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TNO report

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Roadworthiness Test Investigations of Diesel Particulate Filters

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Summary

Since 2002 wall flow type diesel particulate filters (DPF) have entered the Dutch market and nowadays all new registered light duty diesel vehicles are being equipped with a DPF.
It makes sense to check their functionality in roadworthiness tests because a possible loss in filtration efficiency (i.e. from 99.5 to 97%) effects real world PM emissions significantly. Another reason to check their functionality is the fact that traps are apparently being replaced by dummy's or deliberately destroyed in order to avoid the cost of cleaning other maintenance or replacement, simultaneously adapting the OBD software to avoid detection.

In this project an investigation is made for development of a new smoke emission test procedure for roadworthiness purposes. In an engine test set up several smoke meters with lower measuring ranges are connected to the tail pipe of the Euro 5 diesel engine with DPF's with different filtration efficiencies. In steady state engine tests and the common free acceleration tests smoke, particulate mass (PM) emissions and particulate numbers (PN) were investigated.

Application of wall flow particulate filters or diesel particulate filters (DPF) in vehicles with filtration efficiencies of 95-99% decrease the particulate emissions significantly. Consequently, the measured smoke emissions in roadworthiness tests with good functioning DPF's are around or below the detection level (0.01 m^{-1}) of current measuring equipment with a measuring range of 0 -10 m^{-1}. Due to these very low smoke emissions and a relative high measuring range of the measuring equipment an adapted smoke emission roadworthiness test procedure is needed.

The smoke emission tests resulted in the following conclusions for roadworthiness testing of Euro 5 diesel engines with diesel particulate filters (DPF):

1. Smoke emissions of vehicles with modern diesel engines with and without DPF are relatively low and the new roadworthiness test procedure must be able to accurately identify smoke emissions of 0.0 – 0.5 m^{-1} corresponding to 0 - 117 mg/m^3.

2. Steady state tests without or with engine load are not suitable for roadworthiness tests, since engine load cannot be applied in a standard service shop. The engine out smoke emissions without engine load are too low (approx. 0.10 m^{-1}) for a practical measurement.

3. The free acceleration test is a good candidate for roadworthiness test purposes, provided that an accurate smoke meter and a heated sampling line are used.

4. In the free acceleration test common engine out smoke emission is 50-100 mg/m^3, while with DPF this is 0-10 mg/m^3. The currently available smoke meters with a measuring range from 0 – 700 mg/m^3 are suitable to detect complete DPF failures, but are not ideally suitable to detect modest DPF failures (with remaining filtration efficiency of 60-70%). Further optimisation of sampling and test equipment might result in a suitable test procedure.

5. In free acceleration tests the smoke and particulate number (PN) emissions have comparable trends. Furthermore particulate mass (PM) emissions in steady state tests show the same trend as PN and smoke emissions in a free acceleration test. This means that smoke tests are suitable for roadworthiness tests of diesel vehicles with diesel particulate filters. However, the smoke test equipment must be able to measure low smoke emissions accurately.

It is recommended to develop a final roadworthiness test with a smoke meter with a measuring range of 0 – 3 m^{-1} or 0-700 mg/m^3 and a heated sampling line.
The current roadworthiness test procedure with the free acceleration smoke test can be adapted to be used for Euro 5 vehicles with a diesel engine and DPF.

Contents

1 Introduction

Since 2002 wall flow type diesel particulate filters (DPF) have entered the Dutch market and nowadays all new registered light duty diesel vehicles are being equipped with a DPF.
It makes sense to check their functionality in roadworthiness tests because a possible loss in filtration efficiency (i.e. from 99.5 to 97%) effects real world PM emissions significantly. Another reason to check their functionality is the fact that traps are apparently being replaced by dummy's or deliberately destroyed to avoid the cost of cleaning other maintenance or replacement, simultaneously adapting the OBD software to avoid detection.
Currently the roadworthiness test method has been based on engines with relative high PM-emissions (without DPF) and the measuring range of current test equipment doesn't match with PM emission levels of DPF equipped vehicles. This optical test method has been based on opacity or light absorption. The smoke emissions in a free acceleration test of most vehicles with DPF do not exceed the detection limit of current test equipment. And even for vehicles of which the trap has been removed or destroyed the opacity value often stays below the reference value determined during the type approval, including a margin error of 0.5 m^{-1}.
Due to the relative low smoke emissions of modern diesel vehicles with or without DPF it is needed to develop a new DPF Roadworthiness Test Procedure (RTP). Special attention is given to the smoke emission test and the required test equipment which is able to measure low smoke emissions.

The Dutch Ministry of Infrastructure and the Environment has conducted a project for development of a DPF roadworthiness test procedure. This report is a first step in the development of a DPF roadworthiness test procedure and is an investigation of possible test equipment and DPF roadworthiness tests.

The test program was conducted at the Aristotle University of Thessaloniki (Greece) in an engine test bed of the Laboratory of Applied Thermodynamics (LAT). Different diesel particulate filters with different filtration efficiencies were tested with different smoke meters and different test procedures.

2 Objectives

This project has the next objectives:

- Development of a roadworthiness test procedure for vehicles type approved with “wall flow” diesel particulate filters (DPF) which can be applied in a service shop. Wall flow type means a particulate number filtration efficiency of more than 99%.

- Investigation of test equipment which can be applied for DPF roadworthiness tests.

- Definition of pass/fail DPF emission levels.

3 Test set up

In this Chapter a detailed description is given from the engine, engine test bed, Diesel Particulate Filters, measuring equipment and test cycles.

3.1 Engine test set up

In this test programme a Toyota 1ND 1.4l diesel (Euro 5) engine was installed on a AVL dynamometer platform. See Figure 1. The clutch installed between engine and dynamometer was able to disengage the engine. The DPF was installed in the exhaust line and could be exchanged according to measurement needs.
The exhaust line was connected to the CVS dilution tunnel.
The dynamometer control was an AVL Puma system with Open software for engine control and data recording. The engine data recording was conducted via ETAS INCA software (speed, load, Tfuel, Tair, Tcoolant, intake flow rate, fuel consumption).

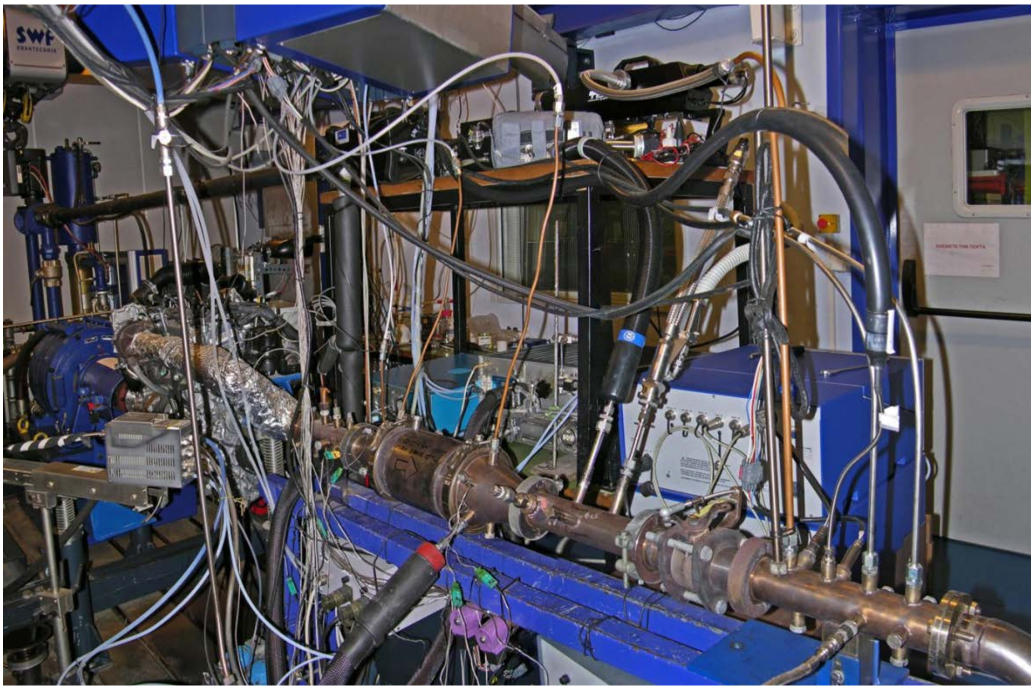

Figure 1: Engine test bed and exhaust line with DPF

In Figure 2 an outline of the test set up is given. Pressures and temperatures were measured pre and post DPF. Exhaust emissions were measured with AVL AMA i60 Analyzers (CO, CO2, NOx, HC), Signal 4000 (NO) measuring at the DPF outlet. Particulate numbers were measured with a TSI CPC 3010 in the diluted exhaust gas at the end of the dilution tunnel. The particulate mass sampling was also taken from the dilution tunnel (47mm Teflon coated TX40HI20-WW filters).
An AVL 483 Micro Soot Sensor and different smoke meters were installed at the DPF outlet. These smoke meters were: AVL DITest Smoke 2000, MAHA MET 6.2, TEN LPA, TEN EDA2, Pegasor Particle Number Sensor measuring at DPF outlet.

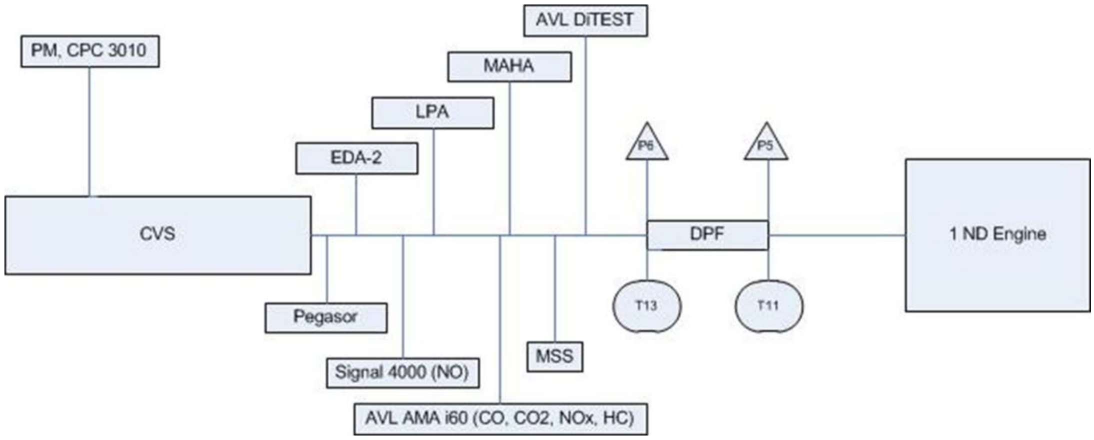

Figure 2: Schematic test set up

3.2 Diesel Particulate Filter configurations

Emission tests were carried out with Diesel Particulate Filters with different filtration efficiencies. The DPFs used for the tests are 5 identical non catalytic filters, SiC, 5.66”x6”, 2.5 liters, 300cpsi with 16 segments and did not contain oxidation catalysts upfront the DPF. In 4 filters a number of plugs on the outlet side was removed to simulate various levels of reduced filtration efficiency.
Before this test program the filtration efficiencies of all DPF’s were determined with a Light Duty diesel Euro 4 engine. The DPFs were named after the PM emissions targeted to achieve on a retrofitted Honda Accord 2.2 i-CTDi (Euro 4) over the New European Driving Cycle (NEDC). More details are shown in Table 1.

Table 1: DPF configurations and efficiencies based on a 2.2 liter Euro 4 diesel engine

DPF code	**Modified filtration efficiency**	**PM emission post DPF**	**Filtration Efficiency PM based**	**Picture**
		[mg/km]	[%]	
No DPF	Yes	40	0	
Above OTL*	Yes	17	60	Figure 3
OTL	Yes	12	73	Figure 4
1,5*TA**	Yes	7	79	Figure 5
TA	Yes	5	89	Figure 6
Full DPF	No	1	99	Figure 7

*OTL = On Board Diagnostic Threshold Limit
**TA = Type Approval

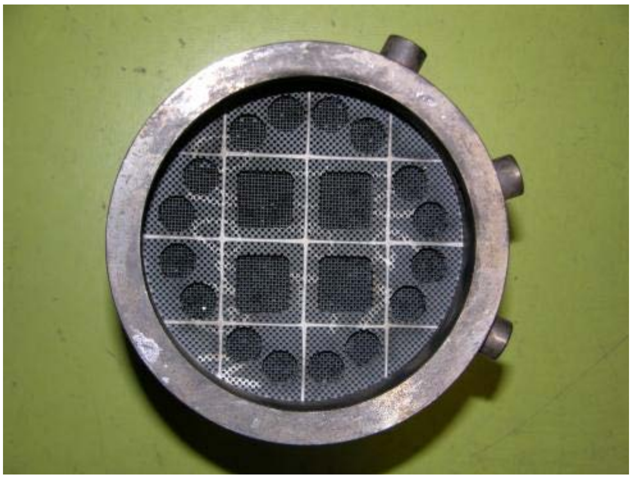

Figure 3: DPF 2 (Above OTL)

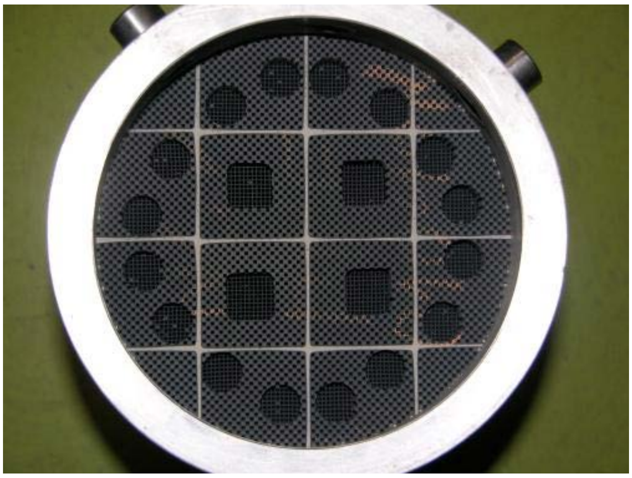

Figure 4: DPF 3 (OTL)

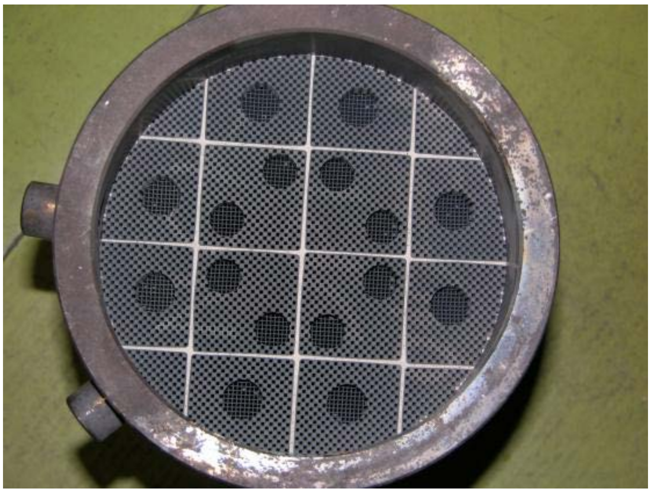

Figure 5: DPF 4 (1,5 * TA)

Figure 6: DPF 5 (TA - 219 plugs removed)

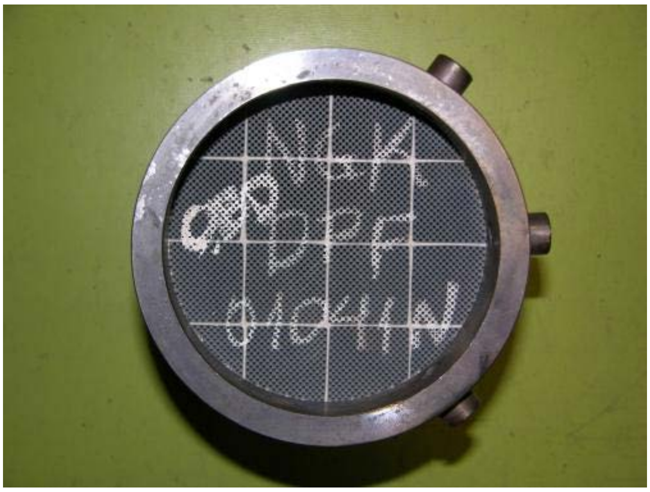

Figure 7: DPF 6 (Full DPF)

3.3 Preconditioning Diesel Particulate Filters

Before this test program the DPFs were fully regenerated (all soot was burnt) and preconditioned, starting from clean condition with PM loading over 3 NEDC tests.

3.4 Smoke emission tests

Three types of emission tests were conducted:
Cold test (cold engine, cold DPF), see

1. Table 2.

Hot test (hot engine, hot DPF), see * PM-measurements

2. Table 3

Free acceleration test (hot engine, cold DPF), see * PM-measurements

3. Table 4.

Table 2: Cold test (total duration 25 minutes)

Engine speed RPM	Engine load [Nm]	Duration [min]
800	5	3*
1500	5	3*
3000	5	3*
1500	50	3*
3000	70	3*
800	5	5
Engine disengaged		
Free acceleration 8 times		

* PM-measurements

Table 3: Hot test (total duration 40 minutes)

Engine speed RPM	Engine load [Nm]	Duration [min]
2000	40	12
3500	5	3
800	5	3*
1500	5	3*
3000	5	3*
1500	50	3*
3000	70	3*
800	5	5
Engine disengaged		
Free acceleration 8 times		

* PM-measurements

Table 4: Free acceleration test

Engine speed RPM	Engine load [Nm]	Duration [min]
Engine disengaged		
Free acceleration 8 times		

During the free acceleration tests the engine was disengaged from the dynamometer using the clutch, before the free accelerations. Starting from low idle speed, the acceleration pedal was set at 100%, the engine reached its maximum speed (5200 rpm) and returned to low idle speed (850 rpm).

All 6 configurations (Engine out + 5* DPF) were subjected to the next test schedule:
- 1 cold test
- 3 hot tests
- 1 free acceleration with cold DPF

3.5 Smoke meters

Different smoke meters with different measuring principles, configurations and measuring ranges were applied. In Table 5 and Table 6 the specifications of the smoke meters are reported. All smoke meters were equipped with samples lines with a length of 1,5 – 2,0 m. In order to reduce the effect of water condensation in the sampling lines the lines were mounted straight and the smoke meters were installed 1 meter above the level of the exhaust. See Figure 1 and Figure 8.

Table 5: Smoke meters (1)

Tester	AVL	MAHA	TEN
Name	Ditest	MET 6.2	LPA
Principle	Laser light scattering	Laser light scattering	Opacity + Laser light scattering
Measuring unit	[m^{-1}] [mg/m^3]	[mg/m^3]	[%]
Measuring range	0.01 - 3.00 0 - 700	0 - 700	0 - 100
Resolution	0.001	0.01	0.1
Size range [nm]	?	100-10.000	?
Meas. frequency [Hz]	100	10	1
Lower measuring limit [m^{-1}] / [mg/m^3]	0.01 / 2	0.01 / 2	
Sampling line	Heated	Non heated	Non heated
Sample pump	Yes	Yes	Yes
Sample flow [l/min]	2	2	2

Table 6: Smoke meters (2)

Tester	TEN	Pegasor	AVL
Name	EDA2	M-sensor	483
Principle	Opacity	Electrical charge	Photo acoustic
Measuring unit	[1/m]	[mg/m^3]	[mg/m^3]
Measuring range	0 - 10	0 - 250	0 - 50
Resolution	0.01	?	0.001
Size range [nm]	?	➢ 23	?
Meas. frequency [Hz]	5	100	5
Lower measuring limit [m^{-1}] / [mg/m^3]		0,01 mg/m^3	-
Accuracy [%]			+/- 3
Sampling line	Non-heated	Heated	Heated
Sample pump	No	No*	Yes
Sample flow [l/min]	No	>0	2
Comment	Current RW standard	-	-

*The Pegasor smoke meter has an ejector which generates an exhaust flow by means of pressurised air.

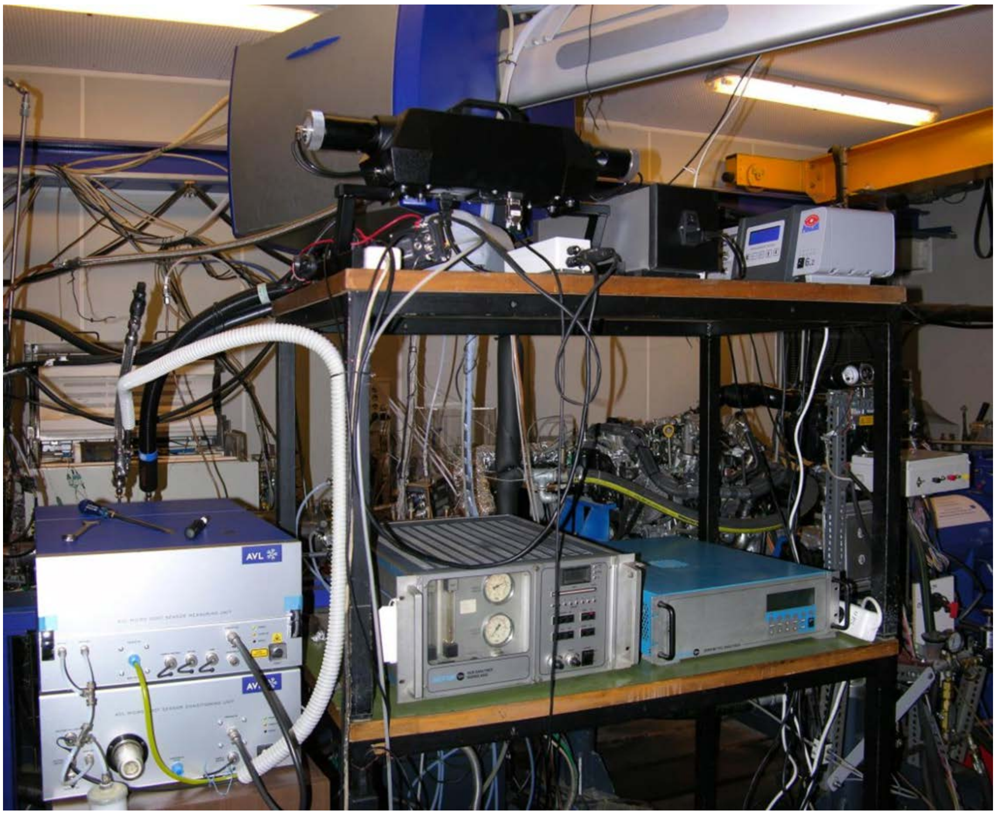

Figure 8: Smoke meters test set up

3.6 Particulate mass and number test equipment

In the engine test set up the engine was connected to a dilution tunnel. In the dilution tunnel particulate mass (PM10) was measured with a single 47 mm sample filter. Furthermore a CPC (Condensation Particulate Counting) was installed, see Figure 2 which measured particulate number emissions (PN).

4 Results

4.1 PM emissions of the DPF's with different filtration efficiencies

Tailpipe PM emissions are the basis of this test program. In order to check the DPF filtration efficiencies on this engine in every test the PM emissions are measured. In Table 7 and Figure 9 the PM emissions and the actual DPF mass efficiencies are reported. All actual filtration efficiencies are near the specifications and show a certain expected trend. The actual DPF filtration efficiencies are 15-22% lower than the specified/targeted DPF filtration efficiencies because different engines were applied (Euro 4 versus Euro 5) and in this test set up the DPFs are not equipped with an oxidation catalyst. The absence of an oxidation catalyst results in higher PM emissions because the heavier volatile fractions are condensed on the PM measuring filter. Furthermore the PM results in Figure 9 have a certain bandwidth for every DPF configuration because during testing the DPF's buffer soot and the effective PM emission will increase in time.

Table 7: PM emissions and DPF filtration efficiencies

	DPF Filtration Efficiency specified	**PM emission**	**DPF Filtration Efficiency Actual**
DPF configuration	[%]	[mg/kWh]	[%]
No DPF	0	440 - 488	0
Above OTL	60	231 - 329	40
OTL	73	203 - 251	51
1,5*TA	79	142 - 204	63
TA	89	86 - 189	70
Full DPF	99	56 - 91	84

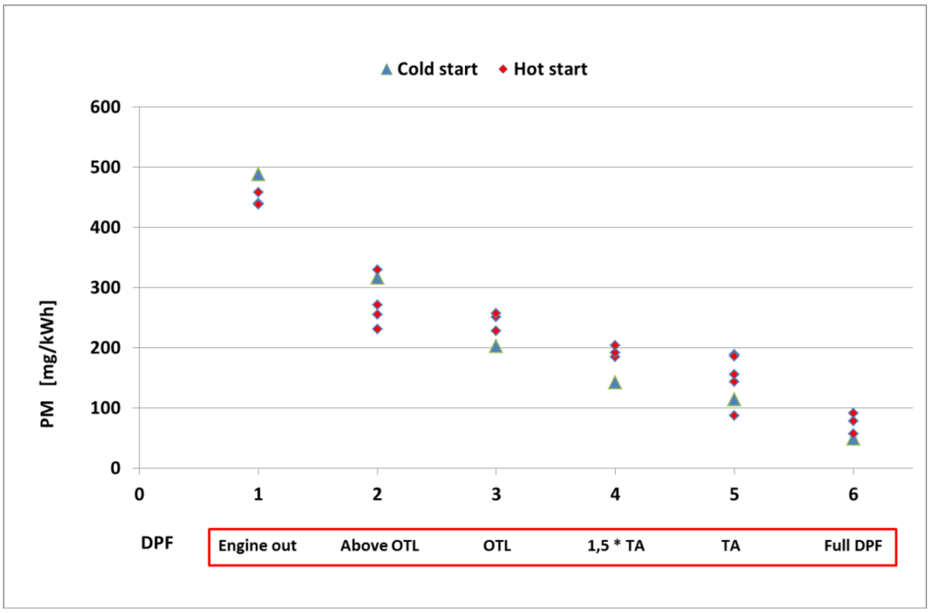

Figure 9: PM emissions in hot smoke emission tests

4.2 Quality of measuring signals

In order to obtain insight in the quality of the measuring signals of all applied smoke meters the quality of some test results is investigated. Steady state engine tests (with and without engine load) as well as free acceleration tests are carried out. Special attention is paid to the stability and level of the measuring results.

When smoke emissions in steady state operation are measured the stability and level of the measuring signals become clear. The quality of the measuring value can be affected in two ways: the stability of the measured sample and the stability of the test equipment. In the (non-heated) sampling lines condensed water absorbs soot and reduces the measured concentration of soot in the sample. Furthermore, condensed water in a smoke meter might disturb the operation of the measuring cell.

In Figure 10 the smoke emissions of unfiltered exhaust gas in a cold test are shown. In the morning this test was started with a period of preparations and all smoke meters were purged with clean air. Probably all moisture in the test equipment was removed/evaporated. In the first 200 s (t = 150 – 350 s) of the cold test most measuring signals are equal except for C (yellow-brown). This smoke meter is stable but has a certain off set.
After t = 350 s the smoke signal of the E meter (red line) increasingly deviates. This indicates that condensed water disturbs the measuring value. The measured smoke emissions are relatively high.

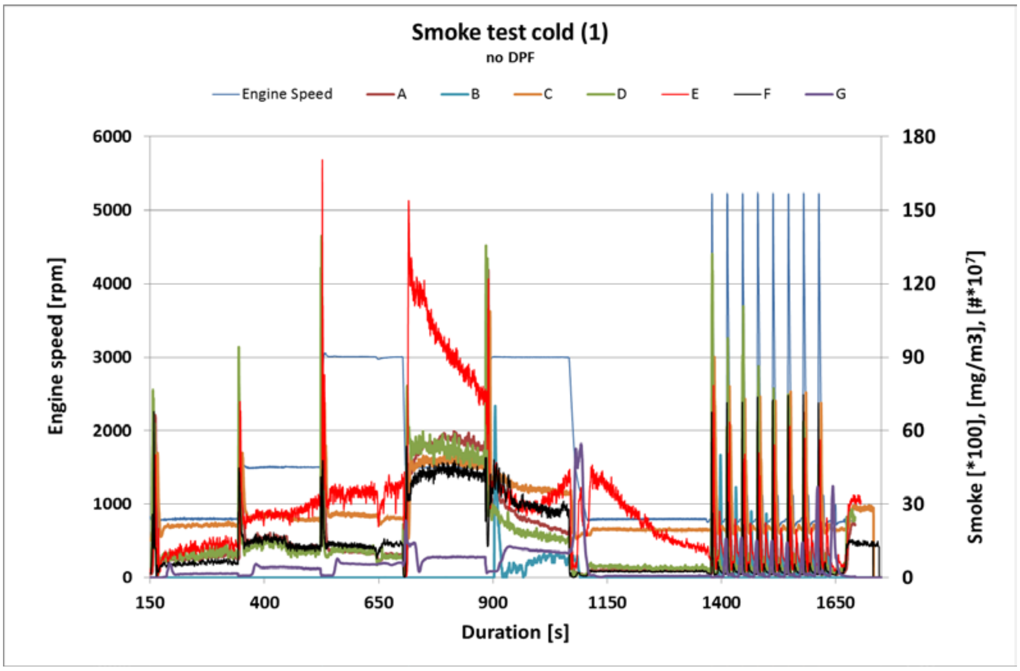

Figure 10: Engine out smoke emissions of cold smoke emission test

In Figure 11 the smoke emissions of unfiltered exhaust gas in a hot test are shown. In the first 200 s it is shown that all smoke meters register increasing smoke emissions, only smoke meter G is stable. After t=200s most measuring signals become relatively stable.
The smoke meter E (red signal) has relatively unstable measuring signals and the absolute level of the smoke emissions is relatively high and deviates from the other signals.
At higher smoke emission levels the smoke meters measure different concentrations (i.e. 1200 – 2400 mg/m3). The smoke meters A,D and F are relatively stable and have the highest measuring values, these smoke meters are all equipped with heated sampling lines.

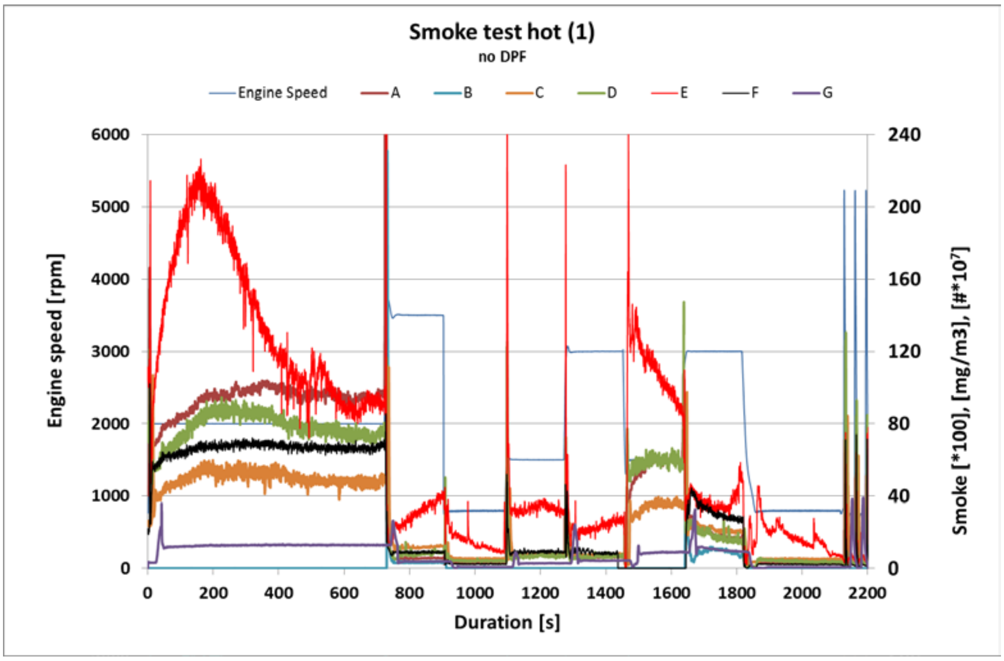

Figure 11: Engine out smoke emissions of hot smoke emission test

In Figure 12 the smoke emissions with un-modified DPF are shown. For most smoke meters the measured values are zero. One smoke meter (yellow/brown, C) measures 0-5 mg/m^3 and seems to have a certain off set, this might be caused by the 'prototype' status of this meter. The red measuring signal E is not stable and seems sometimes to be disturbed by moisture.

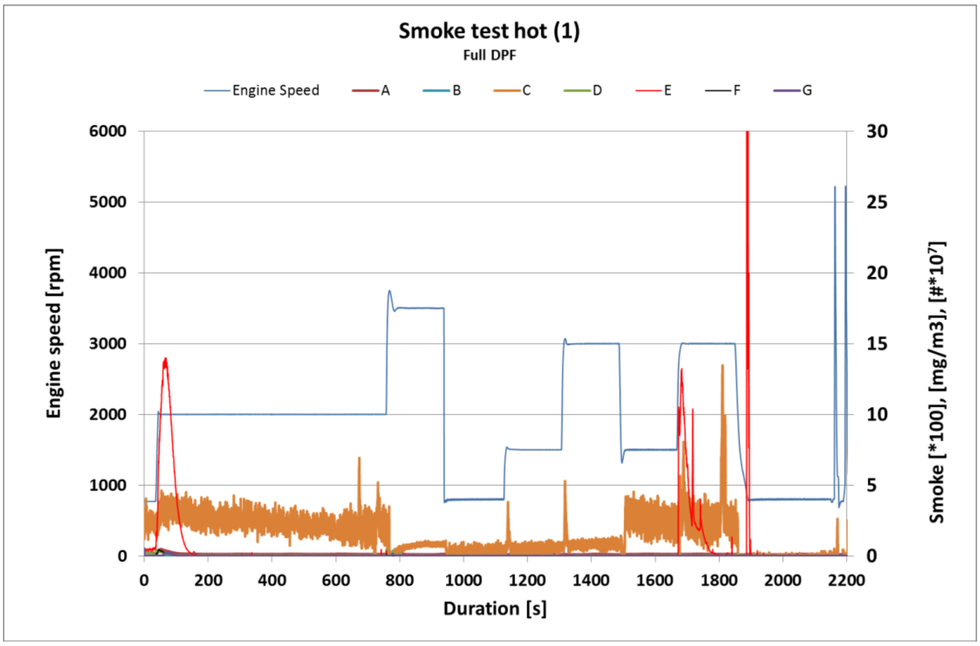

Figure 12: Full DPF smoke emissions with hot engine

4.3 Hot steady state smoke tests @ engine idle operation

In Figure 13 the results of the smoke emission tests at engine idle conditions are shown. Although no DPF is mounted most smoke meters measure smoke levels less than 1% of the measuring range (i.e. 10 mg/m^3). In Figure 14 the results of the same test with un-modified DPF are shown. All test results are below the detection limits.
From these results it can be concluded that the smoke levels at idle conditions are very low in all cases. Due to the lack of discrimination performance at these low levels, idle tests are not suitable for roadworthiness test purposes.

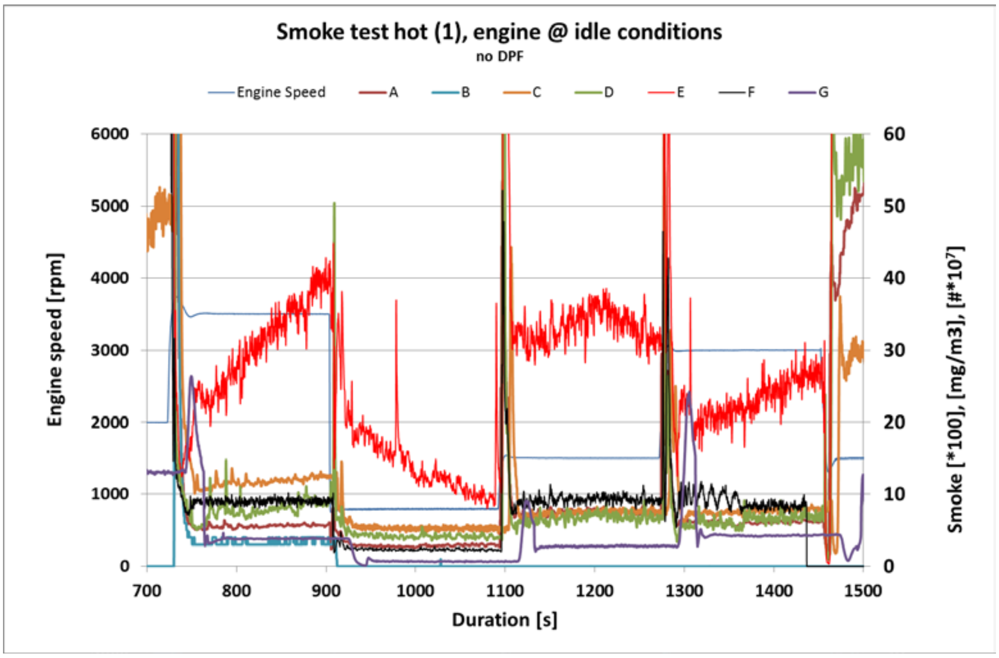

Figure 13: Engine out smoke emissions @ idle conditions

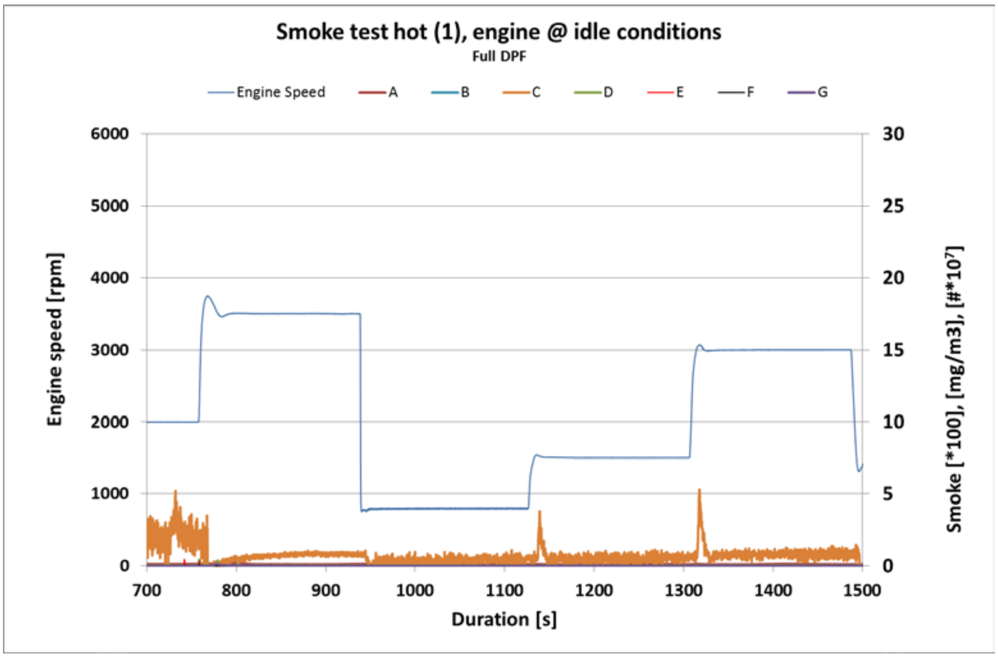

Figure 14: Smoke emissions @ idle conditions (unmodified DPF)

4.4 Hot steady state smoke tests at engine part load operation

In Figure 15 the smoke test results without DPF and with hot engine under part load conditions are reported (8 and 22 kW). Most smoke meters show results of 20 – 60 mg/m^3, this is well above the detection limit. In Figure 16 the results with the un-modified DPF are shown, again all measuring values are well below the detection limit. From these results it can be concluded that the results of a part load test might be used for roadworthiness purposes. However in most service shops there are no means to load an engine and consequently this part load test cannot be applied for practical roadworthiness tests.

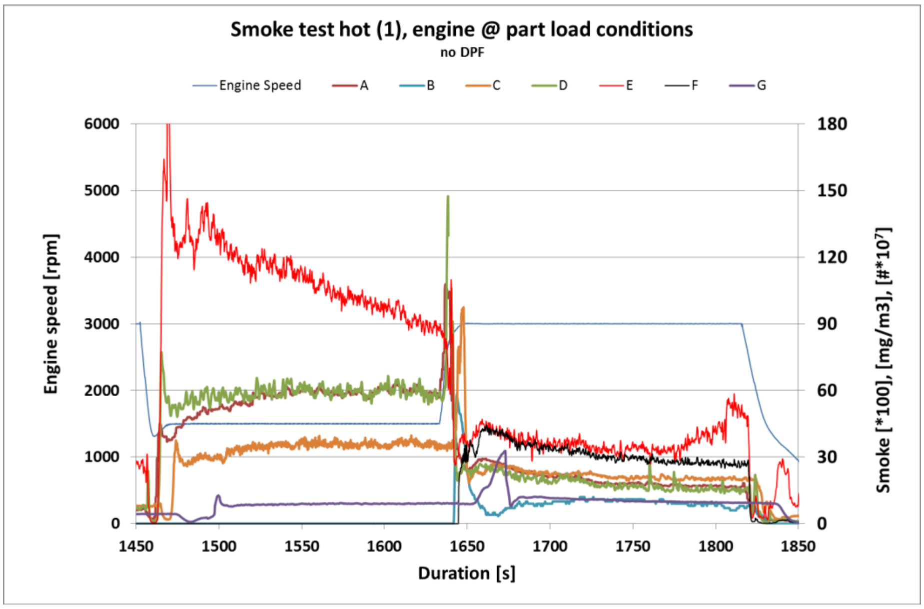

Figure 15: Engine out smoke emissions @ part load conditions

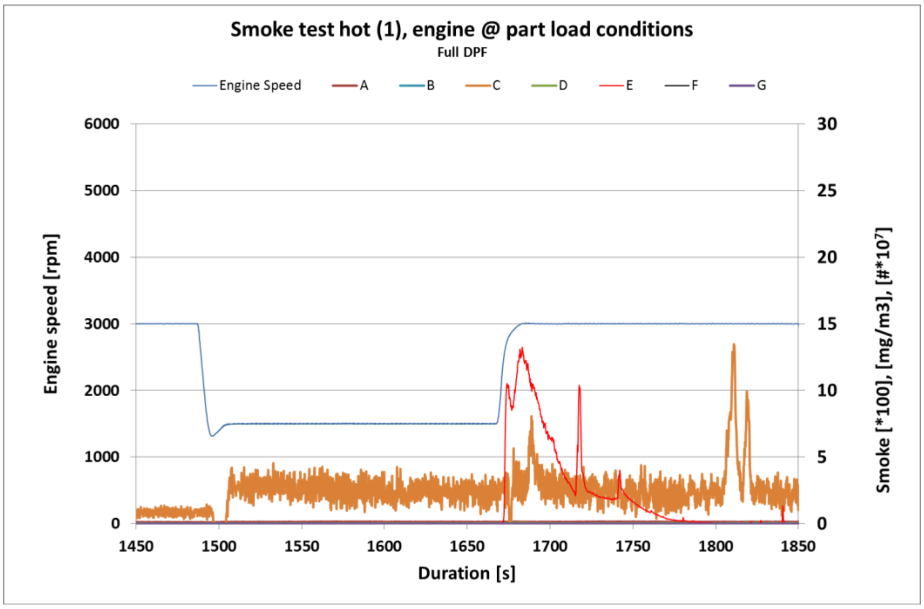

Figure 16: Full DPF smoke emissions @ part load conditions

4.5 Free acceleration tests with hot Diesel Particulate Filters

The common free acceleration test which is currently applied in roadworthiness tests is also performed in this test programme. In Figure 17 to Figure 22 the results of the free acceleration tests with the 6 DPF configurations are shown. Starting with a configuration without DPF in Figure 17 with a peak smoke emission of 50-80 mg/m^3 the peak smoke response becomes lower with higher filtration efficiencies.

The values of all peak smoke response of the 6 DPF configurations of the free acceleration tests are shown in Table 8.

Table 8: Results smoke emissions free acceleration tests with different hot DPF's

	DPF Filtration Efficiency	Smoke Level Indication	Opacity
DPF configuration	[%]	[mg/m3]	[1/m]
No DPF	0	65	0.20
Above OTL	40	25	0.12
OTL	51	20	0.06
1,5*TA	63	10	0.03
TA	70	3	0.01
Un-modified DPF	84	0	0.00

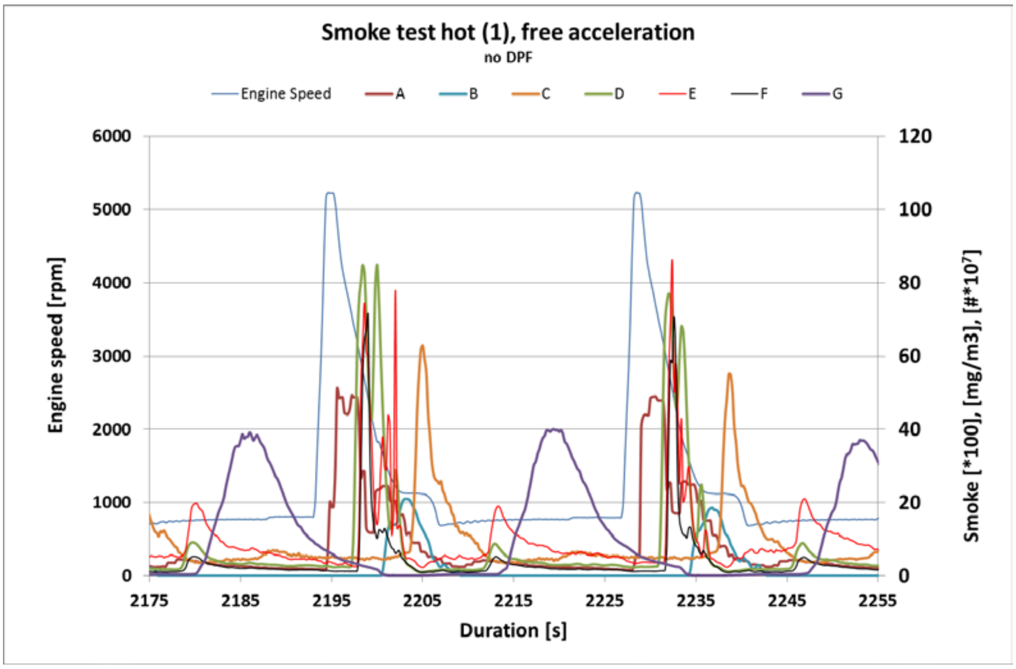

Figure 17: Engine out smoke emissions @ free acceleration

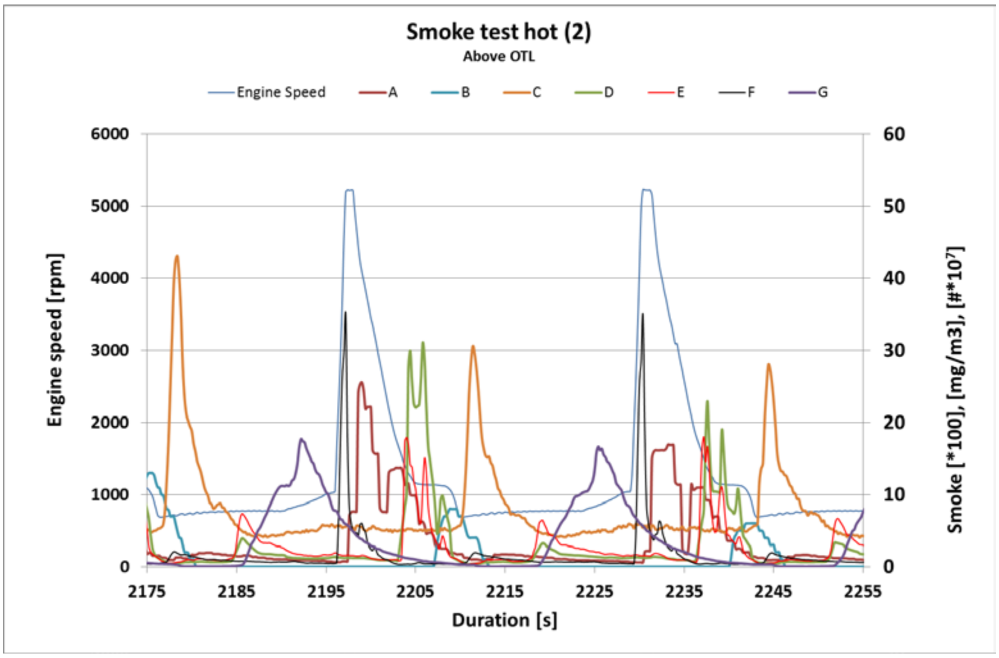

Figure 18: Free acceleration smoke with 'Above OTL' DPF

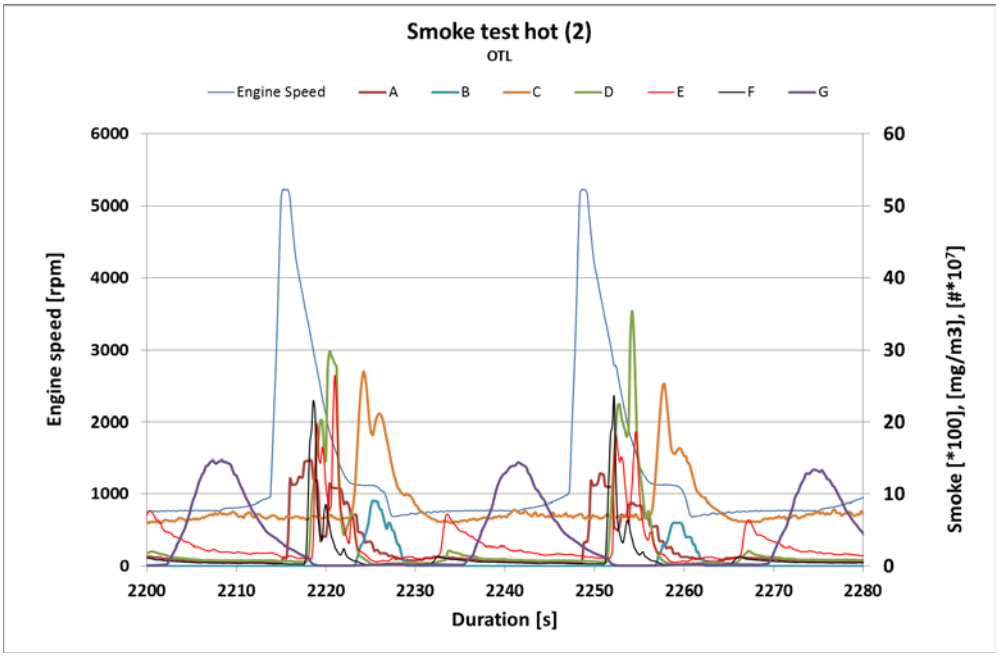

Figure 19: DPF-OTL smoke emissions @ free acceleration

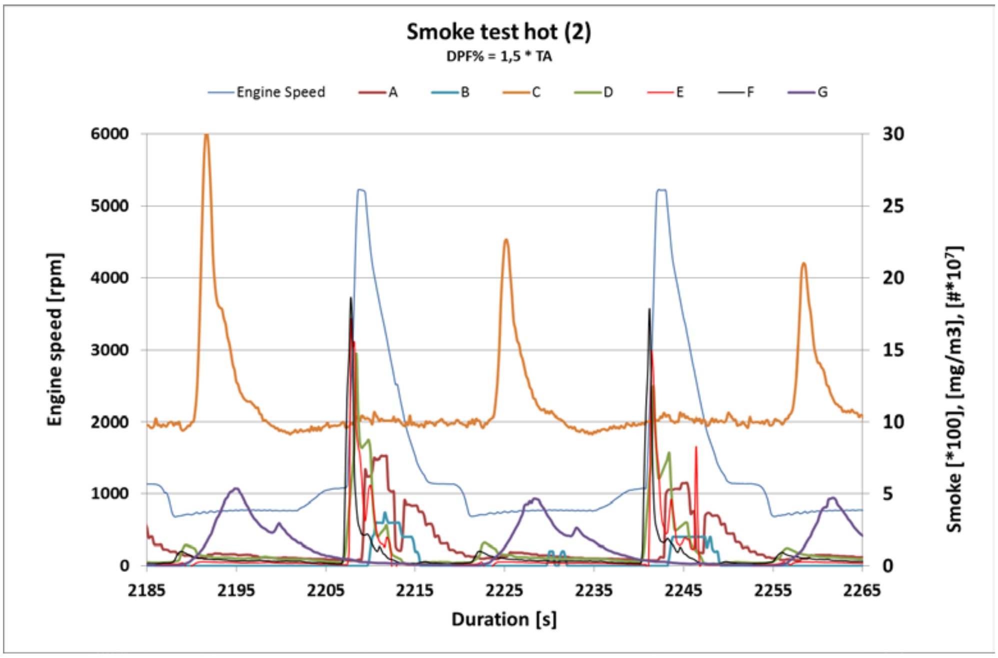

Figure 20: DPF-1,5 * Type Approval limit smoke emissions @ free acceleration

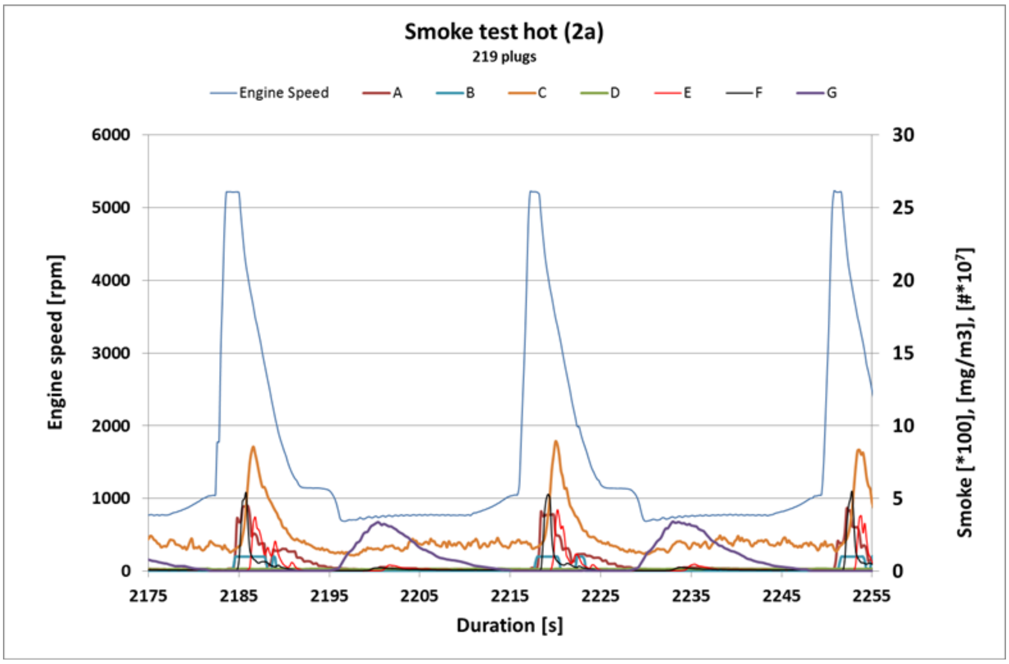

Figure 21: DPF-Type Approval limit value smoke emissions @ free acceleration

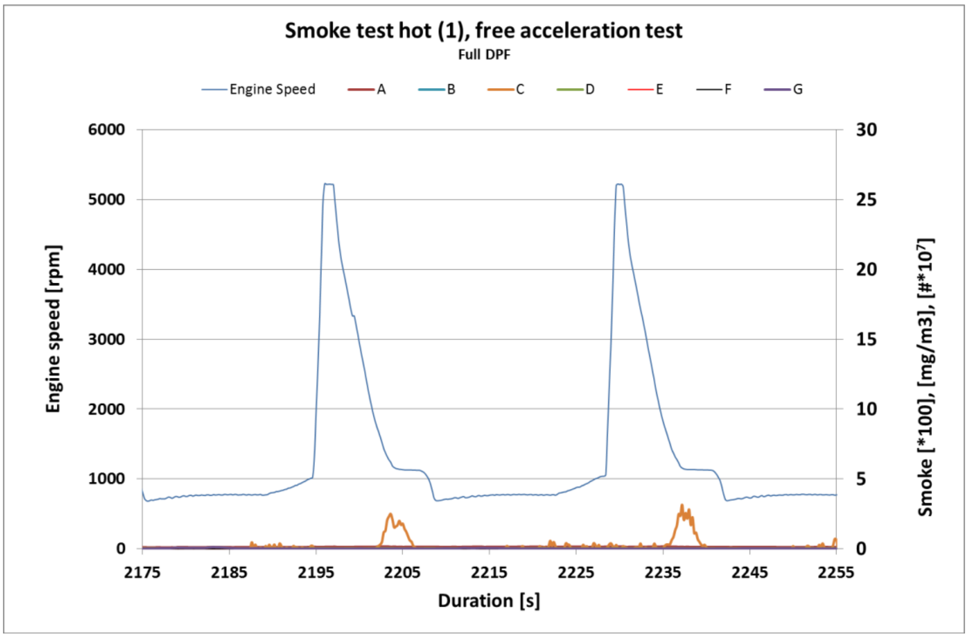

Figure 22: Full DPF smoke emissions @ free acceleration

From these free acceleration tests with hot DPF's with different DPF filtration efficiencies the findings are:

- DPF's with increasing filtration efficiencies generate decreasing smoke levels.
- The standard opacity meter with a measuring range of 0-10 m^{-1} shows also a decreasing smoke emission from 0.20 to 0.00 m^{-1}. However these measured smoke emissions are around 1% of the measuring range and consequently these test results are possibly not accurate enough for determination of the roadworthiness of a DPF equipped vehicle.
- The more sensitive smoke meters with a measuring range up to 700 mg/m^3 measure peak smoke levels from 0 to 65 mg/m^3. This is up to about 10% of the range. These smoke meters are considered sufficiently accurate for roadworthiness testing of vehicles with DPF's.
- Due to the relative high engine out smoke emissions in a free acceleration test the potential discrimination performance of this test is sufficient and a good candidate to develop a final roadworthiness test for diesel engines with DPF.

4.6 Free acceleration tests with cold Diesel Particulate Filters

For the practicality of roadworthiness testing it is preferred to be able to test with an engine not fully warmed up. Therefore some cold tests were performed.
In Figure 23 and Figure 24 some results of cold tests are shown. The measured smoke levels in the cold tests are comparable with the results of the hot tests which are reported in 4.3 - 0. From this it can be concluded, that the roadworthiness test can probably also be carried out with a cold engine and DPF.

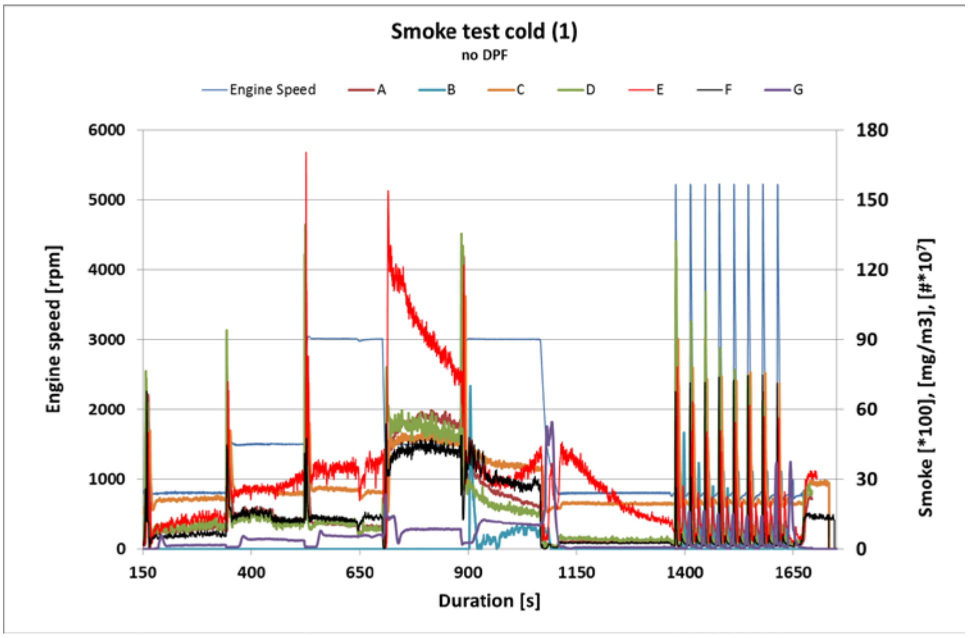

Figure 23: Engine out smoke emissions @ cold test

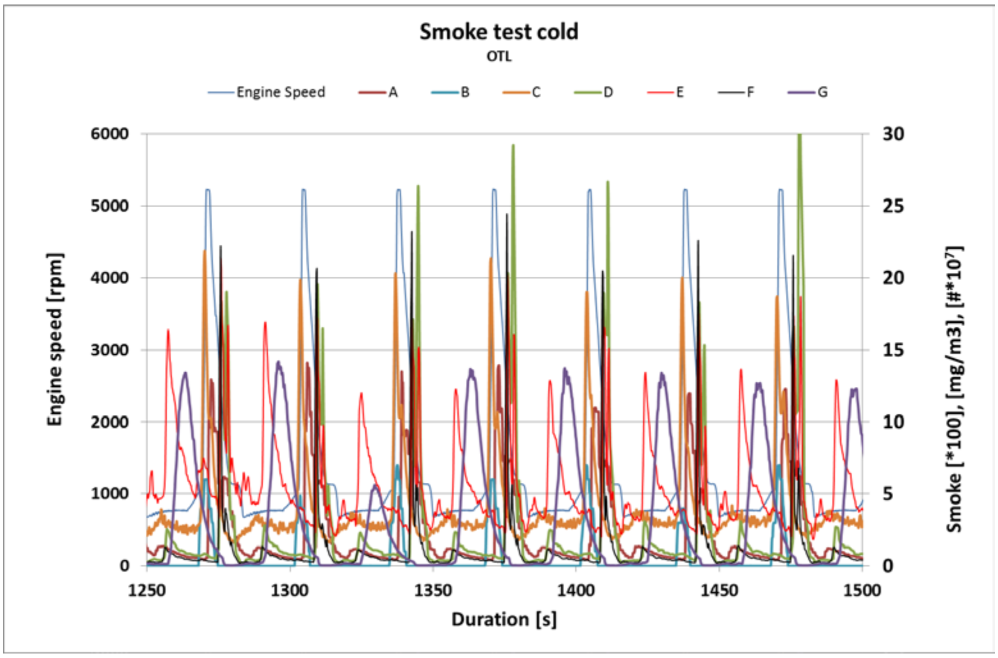

Figure 24: DPF-OTL(cold) smoke emissions @ free acceleration test

In Table 9 The smoke emissions of free acceleration tests with cold DPF are reported. These results are in line with the results of the hot test, see Table 8. However, the results of Figure 24 show that the peak smoke emissions vary between 18 and 30 mg/m^3. This indicates that the conditions of the free acceleration test and the conditions of the test equipment must be improved.
A heated sample line and stable measuring values at low readings are the first needs.

Table 9: Results smoke emissions free acceleration tests with different cold DPF's

	DPF Filtration Efficiency	Smoke Level Indication	Opacity
DPF configuration	[%]	[mg/m3]	[1/m]
No DPF	0	70	0.15
Above OTL	40	35	0.08
OTL	51	27	0.07
1,5*TA	63	15	0.03
TA	70	2	0.02
Un-modified DPF	84	0	0.01

4.7 Particulate number particulate mass and smoke emissions

In Figure 25 for different DPF-configurations the steady state PM emissions are compared with the PN and smoke emissions in the free acceleration test. All three parameters show increasing measured values with a decreasing filtration efficiency. The smoke and PN emissions in the free acceleration test have comparable trends of their measuring values. This indicates that smoke emissions are a good indicator for PN-emissions in a roadworthiness test. Furthermore PM-emissions in steady state tests show the same trend as free acceleration PN and smoke emissions.

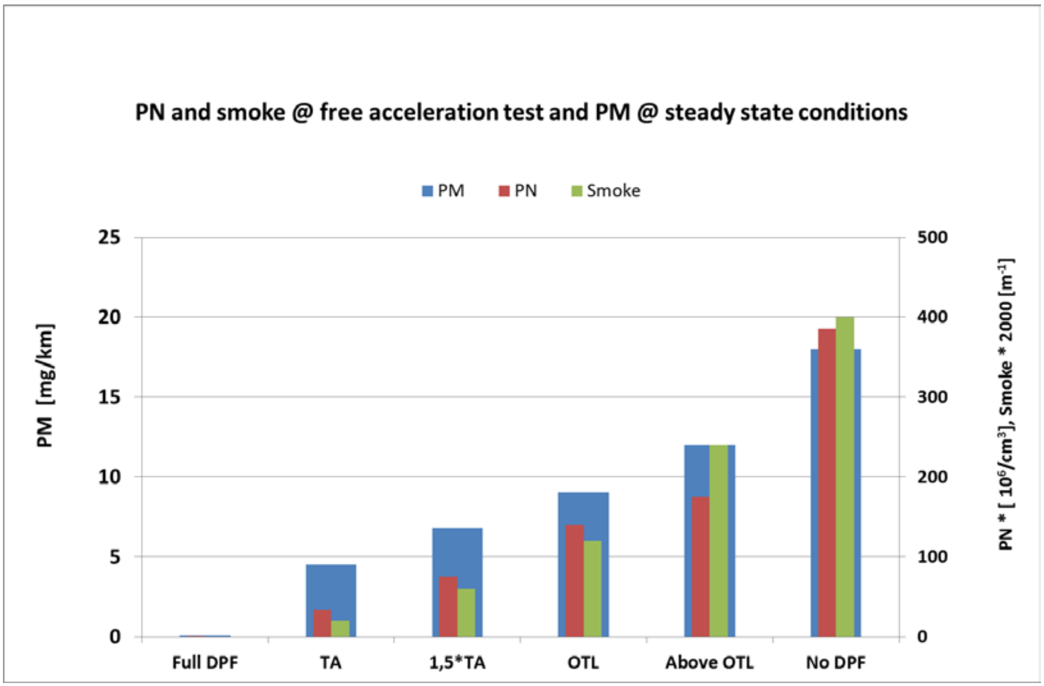

Figure 25: Comparison PM, PN and smoke emissions

5 Discussion

A new roadworthiness smoke test must be able to detect very low smoke emissions.
Current diesel vehicles with Diesel Particulate Filters emit no visible smoke, but also modern diesel engines without DPF have a low particulate emission level (with hardly visible smoke). Consequently it is expected that also DPF with a modest failure such as cracks or some end caps removed, still have very low smoke emissions, in spite of an increase of the particulate number emission with a factor 10 to 100. This indicates that for roadworthiness testing the accuracy and reproducibility of a smoke test must be very good and the detection level extremely low. Therefore, the accuracy of the test equipment, the preparation of the sample and the measuring procedure are important and must be optimised for a new roadworthiness test procedure.

Steady state tests do not meet roadworthiness test requirements.
Steady state emission tests without any engine load show that smoke emission levels without DPF are extremely low (< 10 mg/m^3) . Due to these low smoke emission levels it is not possible to develop a roadworthiness test with these engine conditions. Steady state tests with part load engine conditions would be a solution for this, but this cannot be realised in standard service shops.

Smoke emissions of modern engines are relatively low.
In this test program the Euro 5 engine with the different Diesel Particulate Filters has very low smoke emissions and this confirms the need for an adapted roadworthiness test procedure with test equipment suitable for lower measuring ranges. Current smoke levels of modern engines with and without DPF and measuring ranges of current test equipment are:.

- Typical free acceleration test smoke levels of Euro 5 engines with removed DPF are 0.20 - 0.30 m^{-1} or 40 - 65 mg/m^3.
- Typical free acceleration test smoke levels of Euro 5 engines with a proper working DPF are 0.00 - 0.05 m^{-1} or 0 - 10 mg/m^3.
- Current smoke (opacity) meters have a measuring range of 0 – 10 m^{-1}.
- Modern smoke meters have measuring ranges 0 – 3.0 m^{-1} or 0 – 700 mg/m^3.

Current vehicle smoke emission levels require very accurate test equipment and sample preparation.
Due to the very low smoke emissions of engines with Diesel Particulate Filters test equipment need to be very accurate because a difference in smoke emission of 0.02 m^{-1} or 5 mg/m^3 must be detectable. Furthermore this test program indicates that condensation of water disturbs the readings of the relative low smoke values. Therefore it is strongly recommended to apply a heated sampling line.

Even modern smoke meters with a measuring range of 0 - 700 mg/m^3 hardly have sufficient discrimination performance.
In free acceleration tests smoke emissions of Euro 5 vehicles with DPF filtration efficiencies of 60-70% are 20 - 25 mg/m^3 . This indicates that the pass/fail bandwidth is around 5 mg/m^3 and test equipment with an accuracy of +/- 1 mg/m^3 is needed to have sufficient discrimination potential in a smoke test. For the applied smoke meters no accuracy is specified.

A smoke meter with a measuring range of 0 – 700 mg/m^3 would be operating at 0 – 10% of its measuring range and can therefore hardly be expected to be able to measure DPF-failures.

Detection of high emitters is possible with a modern smoke meter:
Euro 5 diesel engines with dismantled DPF have free acceleration smoke emissions of 50 – 100 mg/m^3 or 0.20 - 0.40 m^{-1} and engines with a DPF with more than 99% filtration efficiency emit less than 5 mg/m^3 or 0.00 - 0.05 m^{-1} . With application of modern smoke meters with a measuring range of 0 – 700 mg/m^3 and heated sampling lines it is possible to detect high emitters.
Currently applied smoke meters with unheated sampling lines and a measuring range of 0 – 10 m^{-1} are not able to detect high emitters because the expected smoke levels of high emitting Euro 5 engines are 0.30 - 0.50 m^{-1} and consequently they have a lack of discrimination performance.

6 Conclusions

Investigations for development of a new roadworthiness smoke test procedure of light duty diesel vehicles with Diesel Particulate Filters with and without simulated failures were carried out on an engine test bed. Smoke meters with different measuring principles and ranges are used and compared.

Three different smoke emission tests were carried out, these are:

- Steady state test without engine load,
- Steady state test with engine load,
- Free acceleration test (hot and cold).

The smoke emission tests resulted in the following conclusions for roadworthiness testing of Euro 5 diesel engines with diesel particulate filters (DPF):

1. Engine out smoke emissions of vehicles with modern diesel engines and DPF are relatively low and the new roadworthiness test procedure must be able to discriminate smoke emissions of 0.0 – 0.5 m^{-1}.

2. Steady state tests with engine load are not suitable for roadworthiness tests, since engine load cannot be applied in a standard service shop. And smoke emissions of steady state tests without engine load are too low (approximately 0.10 m^{-1}) for a practical measurement.

3. The free acceleration test is a good candidate for roadworthiness test purposes of diesel vehicles with DPF, provided that an accurate smoke meter and a heated sampling line are used.

4. In the free acceleration test common engine out smoke emission is 50-100 mg/m3, while with DPF this is 0-10 mg/m3. The currently available smoke meters with a measuring range from 0 – 700 mg/m3 are suitable to detect complete DPF failures, but are not ideally suitable to detect modest DPF failures (with remaining filtration efficiency of 60-70%). Further optimisation of sampling and equipment might result in a suitable test procedure.

5. In free acceleration tests the smoke and PN emissions have comparable trends. Furthermore PM-emissions in steady state tests show the same trend as PN and smoke emissions in a free acceleration test. This means that smoke tests are suitable for roadworthiness tests of diesel vehicles with diesel particulate filters. However, the smoke test equipment must be able to measure low smoke emissions accurately.

7 Recommendations

Provided a more accurate smoke meter becomes available the current roadworthiness test procedure with the free acceleration smoke test can be used for Euro 5 vehicles with a diesel engine and DPF to identify failing or dismantled DPF's. Develop requirements for a more accurate smoke meter having a measuring range of 0-3 m^{-1} or 0-700 mg/m^3 and a heated sampling line.

Investigate the possibilities for a smoke screening test with the current road worthiness test and smoke meters and apply a heated sample line. The stability, accuracy and repeatability around measuring values of 0.10 m^{-1} must be less than +/- 0.01 m^{-1}.

8 Signature

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