screening performance of an opacity test with these limit

values of 0,10 or 0,20 m^{-1} is very low and it may cause false test results. Opacity tests with improved smoke meters are a poor means to detect DPF failures.

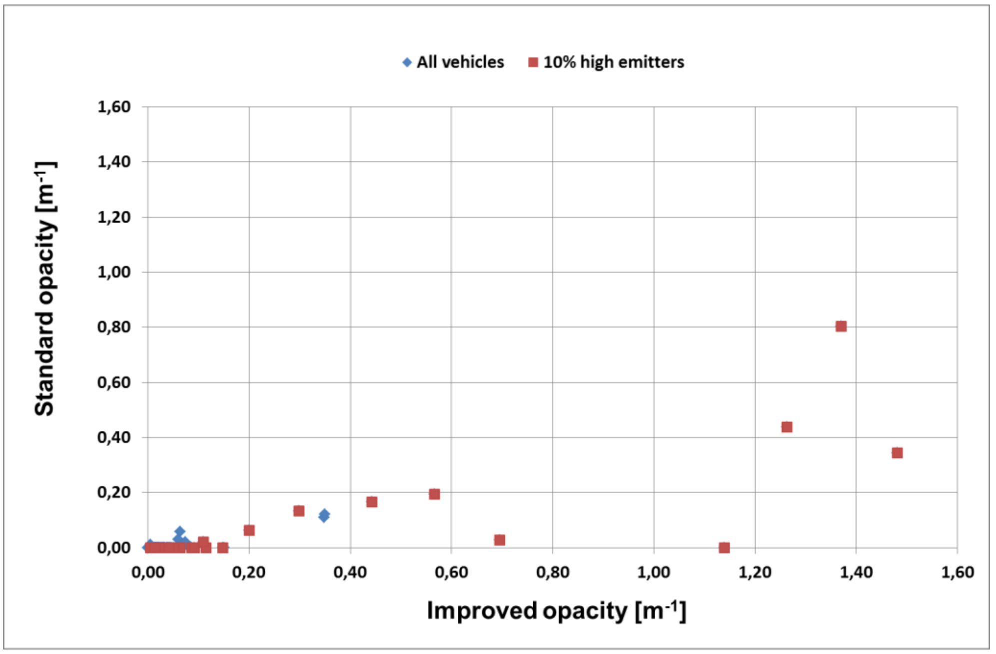

Figure 30: Relationship between improved and standard opacity free acceleration test results.

Although the opacity results of the Improved Opacity (IO) tester seem very stable its screening performance is very poor. Furthermore the execution of free acceleration tests is not very comfortable and tester friendly.

4.4 Investigation into the effect of filter modes of the opacity meters

As was explained in section 2.2, the opacity measurements in this project were carried out in the unfiltered mode as this would allow for a better comparison of particle emissions and opacity. It was found that, in the unfiltered mode, the smoke meters presented different results. Therefore an investigation into the effect of the filtering modes of the equipment was performed. This was done by performing opacity measurements on two high-opacity cars and two low-opacity cars, see Table 11. The opacity measurements were performed both in the filtered mode as well as in the unfiltered mode. The cars tested in this filter mode investigation were not tested as part of the larger testing programme.

Table 11 Properties of the cars tested in the smoke meter filter mode investigation.

Car	Euro Class [-]	Odometer [km]
Car A (high opacity)	3	308,784
Car B (high opacity)	R	234,488
Car C (low opacity)	6	6,879
Car D (low opacity)	6	7,172

Figure 31 shows the result of the opacity measurement of cars A and B using the standard opacity meter and the improved opacity meter which were both in the unfiltered mode.

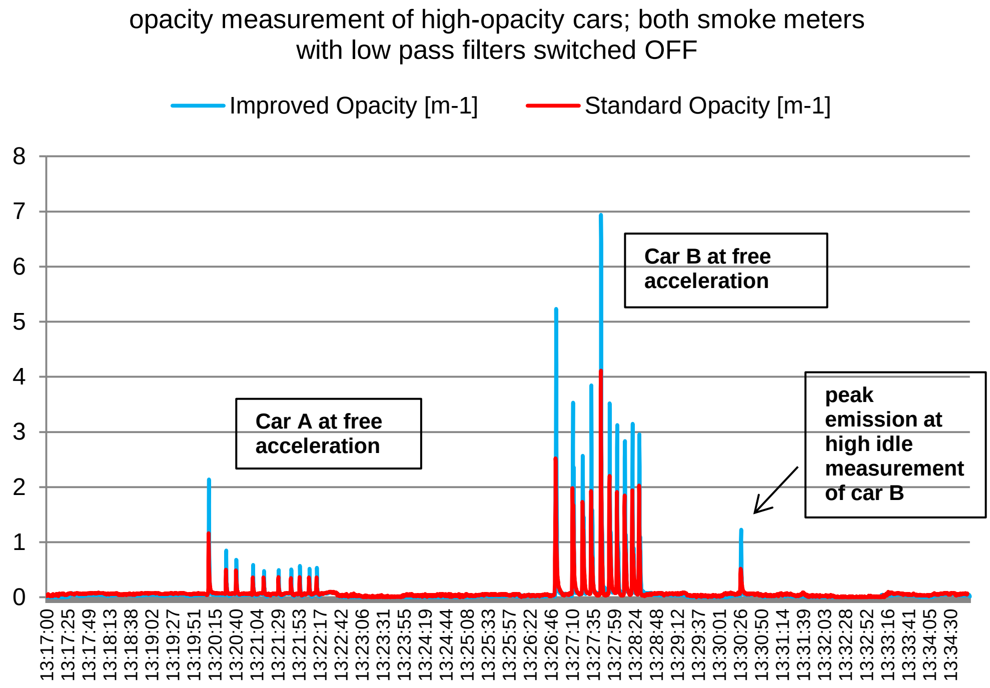

Figure 31 Results of opacity measurement of two cars with high smoke values, using the standard opacity meter and the improved opacity meter, both in the *unfiltered* mode.

As can be seen, the improved opacity meter in the unfiltered mode yielded smoke values approximately twice the smoke values presented by the standard opacity meter in the unfiltered mode.

Measuring the same cars in the filtered mode gives a different result, as Figure 32 displays. In the filtered mode, the smoke meters present virtually the same results. Apparently, the filtering significantly lowers the opacity: improved opacity values go down by almost a factor of 3; standard opacities are approximately halved.

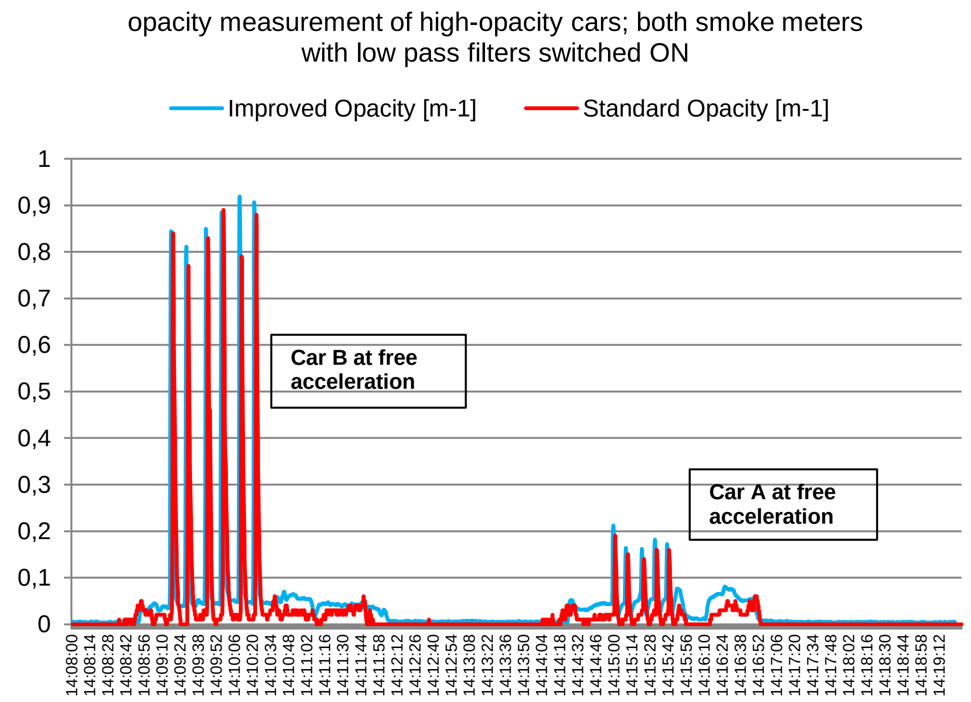

Figure 32 Results of opacity measurement of two cars with high smoke values, using the standard opacity meter and the improved opacity meter, both in the *filtered* mode.

The same measurements were performed on ‘clean’, low-opacity cars. Figure 33 shows the measurements with the low pass filters switched off; Figure 34 gives an impression of clean car test results with the low pass filter switched on.

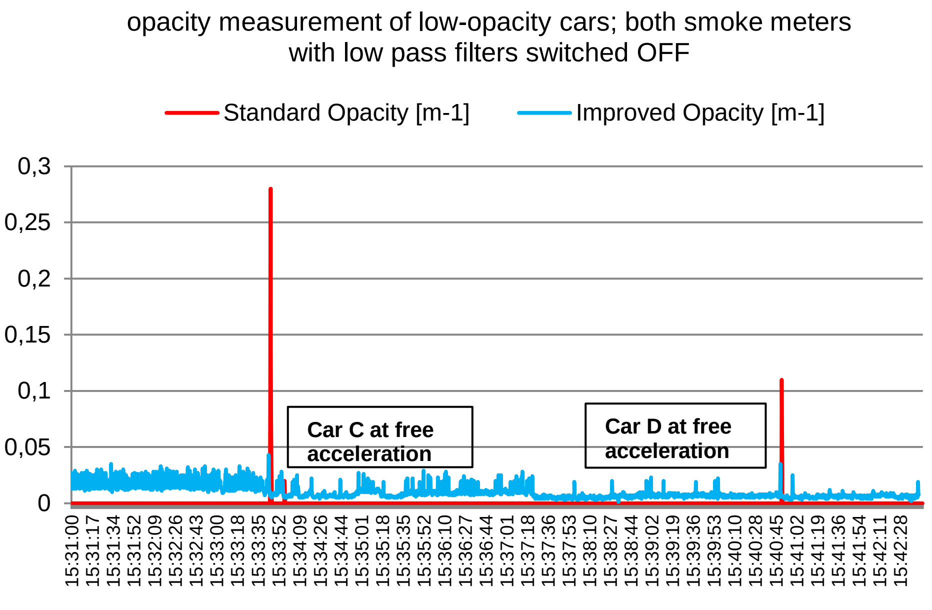

Figure 33 Results of opacity measurement of two cars with low smoke values, using the standard opacity meter and the improved opacity meter, both in the *unfiltered* mode.

The improved smoke meter measures opacities for car C in free acceleration ranging between 0,01 and 0,04 m^{-1} in the unfiltered mode. In the filtered mode, the same smoke meter present smoke values in free acceleration between 0,004 and 0,007 m^{-1}. For car D, in the unfiltered mode, the improved smoke meter reports an opacity between 0,008 m^{-1} and 0,035 m^{-1}, whereas in the filtered mode opacity ranges from 0,007 to 0,01 m^{-1}.

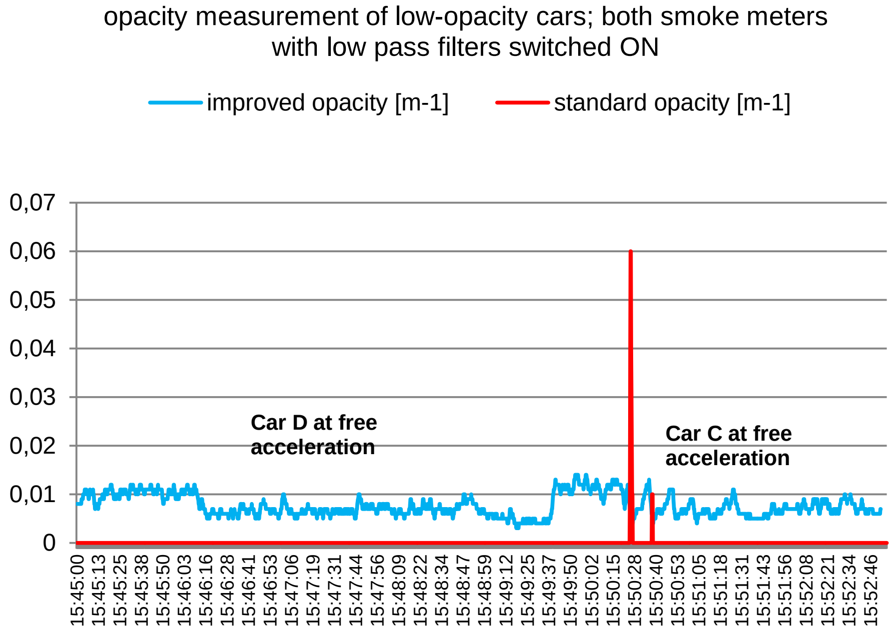

Figure 34 Results of opacity measurement of two cars with low smoke values, using the standard opacity meter and the improved opacity meter, both in the *filtered* mode.

The standard smoke meter presented only a zero-signal and four erroneous spikes in both filter modes. This behaviour was encountered often in the measurement series, which was performed in the unfiltered mode: the standard opacity meter most of the time shows a flat line at zero m^{-1} when testing low-opacity, clean cars. This is not surprising, given the standard opacity meter's low(er) resolution.

From this experiment with two different smoke meters the next lessons can be learnt: In free acceleration smoke emission tests with a standard and improved smoke meter with unfiltered measuring signals different smoke emission results are measured. If the dynamic measuring signals are filtered with the applied low pass electronic filters the smoke emission results of the two meters are equal. This implies that the sensitivity and dynamic response of opacity meters are mainly determined by the applied light sources, sensors, electronic filters and the design of the smoke measuring chamber. From this experiment it is very clear that the dynamic flow of exhaust gas and the sensitivity of the applied light sensor in the measuring chamber mainly influence the measured smoke emission value. Furthermore, standard calibration procedures of smoke meters are based on static optic measurements, the light absorption is only tested. Unfortunately the calibration procedure of smoke meters does not contain a dynamic response test with a dynamic exhaust gas flow that contains a certain smoke emission.

Current smoke opacity meters that are based on the measuring principle of light absorption have not sufficient sensitivity and screening performance to detect Diesel Particulate Filters with a failure. Furthermore the definition of a smoke emission measurement is not well defined because the sample dynamics in the smoke meters which are produced in the dynamic free acceleration test are not taken in to account in the official calibration procedure but they heavily influence the test result.

4.5 Suitability of emission tests with Particulate Number-meters

The applied PN-meter in this project measures PN-numbers with a particle size of 10 – 1000 nm. Now a first attempt was made to apply this PN-meter in undiluted exhaust gas. Exhaust gas contains water and hydrocarbons and these may disturb the PN-measuring signals. However, exhaust gas at low idle speed contains relatively small quantities of water because the engine operates at high air-fuel ratios. Furthermore, the tests are carried out with hot engines and hot DPF's; at these operation conditions most volatile hydrocarbons are oxidised in the oxidation catalyst of the DPF and, consequently, the exhaust gas in the tailpipe only contains small quantities of hydrocarbon. If present, hydrocarbons are measured in the nucleation mode as a particle.

Can PN emissions be determined with cold and hot engines?
Particles can be solid or volatile and both are counted by the PN meter. One specific low idle speed test was carried out with a TSI NPET 3795 device (Psize > 20 nm). This device removes water from the exhaust gas, dilutes the exhaust gas (10:1) and removes the volatile fraction with a catalytic stripper. This sample preparation should result in a more stable measurement result.
For cold engines with cold oxidation catalysts an increased level of particles can be expected. If the catalyst reaches the light-off temperature, the volatile particles will be oxidised and the PN concentration decreases. As Figure 35 shows, the PN-emission of a cold engine with DPF is 17,000 $\#/cm^3$ and with a hot engine this vehicle emits less than 100 $\#/cm^3$. In both measurements, the PN concentration of ambient air is approximately 3,000 $\#/cm^3$.
These tests show that hydrocarbons are counted as a particle. In order to have a maximum PN screening capacity it is needed to run roadworthiness tests with a hot engine and hot DPF.

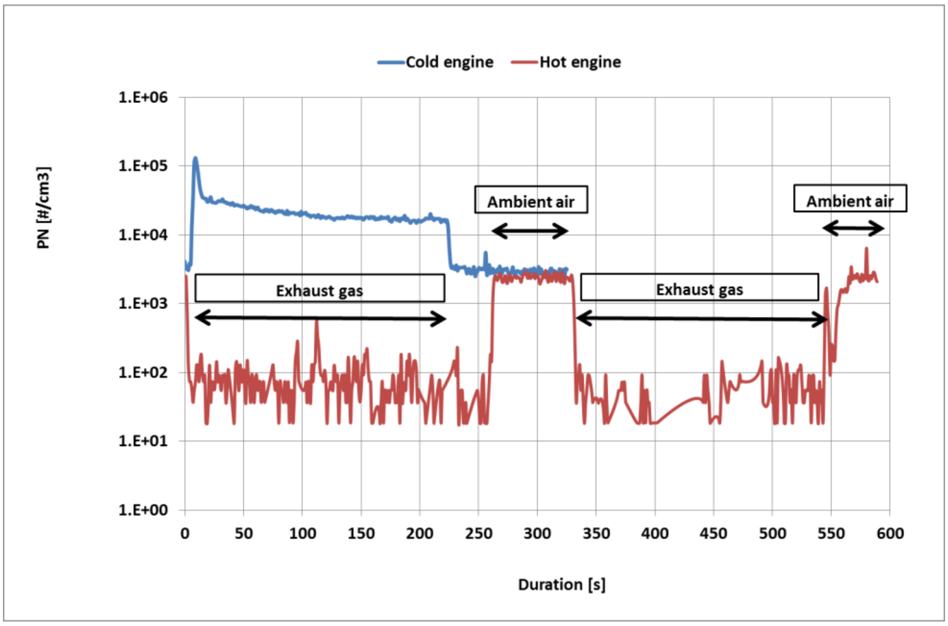

Figure 35 PN emissions of a euro 6 diesel vehicle with DPF at cold and hot engine operation.

The determination of PN emissions with the handheld TSI particle counter at low idle engine speed is a very easy and fast test method. In general, the repeatability and the screening performance are good. Measurements can be carried out very easily and fast (< 10 s). The applied TSI PN counter only once failed around 0 °C because this ambient temperature is outside its operational envelope.

Due to its sensitivity, the tester is able to detect PN emissions from 0 – 500,000 $\#/cm^3$. However the measured PN-numbers are guaranteed up to 100,000 $\#/cm^3$. In order to operate in these tests with more convenient measuring values it is recommended to dilute exhaust gas with filtered air. The proposed dilution ratio is 10:1. With this configuration of the PN-tester it is possible to detect very small DPF leakages. This offers the possibility to set a convenient PN limit value for the determination of pass/fail criteria.

In this test program vehicles with cold engines and cold DPF’s showed very high PN numbers. Very often the PN meter ran out of scale. The same vehicles with a hot engine and a hot DPF showed very low PN numbers. From this result it can be concluded that volatile HC-fractions are counted as a particle. Consequently, the PN test at low idle engine speed should only be carried out with a hot engine and a hot DPF.

As soon as a new measuring principle will be applied the question of a limit value arises. In current NEDC type approval tests a PN limit value of $6{,}0 * 10^{11}$ #/km is applied (Psize > 23 nm @ without water and volatile hydrocarbons). In case of a vehicle with a fuel consumption of 4,0 ltr/100 km and an average lambda of 3, the average PN concentration of exhaust gas in an NEDC test is 500,000 $\#/cm^3$. Limit values for PN emissions at low idle speed are applied in Switzerland. For construction machines, which operate in tunnels, a PN limit value of 250,000 $\#/cm^3$ (Psize > 20 nm) at low and/or high idle operation is applied. For the determination of this PN emission a dedicated PN-meter for field operation was developed (with water separator, 10:1 diluter and catalytic stripper of the volatile fraction). Summarizing this discussion, it is recommended to apply a PN limit value of 250,000 #/cm^3 (Psize > 20 nm) in roadworthiness tests.

91% of the 140 under '1,000 #/cm^3-cars' had clean tailpipes or showed only minor deposits in the tailpipe swipe test. This seems to indicate that a vehicle having a clean exhaust pipe is very likely to have a well-functioning DPF. A reverse deduction, i.e. that a black tailpipe means a DPF is not present functioning properly, is usually not valid.

Initially, some vehicles showed a non-stable PN emission. In those cases, the vehicles were further warmed up by driving over the test site. After this additional warming-up, most vehicles showed a very low PN emission (< 1000 #/cm^3). This indicates that a well warmed-up vehicle is needed for a PN-test.

Particulate Number tests at low idle engine speed are easy to carry out, the results are very stable and repeatable and the screening performance of this test method is good. Moreover, the fact that the engine does not have to be tested at full throttle but rather is tested at low idle speed means a smaller health burden to the tester.

4.6 Relation between smoke and particulate number emissions

In Figure 36 the relation of improved opacity in free acceleration tests and PN emission results in low idle engine speed tests is shown. Not all 10% high emitters (PN-based) have also a high smoke emission. From this figure it is clear that PN results are more sensitive than opacity results and they have a better screening performance because the PN test results of the vehicles are more distributed over the measuring range than the opacity test results.

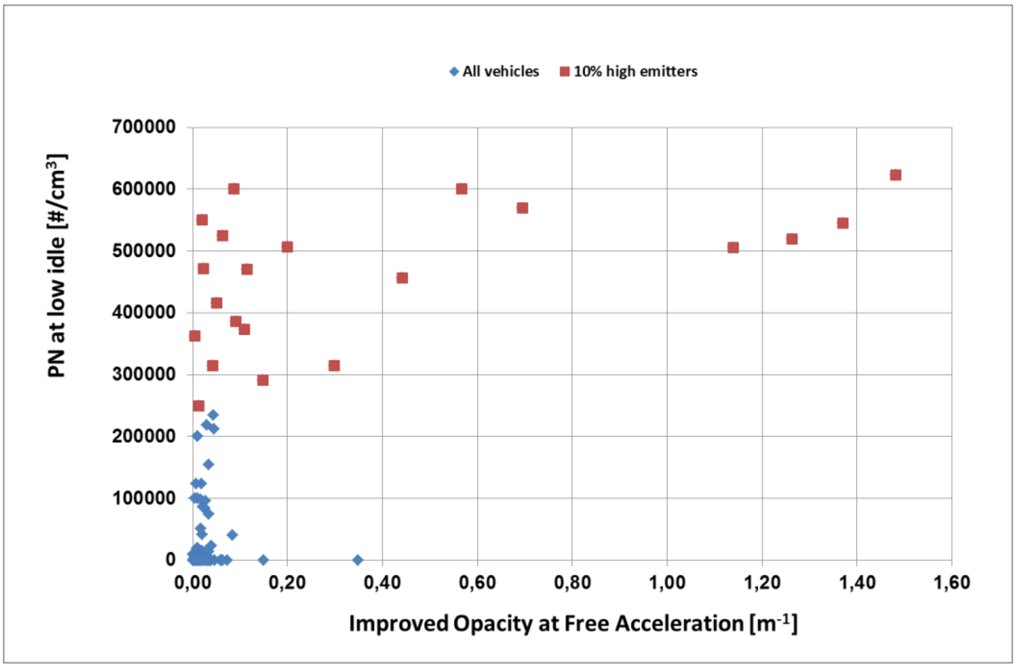

Figure 36: Relation between improved opacity in FA-tests and PN emission at low idle speed.

4.7 Suitability of Tissue Filter Test

The Tissue Filter Test is a very easy test method but the results are very poor. Only 5 of 68 potential high emitting vehicles were detected as high emitters (moderate or heavy deposits) with this test method. From this result it is concluded that the Tissue Filter Test method is not suitable for detection of DPF failures.

4.8 Pass and fail criteria

In Figure 37 and Figure 38 the pass and fail percentages of the two opacity test methods (SO and IO) and of the PN test method are shown.

In opacity tests, limit values of 0,10 – 0,50 m^{-1} must be chosen to detect DPF failures. In this test program with a smoke limit value of 0,10 m^{-1}, only 3-6% of the tested vehicles fail. This is a maximum percentage and it is determined with measuring signals without electronic filtering. In current daily PTI-practice all opacity tests are carried out in a filtered test mode and opacity results are probably around 50% lower. This signal filtering reduces the screening performance of the test method and a maximum failure rate of approximately 1,5 to 3% is expected.

The PN test method shows a linear correlation between PN emission limit values and failure rates. This provides the possibility to set a PN limit value in relation to an expected failure rate and enable stakeholders (Governments & Type Approval Authorities) to choose an accepted failure rate between 0 and 25%. As an example a limit value of 250,000 $\#/cm^3$ is applied for Swiss non-mobile machinery.

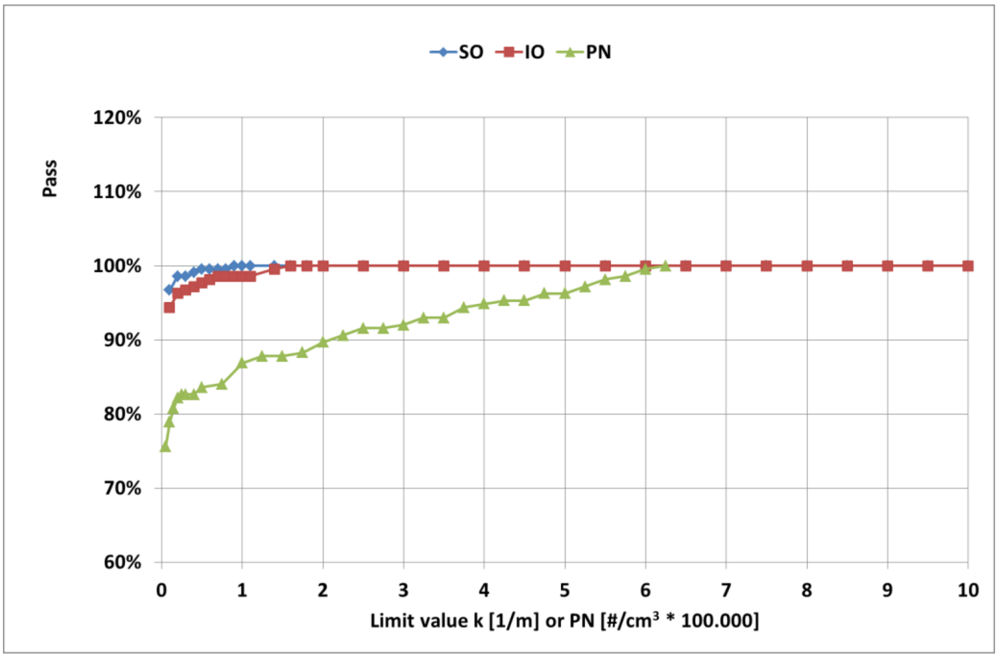

Figure 37: Relation of percentage of passed opacity and PN tests and limit values

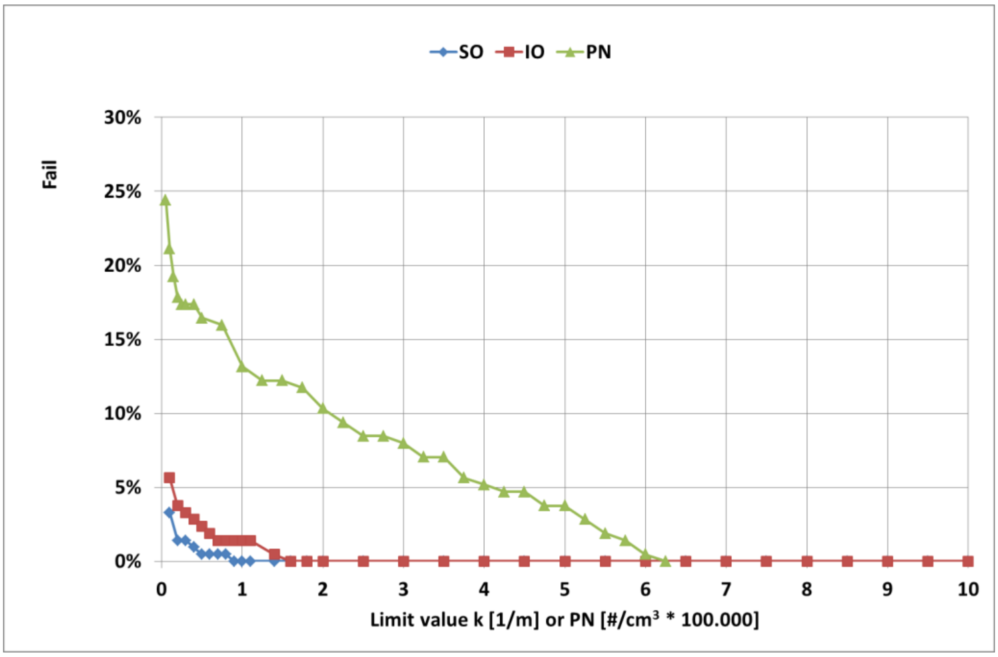

Figure 38: Relation of percentage of failed opacity and PN tests and limit values

4.9 Overall assessment of test methods and limit values

In Figure 39 and Figure 40 the number and percentages of DPF failures which are based on the different test methods and limit values are shown. It is clear that the test method and limit values determine a certain failure rate.

From the Tailpipe Swipe Test it is known that it cannot be applied in PTI-tests because it can be manipulated. However a tailpipe with a certain black soot layer is a first impression and can be marked as a trigger because it is known that well functioning DPF's have a real clean tail pipe. The opposite statement (a clean tailpipe is a marker of a well functioning DPF) is not valid because a clean tailpipe can be arranged.
In general a free acceleration PTI test is experienced as a load because it takes 60-120 s, the test is relatively complicated, a lot of noise is produced and currently only a very small percentage of the vehicles with DPF fail. From the measured results of the free acceleration opacity tests it is clear that the possible limit values (0,10 or 0,20) are in the lower part of the measuring range (0-10) and this offers a very poor screening performance. Furthermore due to margins of execution of free acceleration tests and different designs of smoke meters opacity these test results may even differ. This creates a basis for discussions between vehicle owners, PTI testers and PTI inspectors but also a basis for manipulation.

From the results of the Particulate Number Tests at low idle engine speed the highest sensitivity and screening performance have been determined. The test can not easily be manipulated because it must be carried in a static condition (low idle speed with a hot engine) and it can be easily and fast (15 s) executed in PTI-workshops. For PTI purposes cheap PN-testers must be developed. These testers contain a water separator, a sample diluter (10:1) for a better match between expected PN-emissions and the measuring range and a particle counter. In the next paragraph some cost estimations of application of PN-testers in PTI's are shown.

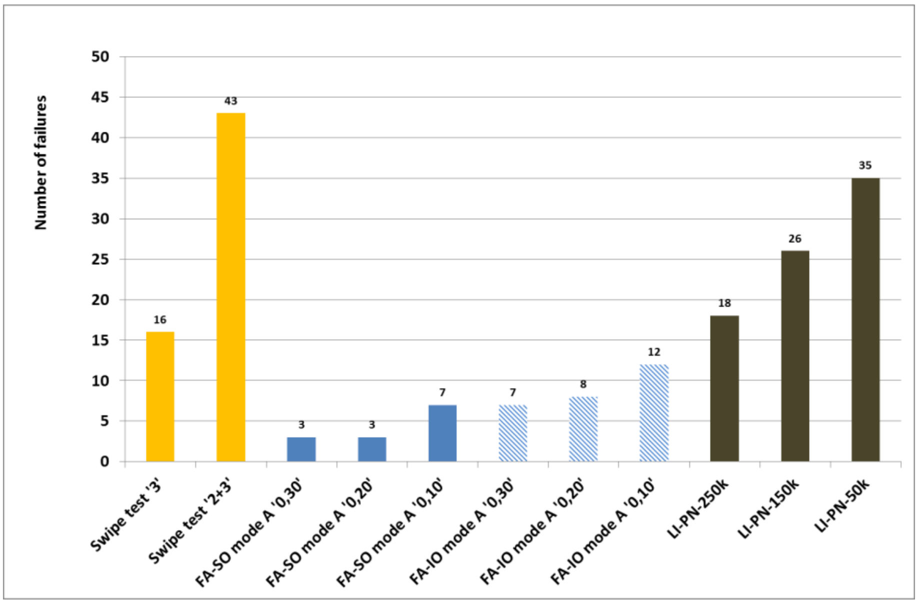

Figure 39: Number of DPF failures based on different test criteria and limit values

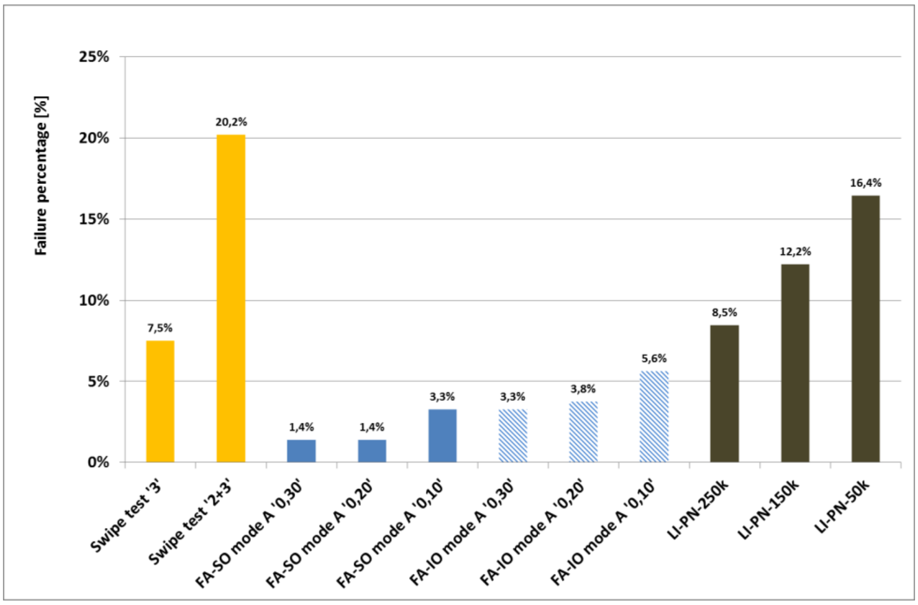

Figure 40: Percentages of DPF failures based on different test procedures and limit values

5 Cost estimates of different test methods and testers

Table 12 and Figure 41 present a specification and cost estimate of different PTI DPF emission tests with different economic lifetime of test equipment. Detailed numbers are reported in Appendix B.

Table 12 PTI DPF emission tests.

	Smoke	**PN**
Costs test equipment	€ 4,000	€ 10,000
Costs test facility	Test set up	No
Vehicle preparation	Warming up engine Installation sample tube and engine speed sensor	Warming up engine
Test specification	1-6 * free acceleration tests	Low idle speed
Test duration	2 minutes	30 seconds
Environment	Noise	
Acceptance customer	Bad	Good
Quality test result	-	++
Cost per test*	See Figure 41	

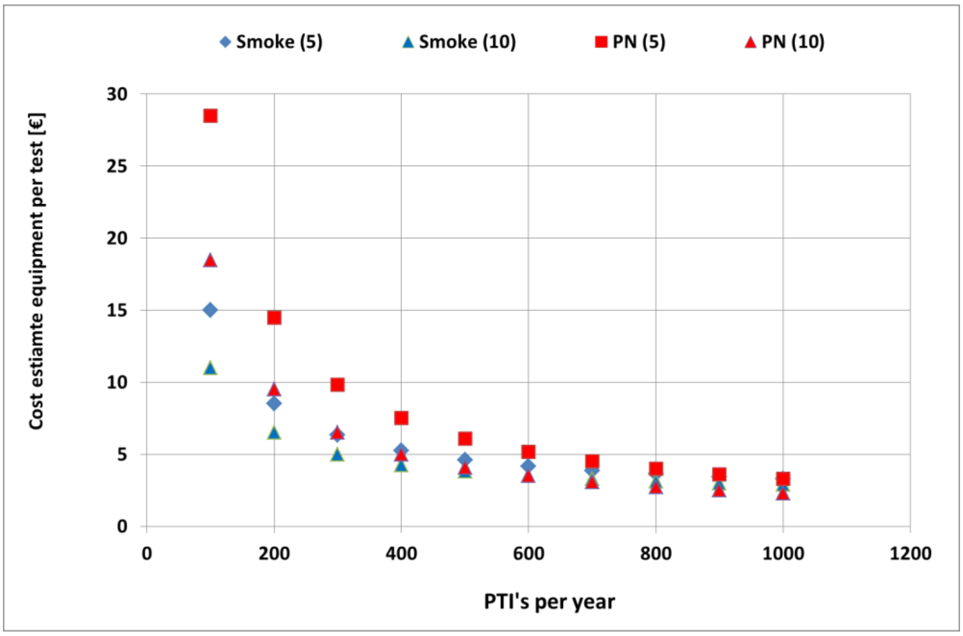

Figure 41 Cost estimate of single PTI DPF tests with smoke or PN meters with economic lifetimes of test equipment of 5 and 10 years.

In case of an economic lifetime of 5 years of a smoke or PN tester and 500 PTI's per year, the costs per PTI emission test with an opacity meter are € 4.60 and in case of the PN-tester each PTI emission test costs € 6.10. The break even point of the two methods can be reached at 1,000 test per year. At that number of yearly tests, the costs per test for both methods are estimated at € 3,30.

6 Overview and assessment of test methods

In Table 13 an overview and assessment of parameters of three different test methods is shown.

Table 13: Overview assessment of parameters of three different test methods

Parameter	Free Acceleration	Free Acceleration	Low idle
	Standard Opacity	Improved Opacity	PN
Comment	Current method	Improved 1 'CITA'	Improved 2
Representativeness	+/-	+/-	++
Sensitivity, threshold	--	+/-	++
Accuracy	-	+	++
Reliability	+/-	+	++
Screening performance	--	-	++
Reproducability	-	-	++
Repeatability	+/-	+/-	++
Executibility	+/-	+/-	++
Costs	+	+	+/-
Costs [€/test]	3.30 – 15.00	3.30 – 15.00	3.30 – 28.50
Test duration	+/-	+/-	++
Comfort for tester	-	-	+
Acceptance vehicle owner	+/-	+/-	++
Maturity	++	+	+
Limit values	--	+	++
Limit values	0.7 m^{-1}	0.10 m^{-1}	250,000 #/cm^3

7 Conclusions

In order to develop an improved PTI smoke emission test procedure for diesel vehicles with a diesel particulate filter, the smoke emissions of 213 Euro 5 and Euro 6 in-use light-duty diesel vehicles with a DPF were investigated. The condition of the DPF's was investigated by means of four different test methods: (1) the tailpipe swipe test, (2) a tissue filter test, (3) a smoke emission test using a standard opacity meter *and* using an improved opacity meter and (4) a particulate number (PN) measurement using a particulate number counter. The two opacity meters were used in free acceleration and high idle tests; the PN test with the handheld PN-meter was used in low idle speed tests.

What can be expected from Tailpipe Swipe Tests?
On the basis of the results of the executed Tailpipe Swipe Tests (TST) and expert opinion it must be concluded that the TST is not suited as an official PTI test because the result of a TST test is not related to the actual condition of the DPF. However the TST result can support the judgement of a DPF condition.

How do smoke emission results of the 213 vehicles of this project relate to former results?
In very conditioned roadworthiness tests with 213 (mainly ex business use) Euro 5 and 6 diesel vehicles, at least 12 vehicles (5.6%) showed elevated smoke emissions (k > 0.10 m^{-1} with an improved opacity meter without signal filtering). This indicates that these 12 Diesel Particulate Filters are either damaged or removed. If a smoke emission limit value of 0.30 m^{-1} is applied only 3.3% of the vehicles fail. This result is not in line with former failure rates of 6% (based on filtered measuring signals of a standard opacity meter and a limit value of 0.30 m^{-1}) of random vehicles. Possibly, the relatively low failure rate is caused by the relatively young and well-maintained test vehicles in this project.

Is an emission test in PTI's needed?
From the 10% highest emitting vehicles, most vehicles are older than 48 months. This indicates that deterioration of diesel particulate filters is related to DPF age and its performance must be checked in periodic technical inspections by means of an adequate test procedure in which also removal of DPF's can be detected.

What is the quality of the current smoke emission test procedure in a PTI?
In former research projects it was found that the current smoke emission test procedure with an improved opacity meter was the best option because no better alternative for PTI-purposes was available. However, after detailed research in this project, it must be stated that the current PTI test procedure is not the most accurate procedure and it can be manipulated. This is mainly caused by the poor definition of the execution of the PTI emission test, the characteristics of the dynamic test procedure and the undefined dynamic sample flow characteristics of sample lines and measuring chambers of (improved) opacity meters. In the official static calibration procedure of opacity meters the sample dynamics in the meters are not taken in to account but they may heavily influence the test result.
Moreover the screening performance of improved opacity meters with a measuring range of 0-10 m^{-1} is low because most vehicles with DPF have opacity results that

are lower than 0.10 m^{-1} while reasonable limit values are in the range of 0.10 - 0.20 m^{-1}.
Furthermore the execution of free acceleration tests is not very comfortable and tester friendly and evokes sometimes resistance for vehicle owners because they think the engine is overloaded.

Are opacity meters suitable for PTI tests of DPF-equipped vehicles?
The experiments confirmed that opacity tests using a standard smoke meter are not suited to determine whether the vehicle is fitted with a well-functioning DPF. Using a modern, improved smoke meter a smoke test *can* be used to detect DPF failures.

Can PN measurements be an alternative for black smoke emission tests?
In this project, alternative DPF tests were carried out with a handheld Particulate Number (PN) tester at low idle engine speed with a hot engine. This PN test procedure is relatively easy and the measurement takes only around 15 seconds. It has a good screening performance and yields very robust test results. Due to the clear and simple definition of the static test, manipulation is not very likely.

In low idle speed tests with a hot engine and a particulate number limit value of 250,000 #/cm^3, 8,5% of the vehicles failed. From these results it can be concluded that a particulate emission test with a PN tester is a very good option for PTI's.
In order to realise a final PN test procedure it is needed to adapt PN test equipment with a water separator and sample dilution system.

How do current smoke emission test results and PN test results relate?
From the results in Figure 42 it is clear that PN-results are more sensitive than opacity results . A PN test shows a better screening performance because the PN test results of the vehicles are more distributed over the measuring range than the opacity test results.

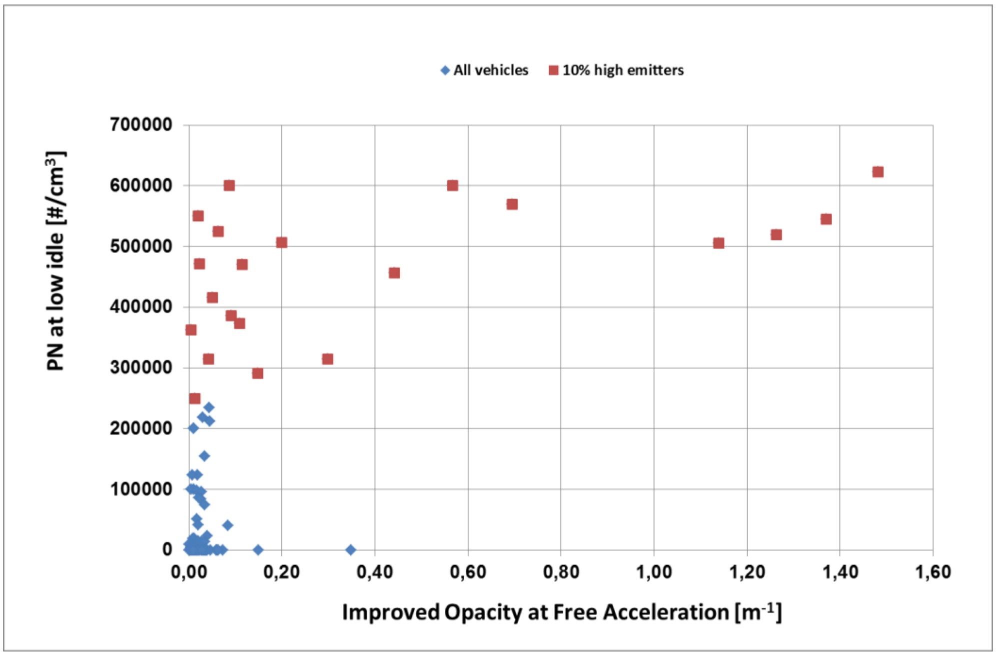

Figure 42: Relation of improved opacity in FA-tests and PN emission at low idle speed

Are PN meters suitable for PTI tests of DPF-equipped vehicles?
The PN test method shows a much better linear correlation between PN-emission limit values and failure rates, see Figure 43. This provides the possibility to set a PN limit value in relation to an expected failure rate and enable stakeholders such as governments and type approval authorities to choose an accepted failure rate between 0 and 25%. Currently, a limit value of 250,000 #/cm^3 is applied for Swiss non-mobile machinery.

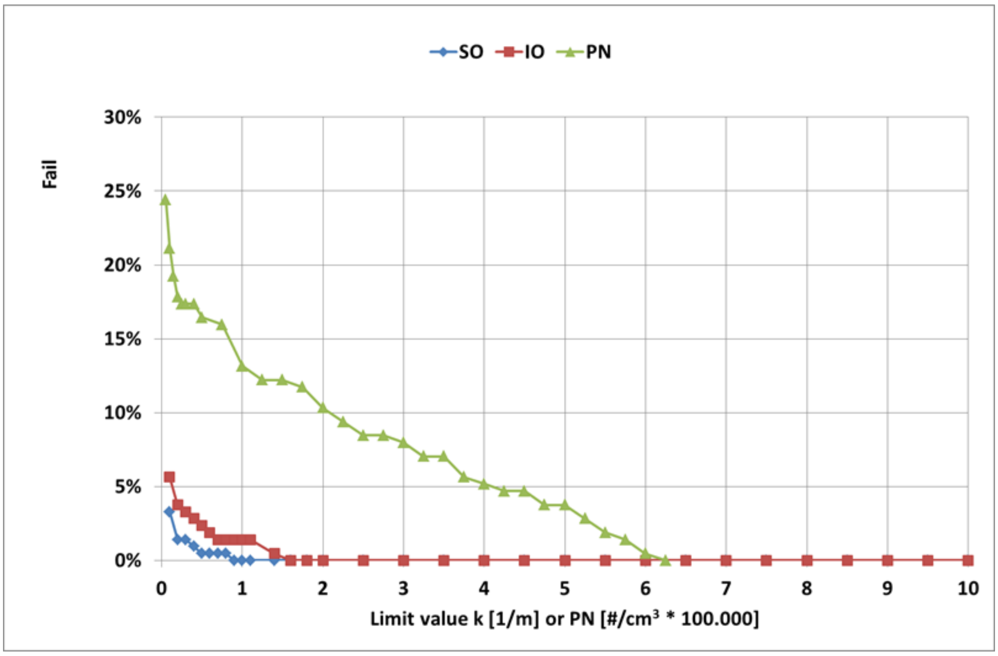

Figure 43: Relation of percentage of failed opacity and PN tests and limit values

What can be expected from Tissue Filter Tests?
The Tissue Filter Test is a very easy test method but the results are very poor. Only 5 of 68 potential high emitting vehicles were detected as high emitters (moderate or heavy deposits) with this test method. From this result it is concluded that the Tissue Filter Test method is not suitable for detection of DPF failures.

What is the screening performance of the different PTI emission tests?
In Figure 44, PTI failure percentages of this fleet are reported for the four different test methods. As stated earlier the Tailpipe Swipe Test cannot be applied for PTI purposes but the test result may indicate a serious DPF failure.
From the test results with a standard opacity meter and a limit value of 0.10 m^{-1} 3,3% fail. This percentage increases to 5.6% with an improved opacity meter. Due to the very low opacity limit value of 0.10 m^{-1} (1% of the full scale), sensitivity, accuracy and stability of the equipment around this value of 0.10 m^{-1} become very important but they cannot be checked in standard static calibration procedures of the smoke meter. From this perspective the reliability of the smoke emission test result is poor.

PN tests allow a higher screening performance (because PN limit values can be set from 50,000 – 250,000 #/cm^3). Due to its sensitivity and linearity, the potential screening performance of PN tests is the highest of all test methods because low PN concentrations can be measured accurately.

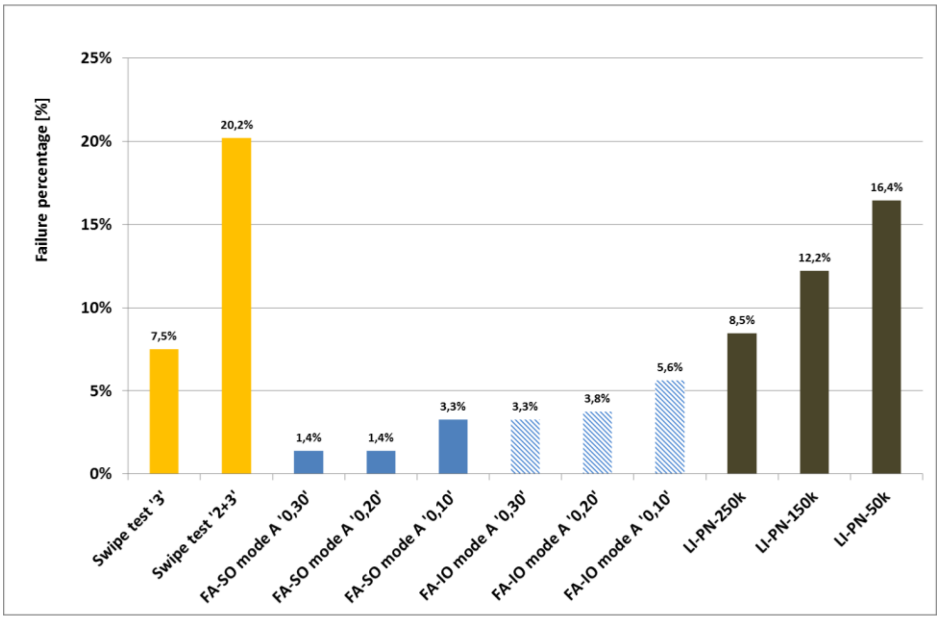

Figure 44: Percentages of DPF failures based on different test procedures and limit values

What are the estimated costs for different PTI emission tests?
The costs per PTI depend on the price and economic life time of test equipment, yearly maintenance and calibration costs as well as labour time per PTI test and the number of executed PTI's per year. For an improved smoke meter of € 4000,- and a life time of five years and on the basis of 100-1000 PTI's per year the estimated price per test is € 3.30 - €15.00. For a PN-meter of € 10.000,- and a life time of 5 years and 100-1000 PTI's per year the estimated price per test is € 3.30 - € 28.50.

8 Recommendations

In this project a preliminary investigation with handheld Particulate Number test equipment is carried out. It is recommended to develop dedicated PN meters for PTI purposes because the results of the PN test at low idle engine speed are very robust and reflect well the condition of the DPF. In order to avoid too high measured PN concentrations, sample dilution with a factor 10 is advised. A cost saving can probably be reached by not implementing the PN meter with a catalytic stripper which removes volatile fractions from the sample. Furthermore it is recommended to develop a dynamic calibration procedure for PN-meters that can be executed in a simple way by service personnel in the workshop.

It is expected that a new PN meter cannot be applied for PTI's of diesel engines without DPF. For these vehicles it is recommended to stick with the current PTI test procedure with opacity meters.

In the past, PTI smoke emission tests were manipulated by adding special liquids or petrol to the diesel tank to reduce smoke emission levels. In general, it is currently very hard to detect malfunctioning or removal of a DPF because smoke emissions of modern engines are very low. In addition new fuels, like BTL and GTL, even reduce smoke emissions with more than 50%. Therefore it is recommended to investigate the effects of such manipulation practices on the results of the improved smoke opacity meter and the PN-counter.

9 References

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[3] Bussink, Onderzoek beoordeling roetfilters, RDW report March 2014.

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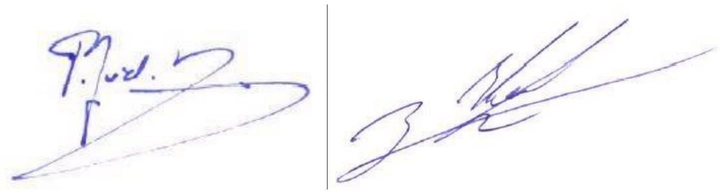
10 Signature

Delft, 10 October 2016 TNO



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A Tested vehicles

Table 14: Tested vehicles

Trade Mark	Number
Alfa Romeo	5
Audi	16
BMW	11
Citroën	7
Fiat	2
Ford	18
Honda	1
Hyundai	3
Kia	1
LANCIA	1
LAND ROVER	1
MAZDA	1
Mercedes	7
Mini	1
MITSUBISHI	1
NISSAN	2
Opel	19
Peugeot	13
Renault	30
Seat	14
Skoda	15
Toyota	2
Volkswagen	26
Volvo	16
Total	213

B Cost estimates PTI DPF tests

Cost estimation PTI DPF emission tests				
All prices excl. VAT				
Costs per test		Smoke	PN	
Equipment+fin.	[€]	5000	12500	
Test time	[min]	2	0,5	
Labour rate	[€/hour]	60	60	
Calibration	[€/year]	300	300	
Economic life time	[year	5	5	
		Costs per test		
Tests per year		Smoke (5)	PN (5)	
100		15,00	28,50	
200		8,50	14,50	
300		6,33	9,83	
400		5,25	7,50	
500		4,60	6,10	
600		4,17	5,17	
700		3,86	4,50	
800		3,63	4,00	
900		3,44	3,61	
1000		3,30	3,30	

Cost estimation PTI DPF emission tests				
All prices excl. VAT				
Costs per test		Smoke	PN	
Equipment+fin.	[€]	6000	15000	
Test time	[min]	2	0,5	
Labour rate	[€/hour]	60	60	
Calibration	[€/year]	300	300	
Economic life time	[year	10	10	
		Costs per test		
Tests per year		Smoke (10)	PN (10)	
100		11,00	18,50	
200		6,50	9,50	
300		5,00	6,50	
400		4,25	5,00	
500		3,80	4,10	
600		3,50	3,50	
700		3,29	3,07	
800		3,13	2,75	
900		3,00	2,50	
1000		2,90	2,30	