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TNO report

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Real world efficiency of retrofit partial-flow diesel particulate filters for trucks

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Samenvatting voor beleidsmakers

Aanleiding
Om de uitstoot van fijn stof door vrachtverkeer te verminderen, heeft het ministerie van VROM in 2006 een stimuleringsregeling opengesteld voor retrofit roetfilters op Euro II en Euro III vrachtwagens. Het gaat in deze regeling om zowel zg. half-open of open roetfilters als zg. gesloten roetfilters. In de periode 2007 tot januari 2009 zijn ongeveer 15,000 halfopen roetfilters en 8,000 gesloten roetfilters gemonteerd.
Van de halfopen roetfilters wordt vereist dat ze in de typegoedkeuringstest tot 50% reductie in fijn stof uitstoot leiden.

In 2008 is door TNO een laboratorium onderzoek naar het filtratierendement van half-open roetfilters verricht op een motorproefstand – hierbij zijn zes roetfilters getest op 1 type (zware) motor. Dit onderzoek liet teleurstellende rendementen zien: 5-20% bij stadsgebruik en nationaal snelweggebruik en 20-40% bij langdurig snelweggebruik. Op basis van deze resultaten rees de vraag of deze rendementen representatief zijn voor andere (m.n. middelzware) typen vrachtautomotoren en andere roetfilters, en in hoeverre de rendementen worden beïnvloed door de manier van meten. Om deze vragen te beantwoorden is een vervolgonderzoek opgezet, dat hier wordt gerapporteerd.

Opzet van het onderzoek
In dit onderzoek zijn 9 verschillende open roetfilters (5 verschillende typen) getest op 4 verschillende vrachtwagens. Drie ervan zijn typische distributietrucks, aangezien deze trucks de grootste bijdrage hebben aan luchtkwaliteitsproblemen in steden. De vierde truck is een zware truck, en is gekozen om correlatie met de motorproefstand metingen mogelijk te maken. De roetfilters zijn afkomstig uit de praktijk, en zijn gedurende 10-23 maanden gebruikt door transportbedrijven.

De voertuigen met roetfilters zijn getest in het laboratorium, in een testprocedure die zoveel mogelijk het werkelijke gebruiksprofiel benadert. Dit is van belang omdat het gedrag van roetfilters sterk afhangt van de gebruikscondities (m.n. uitlaatgastemperatuur) en de geschiedenis van de roetfilters. Bij de ontwikkeling van de testprocedure zijn daadwerkelijke gebruiksprofielen van distributietrucks gebruikt.

Resultaat en conclusie
Het onderzoek laat zien dat het gemiddelde filtratierendement tijdens stadsgebruik rond de 40% ligt, en bij gebruik op de snelweg rond de 30%.

De gemeten rendementen zijn gemiddeld lager dan vereist in de typegoedkeuringstest, maar hoger dan die gemeten in het eerste laboratorium onderzoek. Nadere analyse laat zien dat de verschillen toe te schrijven zijn aan de verschillende testprocedures die zijn gehanteerd. Eén van de vijf geteste filtertypen onderscheidde zich in positieve zin met een aanzienlijk beter rendement dan de typegoedkeuringseis.

Het onderzoek laat zien dat zowel de testprocedure als de historie van het roetfilter grote invloed hebben op de gemeten rendementen. Dat betekent dat ook in de praktijk het gebruiksprofiel van het roetfilter van grote invloed zal zijn op het praktijkrendement. De in dit onderzoek gekozen methodiek biedt echter een betrouwbare indicatie van het rendement van roetfilters in de praktijk.

Summary

Background and objective

In 2006 the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) introduced an incentive scheme for retrofitting diesel particulate filters on Euro II and Euro III trucks. This scheme involves both partial flow and full flow diesel particulate filters (also called semi-open or open respectively wall-flow or closed filters). In the period 2007 till January 2009 about 15,000 partial flow filters and 8,000 full flow diesel particulate filters were installed. The minimum filtration efficiency requirement for the partial flow diesel particulate filters is 50% during the type approval test.

In 2008 an engine dynamometer test programme was conducted to measure the filtration efficiency of retrofit open particulates filters of heavy trucks. This led to somewhat disappointing results with average filtration efficiencies in the range of 5-20% during city and national motorway driving conditions up to 20-40% during long distance motorway driving.
This result leads to two main questions: 1) Is this result also representative for medium heavy trucks used for delivery, and 2) do similar efficiencies show up also in tests on entire vehicles, tested under conditions as close as possible to their real world usage profile.
To this end, an additional measurement programme was defined, which is reported here.

Objective

The objective of the study reported here is to determine the real world filtration efficiency of retrofit partial flow particulate filters for a number of trucks under different driving conditions such as city and motorway driving. The emphasis should be on medium heavy trucks typically used for national delivery.

Measurement programme

The measurement programme consisted of measurements with 9 retrofit open particulate filters on four different trucks. There were three typical national delivery trucks and one typical long haul truck. Refer to Table 1, which also gives an overview of total vehicle weights and test cycles used during the chassis dynamometer testing.

Table 1. Overview tests with four trucks with retrofit diesel particulates filters

Truck	Category	Vehicle weights (tonne)		
		National		International
		City	Motorway	Motorway
1	150-225 kW	11.5 and 18.5	11.5 and 18.5	
2	150-225 kW	11.5 and 18.5	11.5 and 18.5	
3	150-225 kW	11.5 and 18.5	11.5 and 18.5	
4	> 225 kW	14 and 24	14 and 24	41 motorway cycle 41, 47.5 constant speed

The tests were conducted at the facilities of VTT Technical Research Centre of Finland.

The test set up consisted of a transient chassis dynamometer (roller bench) equipped with a full-flow dilution tunnel for measuring particulate emissions. In total more than 300 tests were done in two test periods.
The nine retrofit particulate filters were used filters obtained from five transport companies. They had been used on trucks during a period of 10 to 23 months or 30,000 to 235,000 km.

Test cycles and test sequence:

Open particulate filters are very sensitive to the engine load pattern during testing, but also to the usage during the hours, days and weeks before the tests. For that reason the usage pattern of typical national delivery trucks and to a lesser extent typical long haul trucks were extensively investigated. This consisted of evaluations of the driving pattern throughout the day (mix of city, rural and motorway), exhaust gas temperature profile and vehicle weight distribution (due to cargo weight). Input was also obtained from industrial stakeholders. Consequently during the first test period, the test cycles for city and motorway driving were adapted to fit the real world exhaust gas temperature conditions. The sequence of tests throughout the day was chosen to match realistic daily load patterns.

Results

In total 9 retrofit open particulates filters were tested on 4 trucks. In Figure 1 an overview is given of the average and range of filtration efficiency per truck and per test type. Each filter was tested during city and motorway cycles with two vehicle weights. Truck number 4, the heavy truck, was additionally tested with test types representative for international heavy goods transportation. The figure shows that the average filtration efficiency generally varies between 15% and 55%. The exception is truck number 3. For this truck two different filter types were tested. One had a filtration efficiency around 80%. Truck number 4 showed some negative and zero filtration efficiency results.

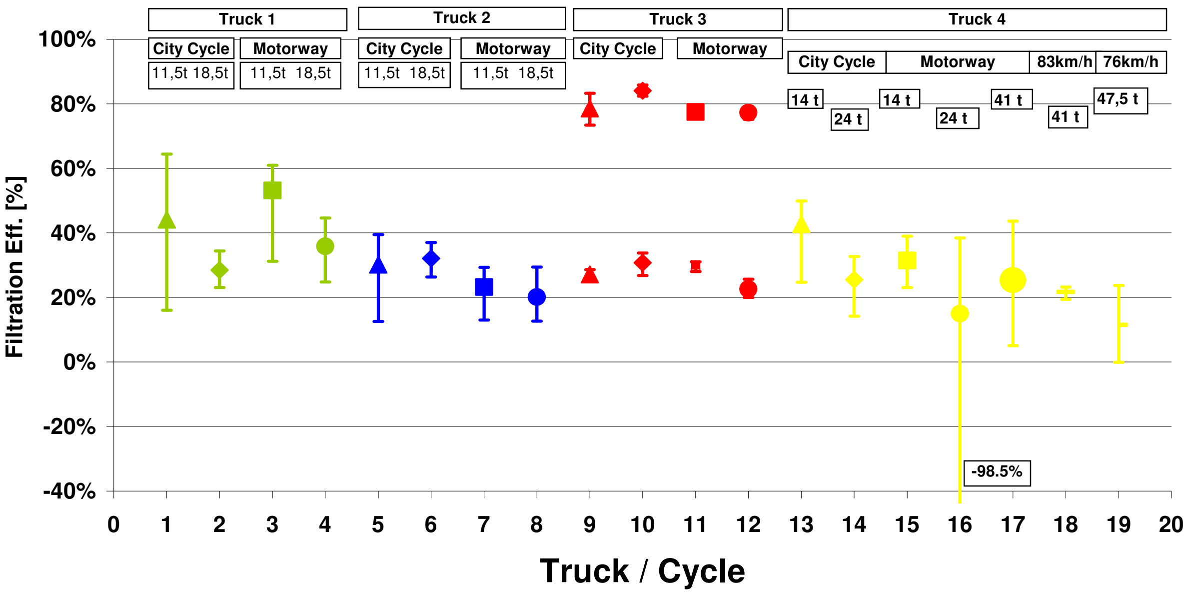

Figure 1. Average and range of filtration efficiencies of retrofit particulate filters on four trucks

In Table 2, the average filtration efficiencies are given for different driving conditions. The upper and lower value of the range are respectively the average of the measurements with the low and the high total vehicle weight. The result for "motorway international" is only based on the tests with the heavy truck, truck 4. The average filtration efficiency in that case was close to 20%. Based on the engine dynamometer tests in 2008 (phase 1), it is likely that with continuous motorway driving (longer than about 3 hours) efficiency would go up to a value in the range of 30% to 40%.

Table 2. Range of average filtration efficiency of retrofit open particulate filters for trucks

Driving condition	Vehicle weight range (ton)	Filtration efficiency
city	11 – 24	36% to 44%
Motorway national	11 – 24	30% to 40%
Motorway international heavy trucks only	41 – 47	20%
Motorway average		30%

Blow-off of stored particulates

The phenomenon of blow-off of stored particulates has been regularly reported with passenger car retrofit (partial flow) particulates filters. The test programme was organised in such a way that the release of particulates during blow-off would be measured. This was done by avoiding any conditioning or pretesting and to always have the dilution tunnel and particulates sampling system operational when the truck was running.

During the measuring programme of in total about 300 tests, there were four tests with a possible release or blow-off of stored particulates. One test showed an emission increase of 100% compared to engine out level, which indicates a release of stored particulates.

Correlation with phase 1 results

Phase 1 consisted of engine dynamometer tests with 6 retrofit open particulate filters. The results are correlated with those of the heavy truck (truck 4) which has an identical engine.
The results are as follows:

- There is a good correlation for the tests simulating motorway driving (based on tests with a vehicle weight of 41 to 47 ton). Also the ETC tests correlated well with the corresponding chassis dynamometer tests.
- There is a considerable difference between the tests simulating city driving. The average filtration efficiency is respectively 13% and 26% for the engine dynamometer and chassis dynamometer tests.

The main reasons identified for the difference during city driving conditions are:
a) the difference in average exhaust gas temperature (lower with the chassis dynamometer testing resulting in a higher efficiency) and
b) the difference in test sequence. The more frequent alternations between motorway and city cycle tests has a positive influence on the city cycle efficiency during the chassis dynamometer tests.

Moreover the chassis dynamometer tests cover a wider range of driving conditions and vehicle weights. This also leads to a higher average filtration efficiency under city driving conditions. In addition to that, the distinction can be made between national and international motorway driving. Refer to Table 2.

NO_2 emissions

NO_2 emissions generally increase when a diesel particulate filter is installed. NO_2 is intentionally made by a catalytic coating in order to promote the regeneration of particulates. The NO_2 concentrations were measured with the 7 retrofit filters on the medium heavy trucks. This showed a moderate increase of NO_2 as a percentage of NO_x after application of a diesel particulate filter. For city driving NO_2 increased from a few percent to 8%-15% depending on the vehicle weight. For motorway driving, NO_2 increased from a few percent to about 23%.

Conclusions

A measuring programme was conducted which was focussed on measuring the filtration efficiencies of retrofit open particulate filters of medium heavy and heavy trucks under simulated real-world conditions.
This leads to the following values for the average filtration efficiency:

- For both medium heavy and heavy trucks with a total vehicle weight in the range of 11 to 24 tons:
  - around 40% during city driving
  - around 35% during motorway driving

- For heavy trucks with a total vehicle weight between 40 and 47 tons: around 20% during motorway driving

- Possible blow-off of stored particulates happened only a few times during the phase 2 program (with medium and high vehicle weights > 18 ton).

- The precise load pattern and load pattern history have a large impact on the filtration efficiency. This explains the difference with the phase 1 results. The efficiency is higher with relatively low vehicle weights and after driving conditions which are favourable for regeneration.

Contents

1 Introduction

1.1 Background

In 2006 the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) introduced an incentive scheme in the Netherlands for retrofitted diesel particulate filters for Euro II and Euro III trucks. As a result of this, in the period 2007–2008 some 23,000 closed (wall-flow) and (half)open diesel particulate filters were installed in the Netherlands.

The scheme is described in ‘Type approval requirements for retrofitted particulate matter reduction systems for Euro 2 and Euro 3 motor vehicles that have been permitted based on an approval in accordance with Directive 88/77/EEC or Directive 2005/55/EC respectively’. The scheme includes two categories of diesel particulate filters: at least 50% reduction in particulate mass (typical partial flow or ‘open’ or ‘semi-open’ diesel particulate filters) and at least 90% reduction in particulate mass (typical full flow or closed diesel particulate filters).

An important part of the incentive scheme for particulate filters was a testing programme, to see whether the incentive leads to a sufficient reduction in particulate matter emissions. In this context, in 2008 an engine dynamometer test programme was conducted to measure the filtration efficiency of retrofit partial flow particulates filters of heavy trucks. This leads to somewhat disappointing results with average filtration efficiencies in the range of 5-20% during city and national motorway driving conditions up to 20-40% during long distance motorway driving.
This result leads to two main questions: 1) Is this result also representative for medium heavy trucks used for delivery? and 2) do similar efficiencies show up also in tests on entire vehicles? To this end, an additional measurement programme was defined, which is reported here.

In addition to the above test programme which took place at TNO on an engine test bench in 2008 [3] TNO was ordered by SenterNovem to perform tests with open diesel particulate filters on a chassis dynamometer. In this second test programme 6 used particulate filters have been selected for 3 truck types (2 per truck type) which have preferably been used for 50.000 km or more. The selected trucks are three delivery trucks. Special attention has been paid to the real world efficiencies of these used partial flow diesel particulate filters. Later, a second instruction was issued and the chassis dynamometer programme was extended to include measurements of two used partial flow diesel particulate filters of a long haul truck.

In the test programme, reported here, four types of retrofit partial flow diesel particulate filters for distribution trucks and one type diesel particulate filter for a long haul truck are examined. These retrofitted partial flow diesel particulate filters should have an efficiency of at least 50% during the type approval test. Other names which are used for the partial flow diesel particulate filter are: PFF, open or semi-open diesel particulate filter or PM-cat (PM kat). Within this report it is also referred to as DPF.

1.2 Objective

In the context of the relatively low filtration efficiencies of retrofit partial flow diesel particulate filters measured in 2008 for a heavy truck, the objectives for this study were:

- Measurement of the real world filtration efficiency under different driving conditions of partial flow diesel particulate filters for medium heavy trucks, typically used for national delivery.
- Investigate the influence of the measuring procedure by also including one heavy truck with retrofit diesel particulate filter.

1.3 Approach

To reach the objective, a test programme was defined in which 3 trucks and 6 diesel particulate filters were examined at VTT, Finland. The trucks were selected to be representative for national delivery, as the main air quality problems are associated with freight distribution in cities. Also, a long-haul truck was chosen to allow correlation with the phase 1 results.
The trucks were subjected to a test sequence based on actually determined driving profiles for this truck type, so as to provide as much as possible a representative scenario.
The following activities were carried out in this programme:
- Selection of truck/engine types and diesel particulate filter types.
- Selection of eight used diesel particulate filters.
- Determination temperature profile retrofit open particulate filter of a distribution truck.
- Determination test loads and the test sequences.
- Fit chassis dynamometer temperature profile on real world profiles.
- Determination of real world emissions of retrofit open particulate filter’s on three delivery trucks.
- Determination of real world emissions of retrofit open particulate filter’s on a long haul truck.

The test programme was to be carried out on four different trucks on a heavy-duty chassis dynamometer and eight used diesel particulate filters (nine filters were actually tested).

1.4 Operation of partial flow diesel particulate filter

In this project nine (passive) partial flow diesel particulate filters of five types were tested. The particulate filter consists in principle of two parts: an oxidation catalyst and a semi-open diesel particulate filter. The word ‘passive’ relates to the nature of the activation of the diesel particulate filter regeneration. This means that the regeneration of the diesel particulate filter will occur when a certain temperature level is exceeded; no special activation mechanisms are present. ‘Semi-open’ provides information about the geometry and the filtration mechanism; despite loading, the diesel particulate filter is not easily blocked. Due to the semi-open structure, however, the filtration efficiency is limited. Some of the exhaust gas can flow through unimpeded.

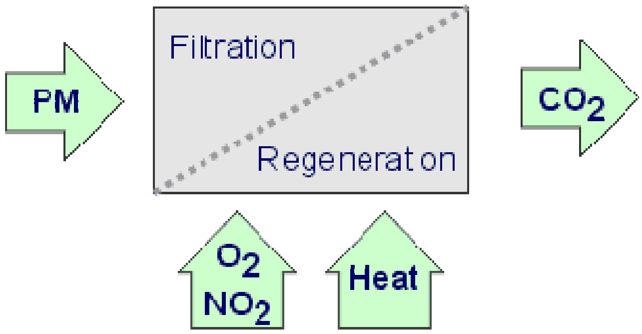

Figure 2: Schematic particulate filter with thermal regeneration

When the engine is running any one of four situations can occur in a semi-open diesel particulate filter; these can also occur simultaneously (Figure 2):

1 diesel particulate is oxidised
2 diesel particulate is captured
3 diesel particulate passes through
4 captured diesel particulate is released and emitted.

The result of these four situations is a capture efficiency or conversion efficiency of the diesel particulate filter, also referred to simply as the efficiency.

During the regeneration of a diesel particulate filter a diesel particulate is oxidised. This can occur in the following two ways [2]:

- Diesel particulate + NO_2: Depending on the catalytic loading of the diesel particulate filter, upwards of a certain temperature level (175 °C) the oxidation of diesel particulate takes place by means of NO_2. The catalytic element is primarily used in the conversion of NO to NO_2. As well as sufficient NO_2 and a certain temperature level, this reaction requires sufficient time to burn a certain quantity of diesel particulate. The reaction of NO_2 with diesel particulate progresses relatively slow and accelerates at higher temperatures. Upwards of 250 – 275 °C the regeneration capacity is sufficient to oxidise the diesel particulate produced by the engine.
- Diesel particulate + O_2: At temperatures in excess of 400 °C diesel particulate reacts with the oxygen present and burns away. If sufficient diesel particulate is ignited and sufficient thermal energy is generated, the adjacent diesel particulate will also ignite.
  In this way, the reaction amplifies itself and can progress very quickly. If sufficient oxygen is present, a diesel particulate filter can regenerate completely within a couple of dozen seconds.

If the conditions for regeneration are present in the diesel particulate filter (sufficient diesel particulate +NO_2, sufficient reaction time and a sufficiently high temperature level), the captured diesel particulate will react with NO_2 and oxidises. However, at lower exhaust gas temperatures, no oxidation of diesel particulate occurs and some of the diesel particulate emission is captured in the diesel particulate filter. In this case, capture or buffering is said to be occurring.

For a diesel particulate filter to function well a certain temperature level must be reached regularly, as a result of which the diesel particulate filter regenerates. In practice, the following rule of thumb applies to this type of diesel particulate filter: for an 8-hour period the temperature behind the diesel particulate filter must exceed 300 °C at least 5% of the operating time.

1.5 Load factor and diesel particulate filter history

The load factor of a diesel particulate filter is determined primarily by the quantity of captured diesel particulate and this depends largely on the vehicle's recent use. At temperatures below the regeneration temperature the filter is loaded with diesel particulate; in urban traffic this can occur over a prolonged period. If the regeneration temperature is exceeded, some of the captured diesel particulate is oxidised. In general, regeneration commences at 250 °C and will continue to completion in excess of 300 °C.

The load factor of a diesel particulate filter is determined by measuring the exhaust back pressure in front of the diesel particulate filter under certain engine conditions. A high exhaust back pressure indicates a loaded diesel particulate filter, a low exhaust back pressure an unloaded diesel particulate filter.

The diesel particulate filter loadings and the regenerations determine the current loading of the diesel particulate filter and together they form the diesel particulate filter history. A complete regeneration of the diesel particulate filter can remove all the captured diesel particulates; this happens when temperatures exceeding 350 °C are maintained for an extended period.

As the previous history of the selected diesel particulate filters was not known, these filters were tested in the condition in which they were received. In this study, the filtration efficiency of real world loaded diesel particulate filter was determined.

1.6 Determining diesel particulate filter efficiency

- Type approval procedure diesel particulate filter:

The type approval procedure for retrofitted diesel particulate filters is conducted in accordance with Directive 88/77/EEC and Directive 2005/55/EC respectively. It is carried out on an engine test bench and is valid for the entire engine family. An engine family is characterised by identical dimensions and identical hardware; only the tuning (the maximum power) varies.
The standard procedure is as follows. Firstly, the particulate matter emission of the engine (without diesel particulate filter) is determined in a European Transient Cycle (ETC test). Next, the diesel particulate filter is installed and the ETC test is repeated. Based on these two results, the efficiency of the diesel particulate filter is determined. For semi-open diesel particulate filters used on trucks a minimum efficiency requirement of 50% applies in the type approval test procedure.

The efficiencies of the tested diesel particulate filters were determined on the basis of the measured PM emissions (Particulate Matter) in front of and behind the diesel particulate filter. PM emissions are measured by allowing diluted exhaust gas with a temperature lower than 52 °C to flow through Teflon-coated paper filters. Solid particles collect on the paper filter. Weighing the filter before and after the test determines the captured particulate mass and calculations are made to determine total emissions. Diesel particulate filtration efficiencies are calculated using the following formula:

$$\acute{\eta}_{DPF} = 1 - PM_{postDPF} / PM_{preDPF}$$

In principle, two test results are required to determine the efficiency of a diesel particulate filter, and these must be obtained simultaneously. However, it is not possible to achieve with the measuring equipment that was used. An alternative customary method consists of the consecutive measurement of the PM emissions of the engine and the diesel particulate filter. In general, an engine's PM emission reproduces between tests and within certain limits can be assumed to be constant. In this programme the engine's PM emissions were measured before and after retrofit open particulate filter testing. These results provided the basis for determining the engine's PM emission in a test with a diesel particulate filter.

The previous described measurement procedure is the base for this test programme except the applied test cycles. In order to simulate real world conditions more convenient test cycles are run.

2 Experimental design

2.1 Selection of truck and diesel particulate filters

The selection of the used retrofitted diesel particulate filters took place in consultation with SenterNovem's diesel particulate filter registration system. It was decided to test particulate filters of delivery trucks (150 – 225kW). After testing of the three delivery trucks TNO was asked by SenterNovem to perform tests with retrofit open particulate filters on a chassis dynamometer with a long haul truck with equal engine and diesel particulate filter specifications as used in the engine dynamometer programme at TNO laboratory in Helmond [3], to allow correlation of the results of the different test series.

Furthermore, the primary selection of the used diesel particulate filters was based on the following criteria:
- National transport, 50,000 – 100,000 km.
- International transport, 100,000 - 200,000 km.

Next, haulage firms were approached and five agreed to cooperate in the study. In total, they made eight used diesel particulate filters available. On one selected truck was a particulate filter mounted. With this ninth filter also some measurements were executed.

The three selected 20 tonne delivery test trucks were placed at TNO's disposal by three different importers of three different trade marks and were shipped from The Netherlands to Finland. These trucks have been used for national distribution transport. The 42 tonne long haul truck was rented from a Finnish local truck dealer. All four trucks were equipped with Euro III technology. The main engine characteristics are presented in Figure 3.

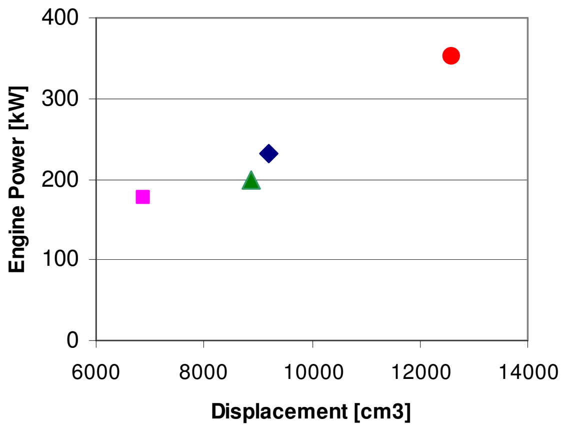

Figure 3. Engine rated power and cylinder displacement of the four test trucks

2.2 Diesel particulate filters; origin and history

The diesel particulate filters were selected in consultation and with due regard for the selection criteria. In Table 3 the specific data of the particulate filters are reported.

In some cases the exact history and operating conditions of the diesel particulate filters were not known. Mostly general information was available of these vehicles.

- Diesel particulate filter 1 was not part of the retrofit open particulate filter selection. It was mounted on a selected truck. The history of this retrofit open particulate filter is unknown.
- Diesel particulate filters 2 and 3 were applied on a truck which transports regional goods to 8 shops in 8 cities per day.
- Diesel particulate filter 4 was applied on a parcel delivery truck.
- Diesel particulate filter 5 was applied on a salvage truck in a city.
- Diesel particulate filter 6 and 7 were applied on a national delivery truck.
- Diesel particulate filters 8 and 9 were applied on long haul trucks.

Table 3: Tested semi-open diesel particulate filters

Diesel particulate filters, delivery trucks national use							
DPF	1	2	3	4	5	6	7
Vehicle type	1	1	1	2	2	3	3
Date of installation				24-12-2007	19-12-2007	12-2-2008	16-11-2007
Mileage [km]		466,882	382,870	57,266	150,404	462,000	271,707
Date disassembling	on truck	March 2009	March 2009	11-11-2009	11-11-2009	30-1-2009	1-3-2009
Mileage [km]	417,000	580,000	460,000	109,757	106,934	548,000	345,753
Mileage DPF [km]	30,138	113,118	77,130	52,491	56,530	86,000	55,000

Diesel particulate filters, long haul truck international use			
		8	9
Vehicle type		4	4
Date of installation		17-3-2008	5-11-2007
Mileage [km]		367,120	235,311
Date disassembling		16-7-2009	23-7-2009
Milaage [km]		604,923	345,230
Mileage DPF [km]		237,803	109,919

After completion of the measurement programmes the diesel particulate filters were sent back to the owners and replaced under the original vehicles.

2.3 Experimental programme

In this test programme more than 300 emission tests were performed.

The purpose of the experimental programme was to determine the efficiency under real world conditions of six used diesel particulate filters of delivery trucks and two used diesel particulate filters of long haul trucks in unloaded as well as loaded states. The diesel particulate filters were tested in the condition in which they were received from the user; no preconditioning took place. In order to retain the history of the particulate filter as long as possible, the first test series were performed with an unloaded truck setting. After the unloaded series the loaded test series were executed. In principle, performing the emission tests of diesel particulate filters in immediate succession illuminates any effects of the previous history and the preceding emission tests.

This approach provides insight into the diesel particulate filter's efficiency over a certain period.

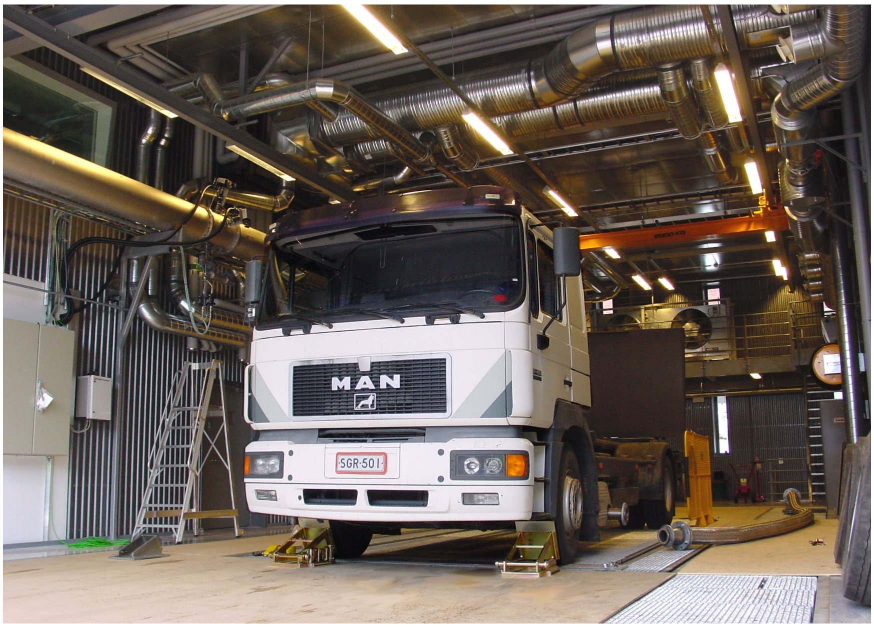

Figure 4: Chassis dynamometer test cell (vehicle shown was not used for the test programme)

2.3.1 *Real world conditions and retrofit open particulate filter temperatures*

Based on previous studies [3] and [4] and feedback from vehicle manufacturers, it was concluded that the filtration efficiency of open particulate filters is quite dependent on the average exhaust gas temperature and also on the amount of stored particulates in the retrofit open particulate filter. The latter is dependent on the historic load pattern, i.e. the load pattern during the last days and possibly weeks. Therefore it is very important to know the precise load patterns conditions and variations throughout the day. These conditions are base input for the several test cycles in this programme. The applied city and motorway driving test cycles should also be in a certain sequence to simulate the variations in day to day driving. Consequently the preparation steps in this test programme are:

- Analysis of the average retrofit open particulate filter temperature profile under day to day use real-world conditions.
- Definition of several test cycles (i.e. for city and motorway driving) and vehicle parameters such as weight.
- Definition of the precise sequence of test cycles in order to represent normal variations in day to day use.

This procedure, and the resulting test cycles, are explained in detail in section 3.

2.3.2 *History effects*

From the open filters, it is known that the filtration efficiency is very much dependent on the particulates load of the filter (which is dependent on the historic load pattern), temperatures and engine out PM-emissions. In order to preserve the filter history (both from their use in practice as well as the testing on the chassis dynamometer), no conditioning tests at all were run: neither at the beginning of the day nor in between tests. During engine running the particulates sampling system was running continuously. The first test of a day was labeled as cold start test.

2.3.3 *Determination of filtration efficiency*

Simultaneous particulate measurements pre and post retrofit open particulate filter are not possible because only one full flow dilution tunnel is available. In this project, engine out emission tests of each truck were performed at the start and finish of the test sequence. These engine out test results are needed to calculate the diesel particulate filtration efficiency. If a diesel particulate filter was installed, only the emission levels post diesel particulate filter was measured.

The first step towards determining a diesel particulate filter's efficiency is to determine the engine emissions. Next, the diesel particulate filter is installed and the tests are repeated and conducted in a certain sequence.

- Truck emission measurements (without diesel particulate filter)
  - City cycle test
  - Motorway cycle test
  - Motorway constant speed test (only long haul truck)
  - Constant engine speed test (only long haul truck)

- Delivery truck: Emission measurements of six particulate filters

The diesel particulate filters of the delivery trucks were thoroughly tested in two load conditions, see Table 4.

- 11.5 tonne load (motorway cycle and city cycle)
- 18.5 tonne.load (motorway cycle and city cycle)

Table 4: Test schedule distribution truck and long haul truck national use

Activity	Load [tonne]	Duration [sec]	Duration [min]
Motorway cycle	11.5	1272	21.2
City cycle	11.5	1234	20.6
Motorway cycle	11.5	1272	21.2
City cycle	11.5	1234	20.6
City cycle	11.5	1234	20.6
City cycle	11.5	1234	20.6
Motorway cycle	11.5	1272	21.2
Motorway cycle	11.5	1272	21.2
Motorway cycle	11.5	1272	21.2
City cycle	11.5	1234	20.6
Motorway cycle	11.5	1272	21.2
Motorway cycle	18.5	1272	21.2
City cycle	18.5	1234	20.6
Motorway cycle	18.5	1272	21.2
City cycle	18.5	1234	20.6
City cycle	18.5	1234	20.6
City cycle	18.5	1234	20.6
Motorway cycle	18.5	1272	21.2
Motorway cycle	18.5	1272	21.2
Motorway cycle	18.5	1272	21.2
City cycle	18.5	1234	20.6
Motorway cycle	18.5	1272	21.2

- Long haul truck: Emission measurements of two diesel particulate filters

The diesel particulate filters of the long haul trucks were thoroughly tested in four load conditions, see Table 5.

- 14 tonne load (motorway cycle and city cycle)
- 24 tonne load (motorway cycle and city cycle)
- 41 tonne load (motorway cycle and constant speed)
- 47.5 tonne (constant engine speed @1200rpm and fuel cons. of appr. 5.52 g/s)

Table 5. Test schedule additional tests long haul truck international use

Activity with 41 tonne	Load [tonne]	Duration [sec]	Duration [min]
Motorway cycle	41	1272	21.2
Motorway constant speed (83km/h)	41	1198	20
Motorway constant speed (83km/h)	41	1198	20
Motorway cycle	41	1272	21.2
Motorway cycle	41	1272	21.2
Motorway constant speed (83km/h)	41	1198	20
Motorway constant engine speed 47.5tonne (1200rpm & FC 5.52g/s)	47.5	1198	20
Motorway constant engine speed 47.5tonne (1200rpm & FC 5.52g/s)	47.5	1198	20
Total :		9506	158

Due to the fact that every series started with a low load setting the effect of any loading (history) on emission levels was established. If a test sequence couldn't be finished on one test day the following test day always started with a motorway cycle to warm up the engine and the diesel particulate filter. The test results are reported chronologically in the graphs.

No preconditioning was applied in this test programme, the interval time between tests can be neglected. After three consecutive tests an analysing test step was required, during this period the engine was shut off.

2.4 Fuel and lubricants

In this measurement programme sulphur-free fossil diesel fuel was applied. This was supplied by Neste Oil and it complies with EN 590 specifications. The fuel's exact properties are reported in Appendix 1.

No special lubricant was applied in this programme. All trucks were tested with the original lubricants.

3 Determination of the test procedure based on real world conditions

3.1 Analysis of real-world conditions

To be able to test the selected trucks in a test procedure that is as much possible representative of the real world usage, the following points are critical:

- exhaust gas temperature during the test
- duration of city driving (with low exhaust temperature) and motorway driving (with higher exhaust temperature)
- vehicle weight

In order to estimate driving behaviour and exhaust gas temperature, use was made of information from a supplier, based on 5 trucks that supply warehouses in the Netherlands. Extensive long term particulate filter temperature measurements and logging of five delivery trucks have been carried out by this supplier. Based on this information and real world truck weight information, the test procedure was determined. This process is explained in more detail below.

3.1.1 Exhaust gas temperature profile

For the 5 trucks mentioned above, exhaust gas temperature was logged extensively during usage. Figure 5 shows the temperature histograms for the 5 trucks combined. The data are divided in idle, city/rural and motorway driving. The data for the five trucks individually are given in Table 6. Figure 5 shows that within the city driving part a double distribution can be recognized: a part with an average temperature around 180°C and a part with an average temperature around 310°C. This latter peak might represent driving on sub-urban or rural roads. Some additional statistical information is included in Appendix 4.

Table 6: Truck use divided in idle, city/rural and highway and the accompanying temperatures

Truck	n (high way)	n (idle)	n (average)	fraction idle	fraction city/rural	fraction high way	Temp. idle	Temp. city/rural	Temp. highway
1	1480	528	1219	13,8%	61,5%	24,6%	132,0	259,8	323,2
2	1481	525	1193	14,9%	63,6%	21,5%	153,0	253,7	316,3
3	1471	521	1203	15,0%	60,1%	24,8%	177,1	265,2	317,1
4	1389	494	1118	16,9%	59,6%	23,5%	151,3	262,1	311,1
5	1389	555	1114	26,7%	48,7%	24,7%	165,8	262,9	311,9
average of 5 trucks	1442	525	1169	17,5%	58,7%	23,8%	155,8	260,8	315,9

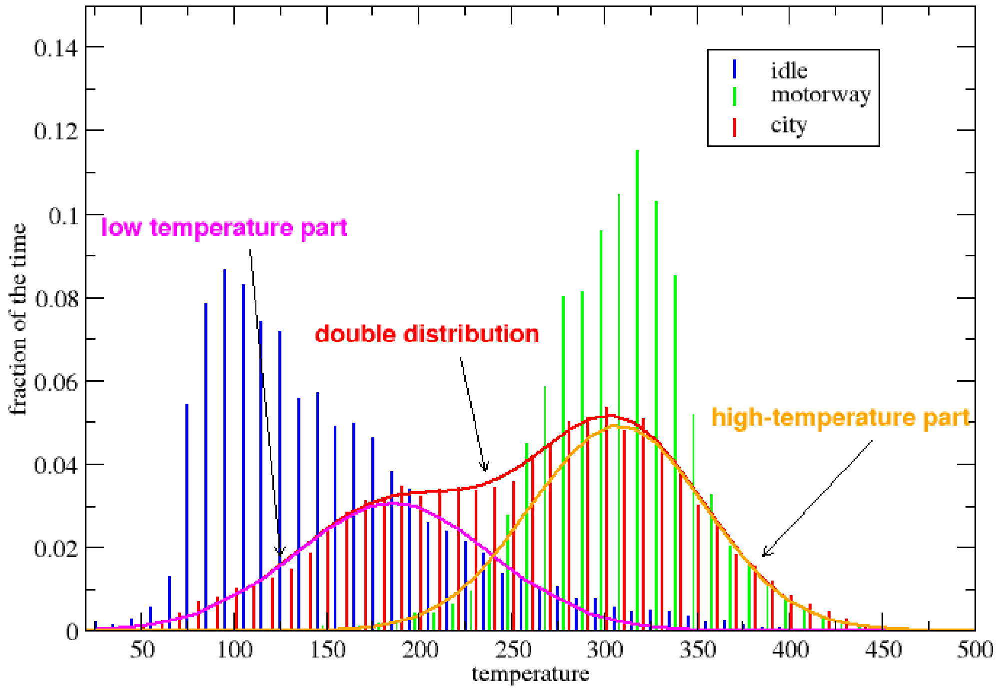

Figure 5 Temperature distribution for 3 (driving) conditions. City in figure refers to “non-motorway”, which is actually city + rural.

3.1.2 Duration of driving modes

Figure 6 shows a time distribution for the length of the periods between motorway driving, based on the real world analysis of the five delivery trucks. This will be used to determine the duration of city respectively motorway driving during the test programme.

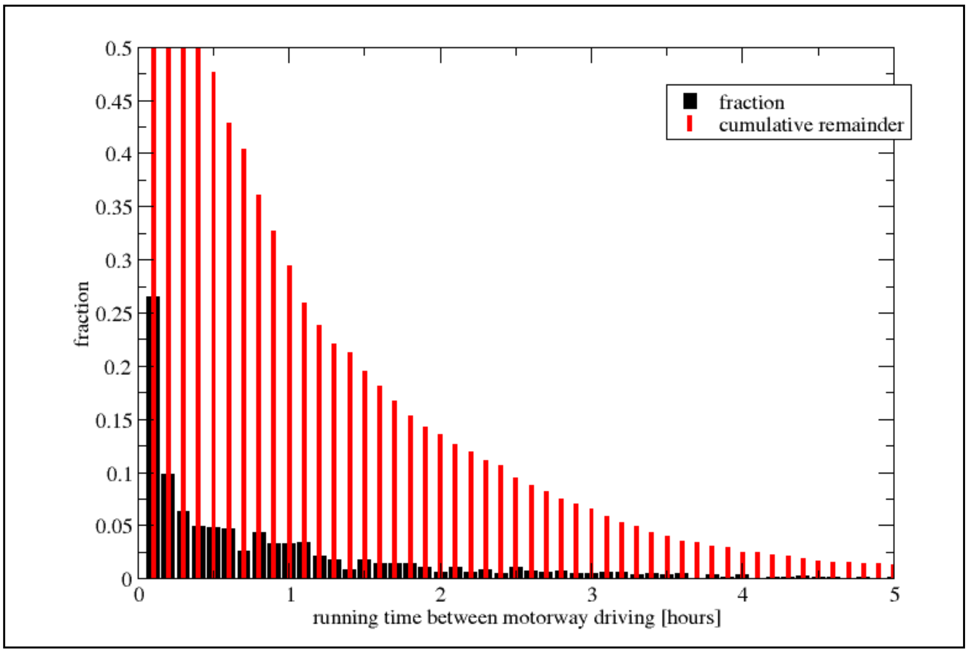

Figure 6. Distribution representing lengths of periods between motorway driving

In Table 7 the time distribution and average temperatures of three driving modes; idle, city + rural and motorway, are given. This is the average of the five trucks .

Table 7: Time distribution and average temperature at three driving modes for delivery trucks

Real world	Time [%]	Temperature average [°C]
Idle	17	155
City + rural	59	260
Motorway	24	315

3.1.3 Weight of the vehicle

In the Netherlands, there are several weighing in motion systems placed on the motorway (sensors within the pavement). The weighing in motion system is used to measure the average weight of distribution vehicles. The distribution vehicles are separated from the other vehicles with the weight of the front axle. The weight distribution of the 20 ton distribution truck is presented in Figure 7. From the figure can be concluded that the average weight is 15 ton. The minimum and maximum weight are respectively 11 ton and 20 ton.

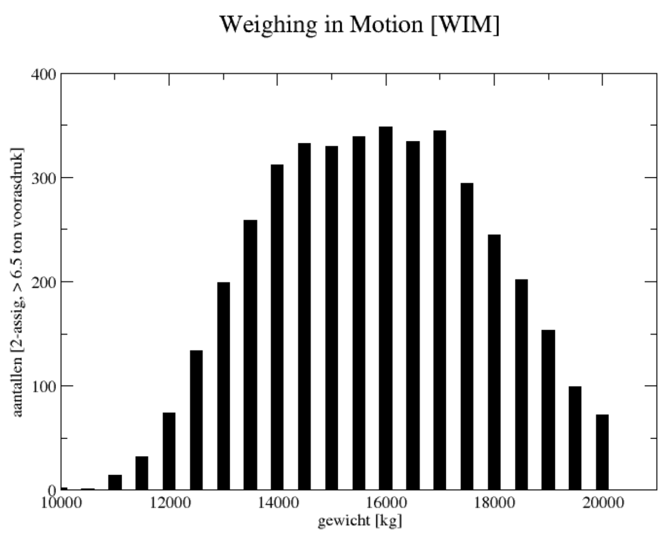

Figure 7. Weighing in motion number distribution for (20 ton) delivery trucks on the motorway.

3.2 Test programme

3.2.1 Test cycles

The objective of the measuring programme was to obtain separate filtration efficiency numbers for use of the trucks within cities and outside cities. Also for efficiency reasons only 2 test cycles could be used. Consequently a typical city cycle and a typical motorway test cycle were chosen. The time split between those 2 cycles is based on the time distribution of Table 7, with the following notes:

- Time for idle + city are combined for the city cycle.
- Time for rural and motorway of Table 7 are combined for motorway. This can be done since the temperature distribution of rural is very similar to motorway, refer to Figure 5 .

This leads to an about even split between city and motorway, see Table 8.

Table 8: Test condition during chassis dyno testing

Test condition	Time [%]
City	50
Motorway	50

The city cycle used is the TNO 12 ton/kW city cycles, refer to Figure 8. The motorway cycle used is the TNO 12 kW/ton motorway cycle, refer to Figure 9.

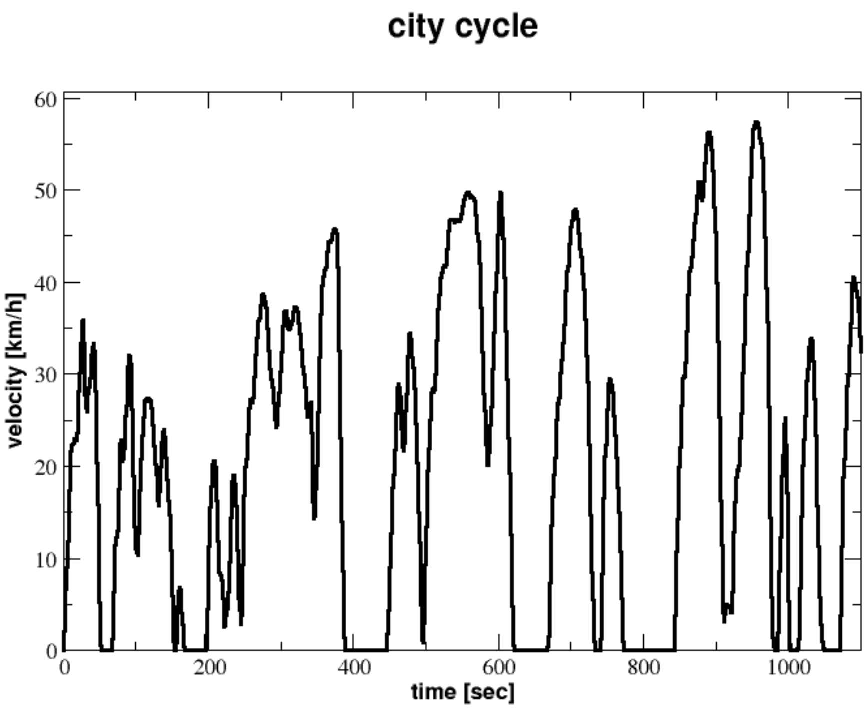

Figure 8: Vehicle speed time profile of TNO 12 KW/ton city cycle (adapted, extended idle time)

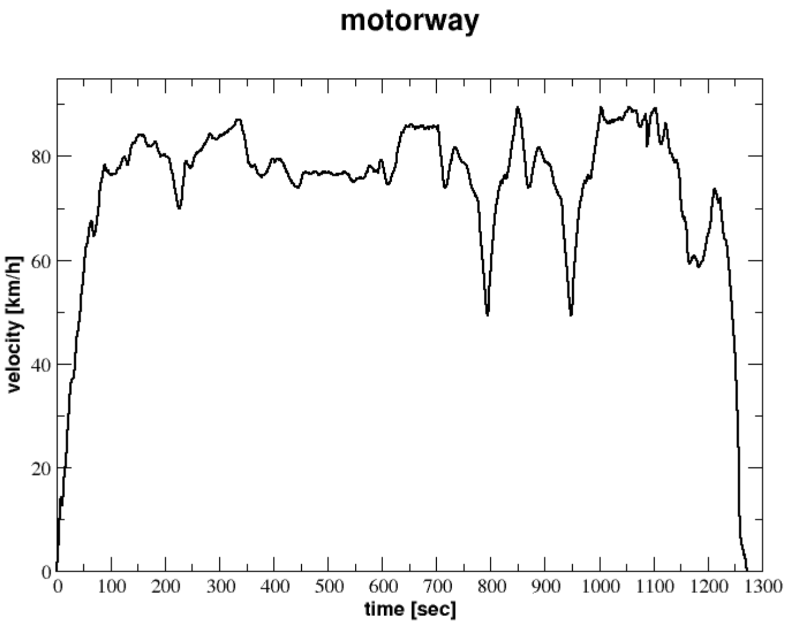

Figure 9: Vehicle speed time profile of TNO 12 KW/ton motorway cycle (adapted with extra deceleration-acceleration)

In order to obtain efficiencies for both vehicles with a low and with a high cargo load, two vehicles weights are chosen based on the weighing in motion results (Figure 7) and also the average exhaust gas temperature during the chassis dyno tests. The temperature distribution is the most important parameter for correlation with real-world. The temperature fit was done with the motorway cycle and the corresponding motorway data. With the one of the distribution truck on the chassis dynamometer, it was determined that with 15 ton vehicle weight setting and extra speed reduction and acceleration (from 80 to 50 to 80 km/hr), the temperature profile would fit the real world temperature distribution (both average as well as distribution). The motorway cycle is shown in Figure 9. In Table 9 the comparison between real world and test cycle of some characteristic temperatures are shown. The average temperature fits well 318 °C for the test cycle compared to 315 °C for real world. The maximum is somewhat lower: 393 °C for the adapted cycle compared to 425 °C for the real world data. Although it should be noted that in real world the variation is generally somewhat bigger than during a test cycle, due to a larger variation in driving pattern.

Table 9. Average and maximum temperatures of real world data compared to chassis dynamometer test (TNO motorway cycle).

15 tonne vehicle weight	T before retrofit filter average °C	T before retrofit filter maximum °C
Real world data	315	425
TNO 12 kW/ton motorway cycle	318	384
TNO 12 kW/ton motorway cycle adapted	318	393

The 15 ton corresponds quite well with the average of the weighing in motion (Figure 7). Based on the latter, 11.5 ton and 18.5 ton (+ and – 3.5 ton from the average) were chosen as the two vehicle weights, i.e. low and high.

The TNO city cycle was also slightly adapted by increasing the total idle duration. Refer to Figure 8. The average temperature during the city cycle is about 200 °C. This is somewhat higher than the 180 °C average of the city mode in Figure 5.

3.2.2 Test sequence

The test sequence was determined based on discussions with the stakeholders and an interview of the logistics manager of warehouse.

A distribution center in the Netherlands is often located near the highway from which the delivery truck starts its daily programme. Also the analysed trucks started loaded in the morning from the distribution center near the motorway and distribute the goods to 3 stores (mostly also meaning 3 cities) in half a day. Drive back empty to the distribution center and re-load to start a new sequence in the afternoon to supply another 2 or 3 stores. Based on this and the time distribution of periods between motorway driving (Figure 6) and the average length of standard test cycles (about 20 minutes), the following test sequence is chosen:

- 1x motorway with cold start (first test of the day)
- 1x city cycle
- 3x motorway
- 3x city cycle
- 1x motorway

This represents both long (about 1 hour) and short (about 20 minutes) periods of city and motorway driving. Also the same tests are repeated a number of times, such that it can be observed whether efficiency changes if for example the amount of soot stored within the filter changes due to the load pattern.

3.2.3 Long haul truck

The long haul truck was tested during the same cycles as the distribution trucks. However the representative weights were determined for this category trucks and also additional weights were used in order to represent the higher weight of international trucks with trailer or articulated truck. Representative weights were again derived from the weighing in motions data. Refer to Figure 10.

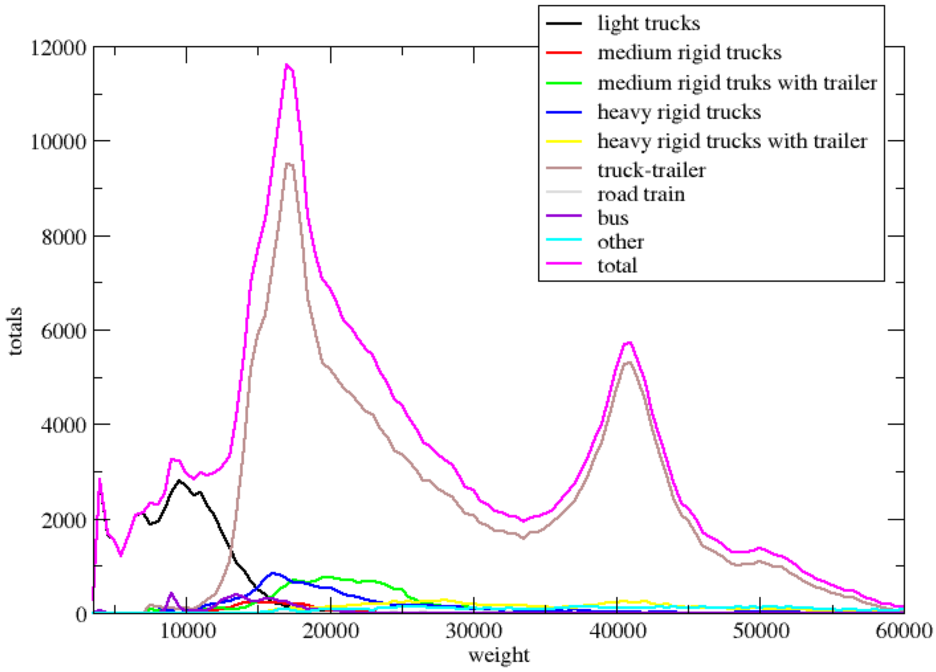

Figure 10. Weighing in motion number distribution for medium heavy and heavy trucks on the motorway

The heaviest category trucks shows two peaks namely at 17.5 ton and at 41 ton. It is assumed that these two peaks represent respectively national and international transport. For national transport the low and high weight chosen are respectively 14 ton and 24 ton. For international transport only 41 ton was chosen, since the variability was relatively small and the total number of tests were limited. However a constant speed test with 47.5 ton was added. This point was chosen to correspond to a constant speed point run on the engine test bed (1200 rpm @ 800 Nm with a fuel consumption of 5.52 g/s).

3.2.4 *Test procedure*

From the open filters, it is known that the filtration efficiency is very much dependent on the particulates load of the filter (which is depended on the historic load pattern) and temperature and other test conditions. In order to preserve the filter conditions (both from their use in practice as well as the testing on the chassis dynamometer), no conditioning tests at all were run: neither at the beginning of the day nor in between tests. The particulates sampling system was running all the time when the truck engine was running, The first test of the day was labeled as test with cold start.

The test schedule for the distribution truck and the national part for the long haul truck is presented in Table 4. The international part for the long haul truck is given in Table 5. Typically, the first test range was with the low vehicle weight while the second one was with the high vehicle weight (for international use more vehicle weights were used from low to high).

4 Test results

4.1 Emission tests of four trucks

During several days more than 300 emission tests were performed. Every first motorway test on each new test day is not taken into account in the calculations.

4.1.1 Truck 1

Originally this Euro III test truck was already equipped with a particulate filter, so three filters were tested instead of two. The measuring programme of this extra filter did not follow the standard sequence. The particulate filters 2 and 3 were taken from two delivery trucks which delivered goods daily to 8 shops in 8 cities.

The test results are chronologically presented in Figure 11, Figure 12 and Figure 13 respectively for retrofit open particulate filter 1, 2 and 3. In the three figures a range in filtration efficiencies is seen from 10% to 65% depending on the test. For the motorway cycles for DPF 2 and DPF 3 an increase in filtration efficiency can be seen, when the repeated three times directly after each other.

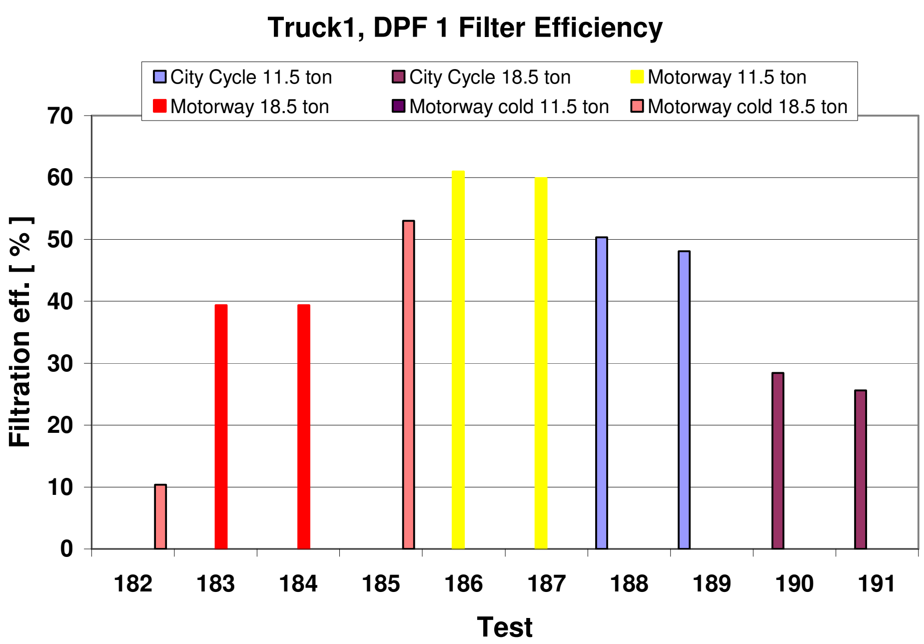

Figure 11. Filtration efficiency, chronological test results of DPF 1 on truck 1.

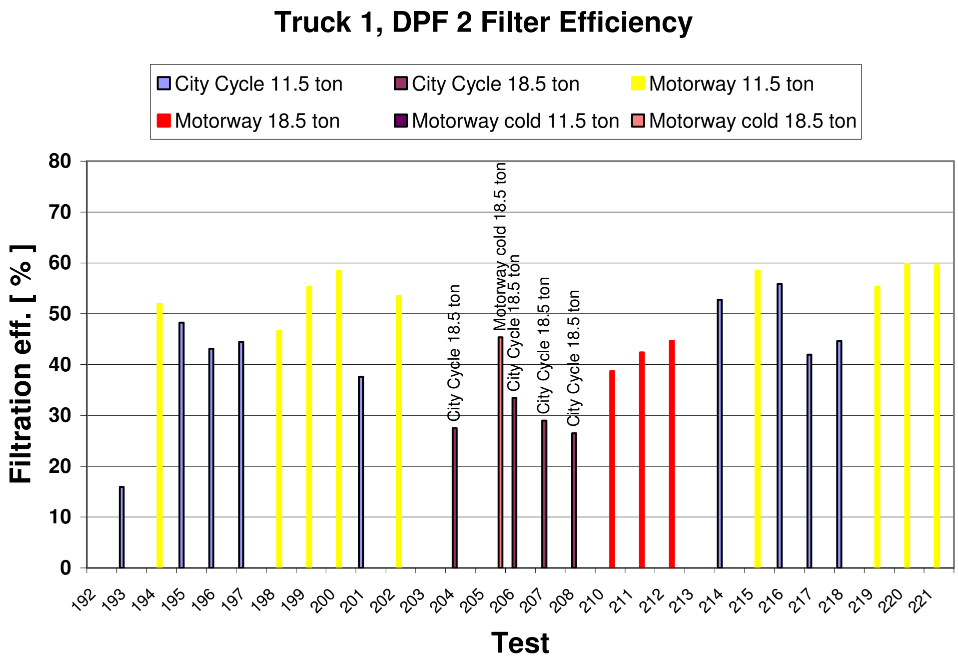

Figure 12. Filtration efficiency, chronological test results of DPF 2 on truck 1

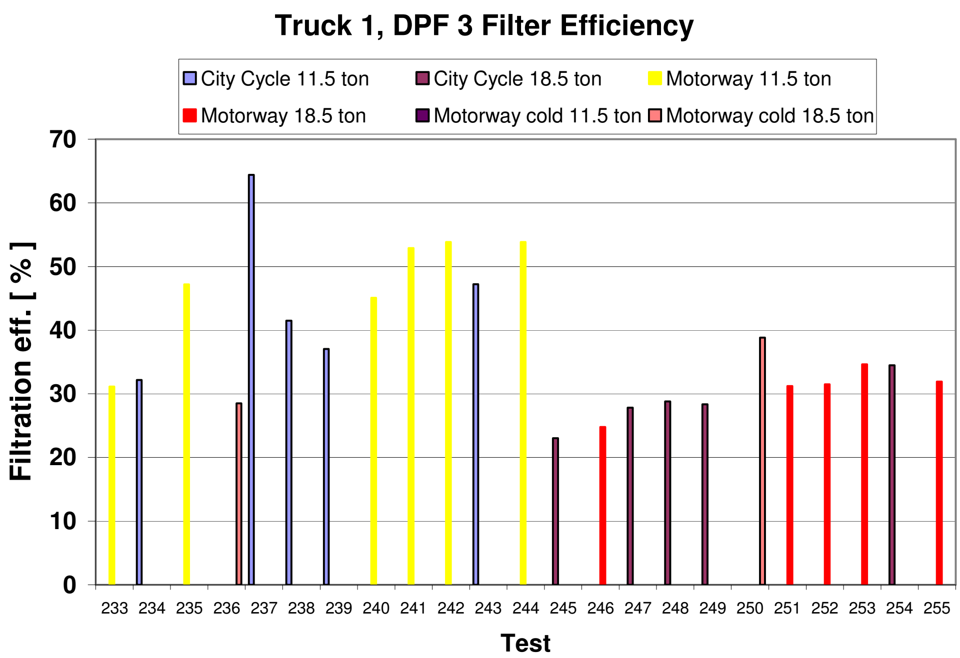

Figure 13. Filtration efficiency, chronological test results of DPF 3 on truck 1

The filtration efficiencies of the three retrofit filters of truck 1 are summarised in Table 10, Table 11 and Table 12. Table 10 shows the average of the city and motorway cycles, while Table 11 and Table 12 show the results of city cycle and motorway cycle separately, including the two vehicle weights (11.5 and 18.5 tonne). In both cycles, the average filtration efficiency is higher with the low vehicle weight.

Table 10. Filtration efficiency of retrofit particulate filters of Truck 1

	Minimum	**Average**	Maximum
DPF 1	25.6	**44.0**	61.0
DPF 2	16.0	**42.3**	59.8
DPF 3	23.1	**37.8**	64.4

Table 11. Filtration efficiency of retrofit particulate filters of Truck 1 in a city cycle.

	City cycle filtration efficiency [%]					
	11.5 tonne			18.5 tonne		
	Minimum	**Average**	Maximum	Minimum	**Average**	Maximum
DPF 1	48.1	**49.2**	50.3	25.6	**27.0**	28.4
DPF 2	16.0	**42.7**	55.8	26.5	**29.1**	33.5
DPF 3	32.2	**44.5**	64.4	23.1	**28.5**	34.5

Table 12. Filtration efficiency of retrofit particulate filters of Truck 1 in a motorway cycle

	Motorway cycle filtration efficiency [%]					
	11.5 tonne			18.5 tonne		
	Minimum	**Average**	Maximum	Minimum	**Average**	Maximum
DPF 1	59.9	**60.4**	61.0	39.4	**39.4**	39.4
DPF 2	46.4	**55.4**	59.8	38.7	**41.9**	44.7
DPF 3	31.2	**47.3**	53.8	24.8	**30.8**	34.6

4.1.2 Truck 2

Two retrofit particulate filters were tested on truck 2 . Particulate filter 4 was used on a parcel delivery truck and number 5 was used on a salvage truck in a city. The test results are presented in chronological order in Figure 14 and Figure 15 for respectively DPF 4 and DPF 5. In the two figures a range in filtration efficiencies is seen from 5% to 40% depending on the test. For the motorway cycle, 11.5 tonne, for both filters an increase in filtration efficiency can be seen, when repeated three times directly after each other (tests 289, 290, 291 and 312, 313, 314).

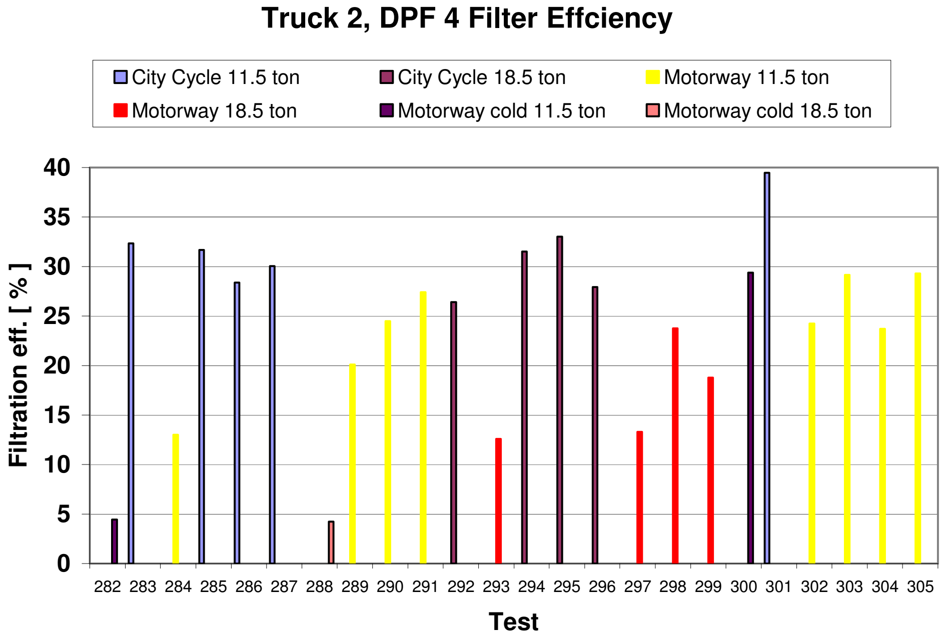

Figure 14. Filtration efficiency, chronological test results of DPF 4 on truck 2

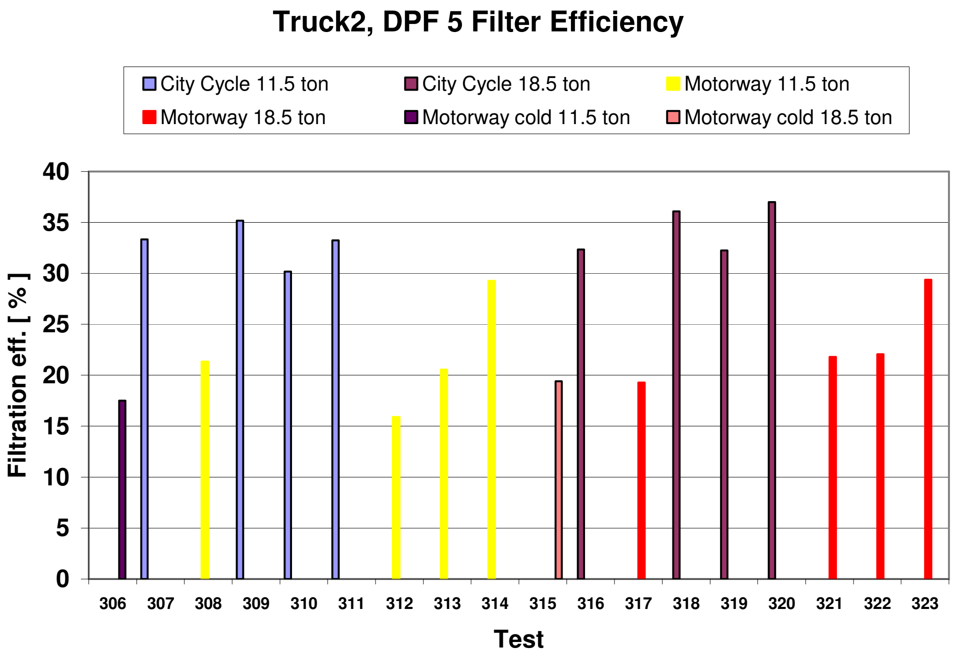

Figure 15. Filtration efficiency, chronological test results of DPF 5 on truck 2

The filtration efficiencies of the three retrofit filters are summarised in Table 13, Table 14 and Table 15. Table 13 shows the average of the city and motorway cycles, while Table 14 and Table 15 show the results of city cycle and motorway cycle separately, including the two vehicle weights (11.5 and 18.5 tonne). In the city cycles the filtration efficiencies are higher than the motorway cycles.

Table 13. Filtration efficiency of retrofit particulate filters of Truck 2.

	Minimum	**Average**	Maximum
DPF 4	12.6	**25.7**	39.5
DPF 5	15.9	**28.1**	37.0

Table 14. Filtration efficiency of retrofit particulate filters of Truck 2 in a city cycle

	City cycle filtration efficiency [%]					
	11.5 tonne			18.5 tonne		
	Minimum	**Average**	Maximum	Minimum	**Average**	Maximum
DPF 4	28.4	**32.4**	39.4	26.4	**29.4**	33.0
DPF 5	30.2	**33.0**	35.2	32.2	**34.4**	37.0

Table 15. Filtration efficiency of retrofit particulate filters of Truck 2 in a motorway cycle

	Motorway cycle filtration efficiency [%]					
	11.5 tonne			18.5 tonne		
	Minimum	**Average**	Maximum	Minimum	**Average**	Maximum
DPF 4	13.0	**23.9**	29.3	12.6	**17.1**	23.7
DPF 5	15.9	**21.8**	29.3	19.3	**23.1**	29.4

4.1.3 Truck 3

The particulate filters tested on this Euro III truck were in contradiction to the other trucks of two different types. Both are however open passive particulate filters. Both particulate filters were used on (national) delivery trucks.

The test results in chronological order are presented in Figure 16 and Figure 17 for respectively DPF 6 and DPF 7. In the two figures a range in filtration efficiencies is seen from 10% to 85% depending on the test. The first filter type (DPF) has a much higher filtration efficiency (75% to 85%) than the second type (10% to 40%). With DPF 6 no specific trends are seen when identical tests are repeated directly after each other. DPF 7 does show some improvement with repetition of the motorway cycle.

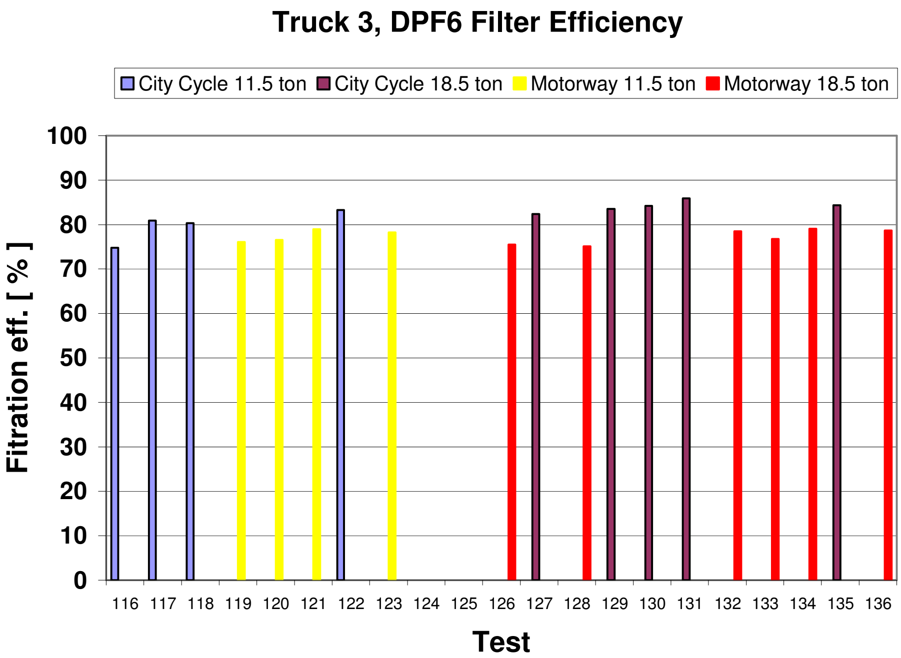

Figure 16. Filtration efficiency, chronological test results of DPF 6 on truck 3

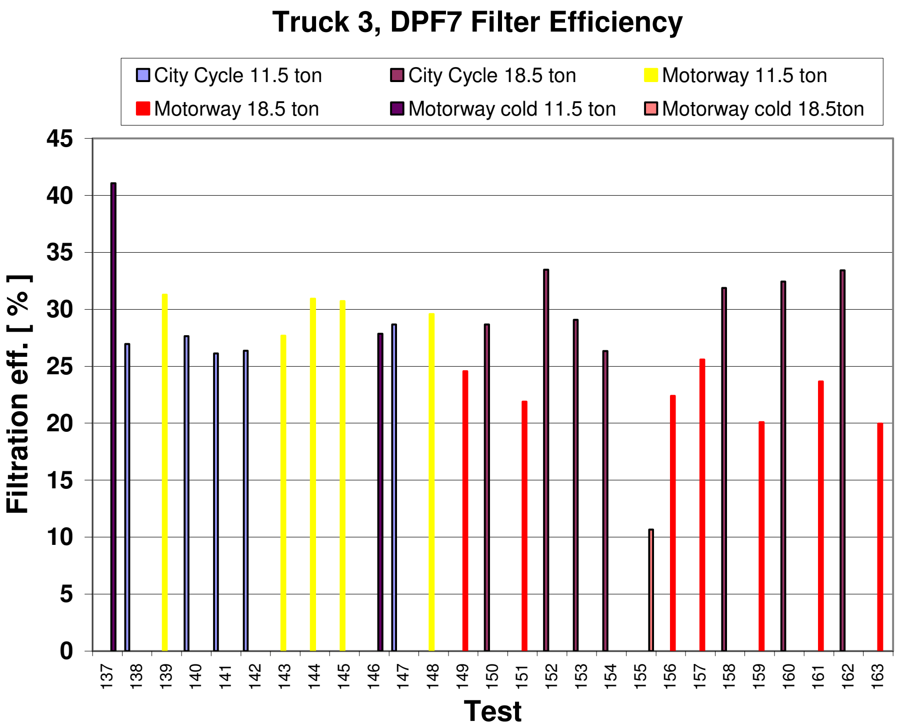

Figure 17. Filtration efficiency, chronological test results of DPF 7 on truck 3

The filtration efficiencies of the two retrofit filters are summarised in Table 16, Table 17 and Table 18. Table 16 shows the average of the city and motorway cycles, while Table 17 and Table 18 show the results of city cycle and motorway cycle separately, including the two vehicle weights (11.5 and 18.5 tonne).

The configuration of these two diesel particulate filters is entirely different and consequently the filtration efficiency of DPF 6 is much higher than DPF 7.

Table 16. Filtration efficiency of retrofit particulate filters of Truck 3

	Minimum	Average	Maximum
DPF 6	73.5	**79.3**	85.9
DPF 7	20.0	**27.6**	33.5

Table 17. Filtration efficiency of retrofit particulate filters of Truck 3 in acity cycle

	City cycle filtration efficiency [%]					
	11.5 tonne			18.5 tonne		
	Minimum	Average	Maximum	Minimum	Average	Maximum
DPF 6	73.5	**78.5**	83.3	82.4	**84.1**	85.9
DPF 7	26.1	**27.2**	28.7	26.3	**30.8**	33.5

Table 18. Filtration efficiency of retrofit particulate filters of Truck 3 in a motorway cycle

	Motorway cycle filtration efficiency [%]					
	11.5 tonne			18.5 tonne		
	Minimum	Average	Maximum	Minimum	Average	Maximum
DPF 6	76.1	**77.4**	78.9	75.1	**77.3**	79.1
DPF 7	27.7	**30.0**	31.3	20.0	**22.6**	25.6

4.1.4 Truck 4

This Euro III truck is a typical long haul vehicle for international transportation. Two types of test series were done. The first series represents national distribution like the trucks 1, 2 and 3. The second series was focussed on international transportation. For this series the total vehicle mass was increased to 41 and 47.5 tonnes, the heaviest weights for truck-trailer or articulated truck combinations. Refer to paragraph 3.2.3. For national transport 14 and 24 tonnes total vehicle weight are used.The 24 tonnes is also used as the minimum weight for international transport.

Two particulate filters were tested on this truck and for both national and international driving patterns were conducted. The filters were both open passive particulate filters of a “turbulent flow” filter type.

The test results in chronological order:
- National transport (distribution):
  Figure 18 and Figure 19 for respectively DPF 8 and 9
- International transport (motorway):
  Figure 20 and Figure 21 for respectively DPF 8 and 9

In the figures for national transport a range in filtration efficiencies is seen from about minus 100% (apparently a release of stored soot) to 50%. For heavy (41 and 47.5 tonnes) international transport this range is 0 to 45%. The negative result of minus 100% (PM emission is doubled) is only one test in a total of 39 tests for national transport. For heavy international transport, we see two tests (both with DPF9) with an efficiency of 0%. This is on a total of 15 tests.

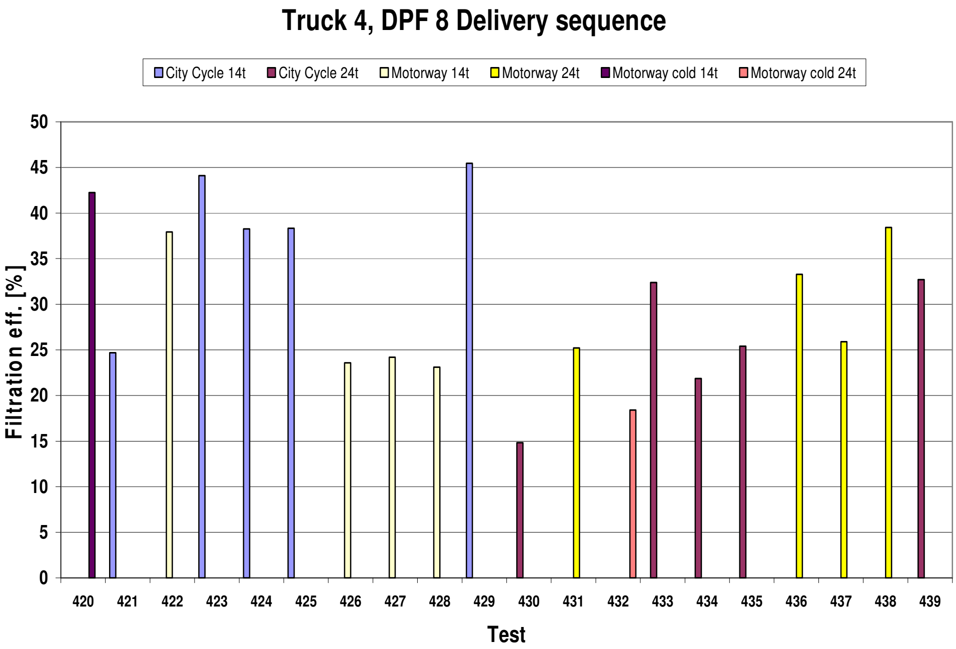

Figure 18. Filtration efficiency (national transport), chronological test results of DPF 8 on truck 4

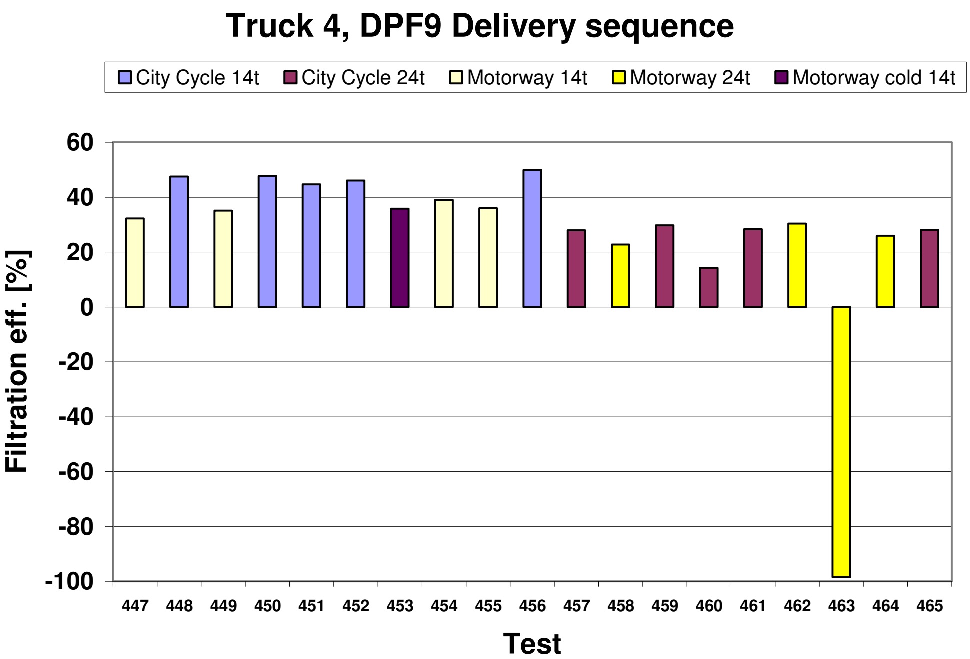

Figure 19. Filtration efficiency (national transport), chronological test results of DPF 9 on truck 4

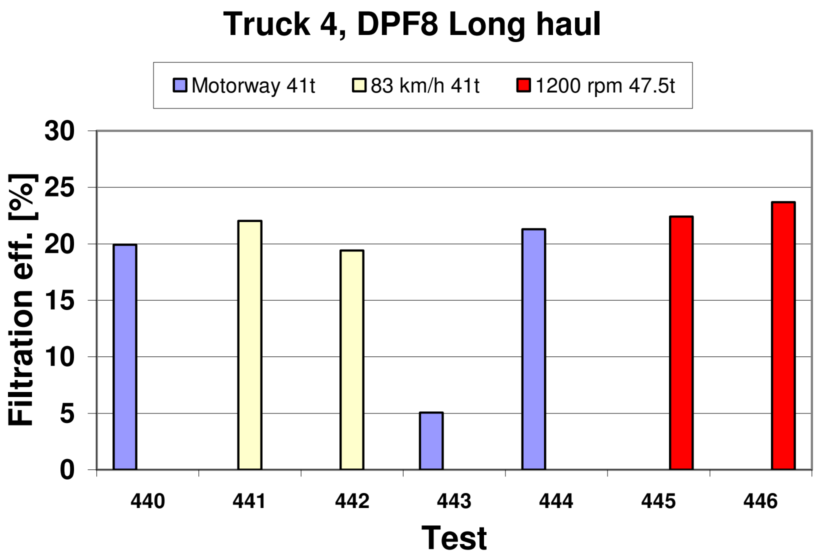

Figure 20. Filtration efficiency motorway and constant speed, chronological test results of DPF 8 on truck 4

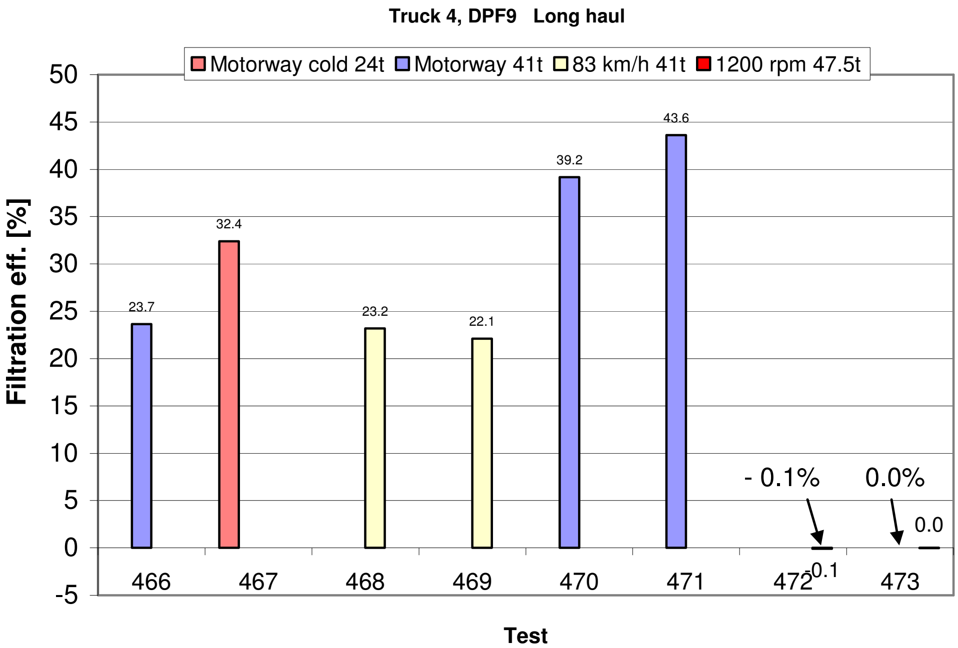

Figure 21. Filtration efficiency motorway and constant speed, chronological test results of DPF 9 on truck 4

Table 19 shows a summary of the filtration efficiencies per DPF. These are average, minimum and maximum values over all tests per filter. It does actually show that the average of all tests for the two filters is fairly close, namely about 26% and about 24%.

Table 19. Filtration efficiency Truck 4, average, minimum and maximum of all tests

	Minimum	Average	Maximum
DPF 8	5.1	**25.8**	45.5
DPF 9	-98.5	**23.7**	49.9

More detailed results of DPF 8 and DPF9 are presented in Table 20 and Table 21 for respectively the city cycle and the motorway cycle. In both cases this is for 14 and 24 tonnes. This weight range is considered representative for national transportation.

The tables show that on the average, the filtration efficiency with 14 tonnes is better than with 24 tonnes. DPF 9 scores particularly bad with motorway 24 tonnes. The number minus 0.7% is the average of 4 tests with one test with an efficiency of minus 98.5%.

Table 20. Particulate filter efficiency Truck 4 in the city cycle per load

	City cycle filtration efficiency [%]					
	14 tonne			24 tonne		
	Minimum	Average	Maximum	Minimum	Average	Maximum
DPF 8	24.7	**38.2**	45.5	14.8	**25.4**	32.7
DPF 9	44.7	**47.2**	49.9	14.2	**25.6**	29.7

Table 21. Particulate filter efficiency Truck 4 in the motorway cycle per load (national transportation)

	Motorway cycle filtration efficiency [%]					
	14 tonne			24 tonne		
	Minimum	Average	Maximum	Minimum	Average	Maximum
DPF 8	23.1	**27.2**	37.9	25.2	**30.7**	38.4
DPF 9	32.2	**35.6**	39.0	-98.5	**-0.7**	30.4

Finally Table 22 shows a summary of all tests for national and international transportation. The retrofit filters perform better in cities than on motorways and vehicle load has a negative impact on particulate filter efficiency.

Table 22. Truck 4 overall average particulate filter efficiencies for the several cycle load combinations

	National						
				International			
	City cycle		Motorway cycle		Motorway cycle	Constant speed 83km/h	Constant speed 76 km/h*
Load	14t	24t	14t	24t	41t	41t	47.5t
DPF 8&9	43%	26%	31%	15%	25%	22%	12%
number of tests	10	10	8	10	6	4	4

* constant engine speed 1200 rpm

In Table 23 the average exhaust gas temperatures are given for the different test cycles and total vehicle weights. The exhaust gas temperature is measured during the chassis dynamometers tests just upstream of the retrofit filters. The table shows that the average temperature ranges from about 160°C with low weight and city driving to about 350°C with high vehicle weight and motorway driving. The average temperature during city driving is 90 to 95° C lower than during motorway driving with the same vehicle weight conditions.

Table 23 Average temperature before particulate filter of Truck 4 in the several test and load situations

	City cycle	Motorway cycle	Constant speed 83 km/h	Constant speed 76 km/h (1200 rpm)
	[°C]	[°C]	[°C]	[°C]
14 tonne	159	249		
24 tonne	191	287		
41 tonne		329	349	
47.5 tonne				342

In Figure 22, the filtration efficiencies for the different test cycles are presented in a graph with on the horizontal axis the average exhaust gas temperature of the test cycle. Each point in the graph is the average of a number of tests with the same total vehicle weight for one filter. The figure shows a decline in filtration efficiency with increasing exhaust gas temperature.

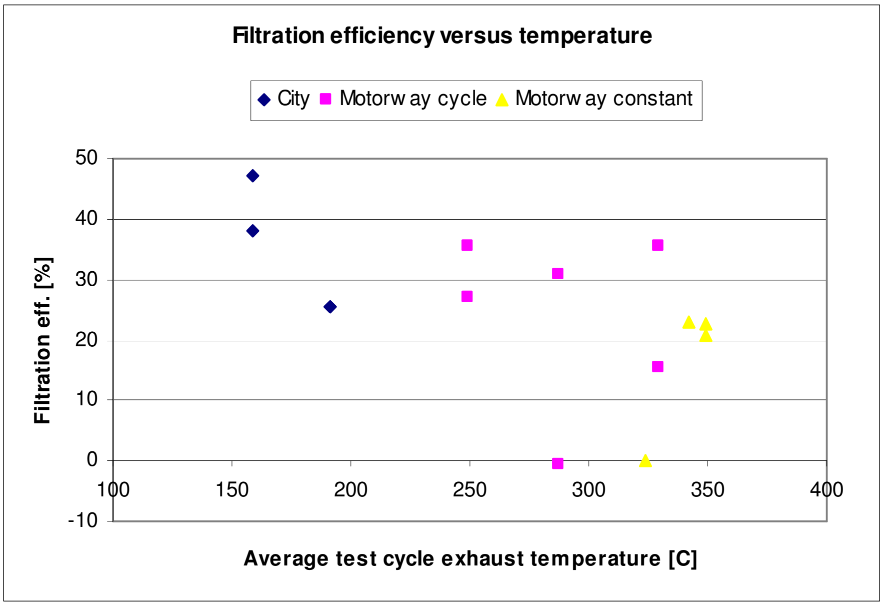

Figure 22. Average filtration efficiency as a function of average exhaust gas temperature. DPF 8 and 9 on truck 4.

4.2 Analysis of the truck results

The results of the individual trucks are presented in paragraph 4.1. In this paragraph the results are summarised and analysed.
An overview of the trucks and the tests carried out are presented in Table 24. The first three trucks are typical medium sized trucks for national distribution. Truck number 4 belongs to the heaviest category which is typical for international transport. Truck number 4 is tested according to the same test pattern as the medium size truck, but in addition it is tested with heavier weights during motorway driving. The tests with constant speed during motorway driving were added in order to better evaluate the correlation with the earlier engine dynamometer programme [3].

Table 24. Overview tests with four trucks with retrofit diesel particulates filters

Truck	Category	Vehicle weights (tonne)		
		National		International
		City	Motorway	Motorway
1	150-225 kW	11.5 and 18.5	11.5 and 18.5	
2	150-225 kW	11.5 and 18.5	11.5 and 18.5	
3	150-225 kW	11.5 and 18.5	11.5 and 18.5	
4	> 225 kW	14 and 24	14 and 24	41 motorway cycle 41, 47.5 constant speed

Table 25 shows an overview of the filtration efficiencies of the retrofit filters per truck type and also split up in low and high vehicle weight and city and motorway test cycle. Also the average results are presented. This shows that with low vehicle weight the average filtration efficiency is higher than with high vehicle weight. It also shows that on the average a cycle with higher dynamics (city) is better than a cycle with lower dynamics (motorway).

Table 25. Overview average filtration efficiencies of four trucks

Truck	Filtration efficiency (%)				
	Low weight*		High weight		
	city	motorway	city**	motorway**	internat. *** motorway
1	46	54	28	37	
2	33	23	32	20	
3	53	54	57	50	
4	43	31	26	15	19.5
Average	44	41	36	31	19.5
Weighing	x	y	x	y	

* 11.5 or 14 ton ** 18, 24 ton *** 41, 47.5 ton

The results of the table can be summarised as follows:

- Filtration efficiency for both medium heavy and heavy trucks with a total vehicle weight in the range of 11 to 24 ton is:
  - around 40% during city driving
  - around 35% during motorway driving

- For heavy trucks with a total vehicle weight between 40 and 47 tons, the efficiency is around 20% during motorway driving

The ratio of trucks with a medium heavy weight (11-24 ton) and a heavy weight (40-50 ton) is about two thirds versus one third (Figure 10), which brings the average filtration efficiency for motorway driving to a value of about 30%.
The results are graphically presented in Figure 23. The figure shows both the average filtration efficiencies as well as the complete range for the different filters (generally 2 per truck) and repeating tests. For truck 3, two different filter types were tested, reason why two sets of results are displayed.
Most results are in a range between 10% and 60%, two exceptions though:

- One filter type of truck 3 performs much better with an average filtration efficiency of about 80%. Also the filtration is quite constant (small range).
- With truck 4 one strongly negative efficiency is seen (increase in PM emission by 100%). Also several other tests drop below 10% efficiency to around 0% efficiency.

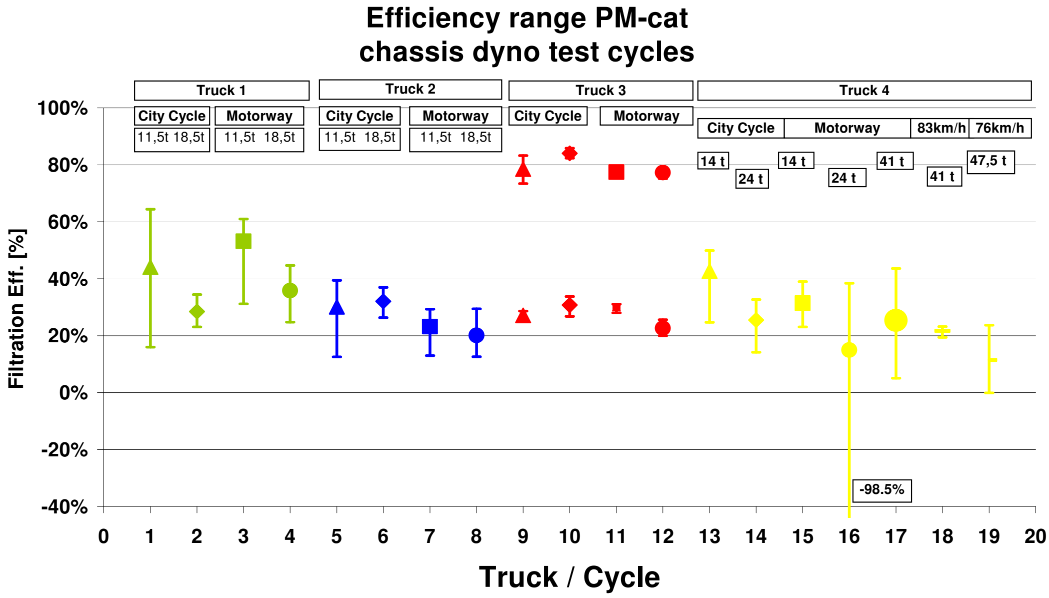

Figure 23. Average and range of filtration efficiencies of retrofit particulate filters on four trucks.

In Figure 24 a very similar picture is shown, but then with average and range of exhaust gas temperature instead of filtration efficiency. Exhaust gas temperature is thought to have a strong effect on filtration efficiency.

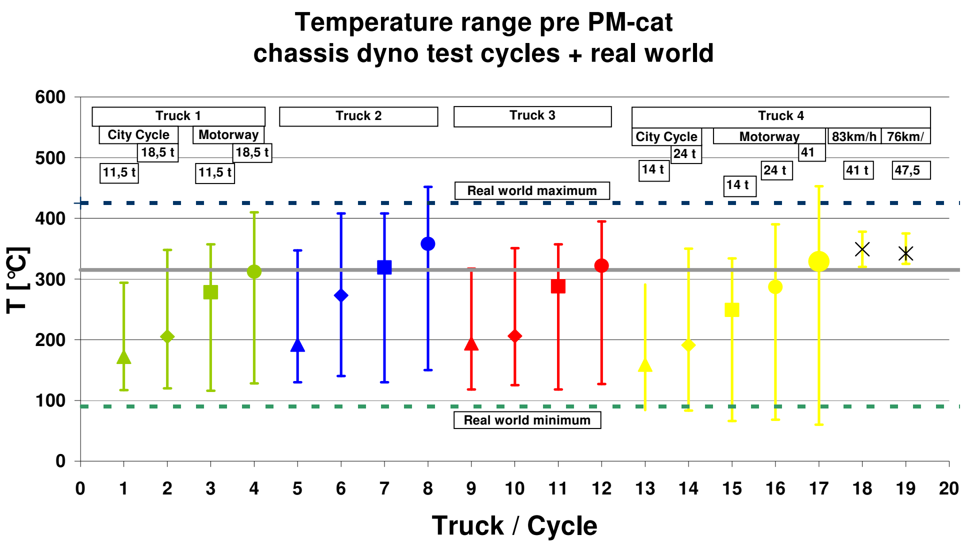

Figure 24. Average and range of exhaust gas temperature of the four trucks (upstream particulate filter)

The results lead to the following main conclusions:

- The filtration efficiency during city driving is generally higher than during motorway driving and the heavier the vehicle weight, the lower the filtration efficiency (only truck number 3 does not follow this pattern)
- Truck number 4, the heavy truck, is the most sensitive to vehicle weight.

However, the data also lead to a number of questions:
- Apparently the filtration efficiency is inversely proportional to average exhaust gas temperature (also refer to Figure 23). Why is this the case?
- Why is truck number 4 more sensitive to vehicle weight?

Filtration efficiency and exhaust gas temperature
Combining the results presented in Figure 23, Figure 24 and also Figure 22, it is demonstrated that for most filters the filtration efficiency goes down with increasing exhaust gas temperature. This is a rather surprising result since particulate regeneration conditions and also hydrocarbon oxidation conditions are more favorable at high exhaust gas temperature. However, it has been shown in other programmes [3], that the storage capacity of particulates in typical open filters is very large. So regeneration may not play an important role during a test sequence. There can also possibly be a long term and short term storage phenomenon with the latter being storage of heavy hydrocarbons (which form a part of the PM after dilution and cooling down). The long term storage its then more likely elementary carbon. Because of the sequence of testing, alternation between city cycle and motorway cycle, the result in the city cycle can benefit from the preceding motorway cycle. In the latter at least the hydrocarbons are oxidized or vaporized which leaves a relatively clean filter for the city cycle. The temperature during the city cycles is rather low (150-200°C) which makes condensation of heavy hydrocarbons quite likely.
Another explanation for a higher efficiency at lower exhaust gas temperature is space velocity or exhaust mass flow. A lower mass flow probably results in a large proportion of the flow passing through the filter-wall as opposed to passing by. This leads to a higher filtration efficiency. This is probably a part of the reason that the tests with a lower vehicle weight on the average show better results than the tests with a high vehicle weight. It can also partly explain the better results with the city cycle as compared to the motorway cycles.

Truck number 3 does not follow this pattern of lower efficiency with higher average exhaust gas temperature to the same extend. The results of this truck are strongly influenced by a different filter technology of one of the filter types tested. This filter technology is apparently better because it demonstrated a continuous high efficiency of around 80%.

So, in summary the main reasons for the higher efficiency at low average exhaust gas temperature are:
- the city cycle (low temperature) benefits from the preceding motorway cycle (high temperature).
- Condensation / adsorption of semi volatile hydrocarbons have a positive effect on the filtration efficiency.
- Lower space velocity (exhaust flow) has a positive influence on the filtration efficiency.

The heavy truck more sensitive to vehicle weight
Truck 4 shows a low efficiency with high vehicle weight. This is primarily caused by one of the two filters (DPF 9). In one test: 24 ton motorway cycle, the efficiency is -100%. This pulls down the average for motorway 24 ton to 0%, while for the other filter this average was 30%. The test with the efficiency of -100% is most probably a case of blow-off of stored particulates. This is possibly caused by the particulates becoming less sticky due to the high temperature and then be released form the filter structure. Another reason could be the evaporation (without oxidation) of heavy semi-volatile hydrocarbons.

These hydrocarbons condense on the particulate mass after dilution and cooling down. The poor performance of DPF 9 can be due to the history of the filter prior to the test period. For example when it was not driven with high load and or speed for some time. Also the results with motorway driving and heavy weights (41 and 47 ton) were not excellent. Both DPFs (8 and 9) showed an average efficiency around 20%, although DPF 8 was more stable. Refer to paragraph 4.1.4.

4.3 Possible role of sulphate particulates

A possible explanation for low filtration efficiency could be a release of sulphate (SO4) from the retrofit particulate filter, which was collected during months of driving the vehicle and is possibly released in a single or a few tests. This may then explain poor filtration efficiency results. It should be noted that by fitting the exhaust temperatures during testing with those of the real world, which has been done, this phenomenon should not happen or if it happens it should also happen under real world driving conditions. The oxidation catalytic coating used within the particulate filters do have a tendency to convert SO_2 to SO_4.

Never the less the SO4 fraction of fourteen sample filters of the four trucks were investigated. For each truck particle samples were analysed of tests with the lowest filtration efficiency (generally tests with high vehicle weight). Detailed results are reported in Appendix B. As a rule of thumb, the sulphates bind 120% of their weight in water. The mass of sulphates including bound water of nine tests are between 1 and 5% of the collected particulate mass. For three tests this fraction is 10-12%.
Based on these results it can be stated that sulphate fractions do not play a substantial role in the filtration efficiencies.

4.4 NO_2 emissions

In Table 26 the average NO_2 emission change due to the installation of the particulate filters of the three medium heavy trucks are presented. The table shows an average increase of NO_2 from 1-5% to 8-23% depending on the test type.
Detailed data are reported in Appendix 3. This detailed overview shows very different results per truck and technology. I.e. a retrofit open particulate filter in a motorway cycle with 18,5 tonne load may result in 9 - 42% NO_2 increase.

Table 26: Average NO_2 increase of trucks 1, 2 and 3 (first value is engine out)

Cycle	Vehicle weight	NO_2 [%]
City Cycle	11.5 ton	5 → 8
	18.5 ton	4 → 15
Motorway cycle	11.5 ton	2 → 23
	18.5 ton	1 → 23

5 Comparison engine and chassis dyno test results

5.1 Engine and chassis dynamometer programme

This vehicle chassis dynamometer programme of 4 trucks with 9 retrofit open particulate filters is a continuation of an engine dynamometer programme [3] in which 5 retrofit open particulate filters are tested on 1 engine. The reported filtration efficiencies in the engine dyno programma were significantly lower than the efficiencies in the vehicle dyno programme. It is important to understand the cause for this difference, as it may shed light on the mechanisms involved in both test series.
Two key points are of importance:
- What is the cause of the differences in reported filtration efficiencies between the engine dyno series and the chassis dyno series?
- What are the implications of this for estimating real-world efficiency of particulate filters?

To this end, a comparison between the two test procedures is done here. One of the engine types was used in both programmes, allowing a comparison. For the comparison, first the engine-out PM emissions of the two measurement series are compared, to see if the baseline for the filtration efficiency tests is the same (section 5.2).
Subsequently, the filtration efficiencies are analysed (section 5.3), and conclusions regarding the cause of the differences are drawn.

Table 27 shows the most important properties of the different test laboratories used, as well as some details of the test sequences.

Table 27: Properties test sites, equipment and test procedures

	Engine dynamometer	Chassis dynamometer
Test site	TNO, The Netherlands	VTT, Finland
Number DPFs	6	9
Number of tests	> 200	> 300
Period	2008	2009
Sample filter set up		
Trade mark test equipment	Horiba	Pierburg
PM sampling specification	EPA 1065	?
Pretreatment cyclone	Yes	No
Number of sample filters	1	2
Heated PM sampling system	Yes, 42-52 °C	No, < 52 °C
Test sequence	Research based	Real world based
Preconditioning DPF	Yes	No
Preconditioning time/temp	900 s, 285 °C	0 s, warm DPF
Regenerations > 450 °C	Yes	No
NO_2 measurements	Yes	Yes
SO_4 measurements	No	Yes

5.2 Engine out PM-emissions

A comparison of the chassis and engine dynamometer engine out test results is made in Table 28. An identical engine type is applied in both test programmes and in this paragraph their engine out PM-emissions are compared. Therefore the PM-emissions in the engine dynamometer programme must be converted from g/kWh to g/km. Based on the specific CO_2 emissions per cycle the specific engine out PM-emissions in g/kWh of the engine are converted to g/km. The conversion ratio in the WHTC urban test is 1.75 and in the ETC-test 1.17.

Table 28: PM emissions engine out

	Average	City Cycle		Motorway	
		11.5 tonne	18.5 tonne	11.5 tonne	18.5 tonne
	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
Truck 1	0.21	0.25	0.39	0.11	0.10
Truck 2	0.14	0.15	0.25	0.06	0.09
Truck 3	0.17	0.22	0.30	0.07	0.08
		14 tonne	24 tonne	14 tonne	24 tonne
Truck 4	0.22	0.29	0.41	0.07	0.13
		WHTC urban		ETC	
		[g/kWh] / [g/km]		[g/kWh] / [g/km]	
Engine	0.20	0.16 / 0.28		0.10 / 0.12	

Comparison engine and chassis dynamometer results:
The engine pm-emissions in the WHTC-urban test are 0.28 g/km which corresponds with the truck 4 pm-emissions of 0.29 g/km in the 11.5 tonne City Cycle test.
The engine pm-emissions in the ETC-test are 0.10 g/kWh which corresponds with the truck 4 pm-emissions of 0.13 g/km in the 18.5 tonne Motorway test.
The engine out pm- emissions of two equal engines (same mark and type) measured on a chassis dynamometer at VTT-Finland and an engine test bed TNO-The Netherlands are in the same order.

Comparison of the PM-emissions of the 4 trucks:
The four trucks have an average PM-emission range of 0.14 – 0.22 g/km. This variation can be marked as normal. For retrofit open particulate filter efficiency evaluation the individual truck PM-emissions should be taken into account.

This analysis shows that the engine-out PM emissions of the two test sites are comparable, taking into account the differences in test procedures.

5.3 Filtration efficiency

In Figure 25, the filtration efficiency is presented as a function of the average exhaust gas temperature. It includes both the chassis dynamometer results as well as the engine dynamometer results with a typical long haul truck respectively engine (truck 4). Every point is the average filtration efficiencies of a number of tests with a certain test cycle. The test cycles between the chassis dynamometer and the engine dynamometer are not really comparable. Putting it in a graph with average test cycle temperature is a way to compare them.

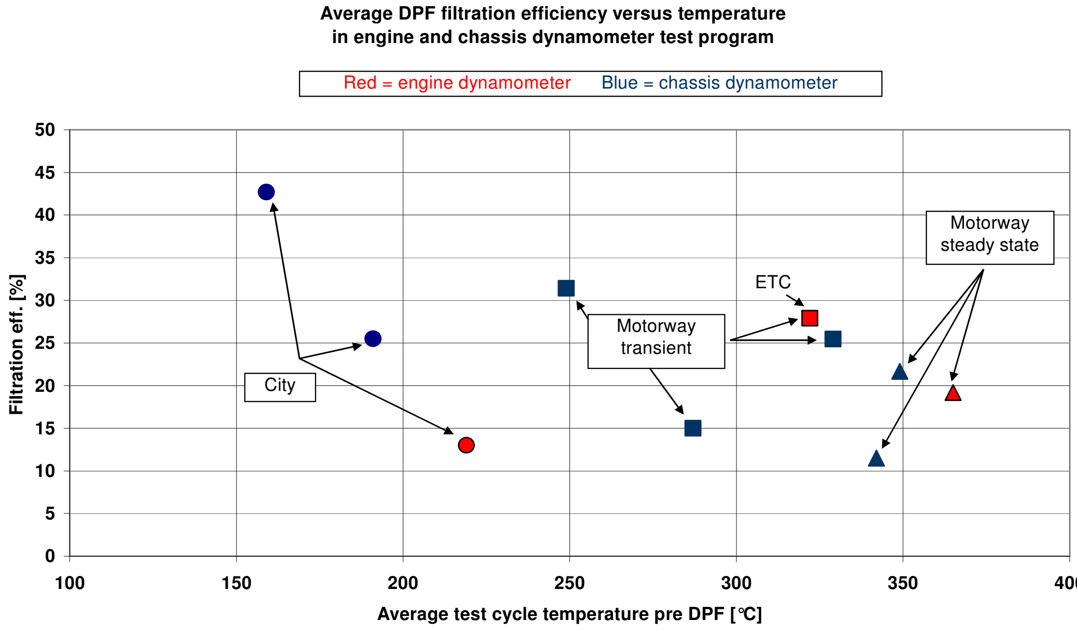

Figure 25. Average filtration efficiency as a function of average test cycle temperature. Comparison of chassis dyno results of truck 4 and corresponding engine dyno results.

An overview of the test cycles used during the chassis and engine dynamometer testing is presented in Table 29. Some notes can be made:

- the exhaust gas temperature of the WHTC appeared to be somewhat higher than the city cycle (30 to 60°C)
- the ETC is more transient than the motorway cycle. The average exhaust gas temperature is comparable with motorway driving when the total vehicle weight simulated on the chassis dynamometer is in the range of 41 to 47 ton. So even though it is a mix of city, rural and motorway driving, due to the average temperature it can best be compared to the motorway cycle with 41 ton vehicle weight. Another reason is the test sequence: both ETC and the (41-47 ton) chassis dyno tests were a repetition of these (highly loaded) tests. This corresponds to several hours or more on the motorway. The motorway testing of 14 and 24 ton was frequently alternated by city cycles (typically 3 times to 1 time per hour). This is representative for national (distribution) transportation.

Table 29. Overview test cycles on chassis dynamometer and engine dynamometer with typical long haul truck / engine.

Representing	Chassis dynamometer	Engine dynamometer
City	City cycle 14 and 24 ton	World Harmonised Transient Cycle or WHTC (city part only)
National motorway	Motorway cycle 14 and 24 ton	European Transient Cycle or ETC (mix of city, rural and motorway, relatively high load)
International motorway	Motorway cycle 41 ton Constant (motorway) speed 41 and 47.5 ton	Constant point simulating constant speed on motorway

In Table 30, the comparison of the average exhaust gas temperatures and filtration efficiencies between the engine and chassis dynamometer tests are made. A direct comparison is only possible for the city cycle and international motorway / ETC. It can be concluded that there is a good correlation for "international motorway". In both cases the filtration efficiency is 19%, even though the temperature for the range of chassis dynamometers tests is somewhat lower than the temperature during the constant load point during the engine dynamometer testing (representing motorway driving). If the ETC would be added to this (average filtration efficiency of 28%), the average filtration efficiency during engine dynamometer testing would be somewhat higher than during chassis dynamometer testing. Interesting to see in Figure 25 that the ETC results corresponds very well with the motorway cycle with 41 ton vehicle weight, both with average filtration efficiency (25-28%) as with temperature (320-325°C).
For the city cycle test results, the opposite is the case. The average filtration efficiency during engine dynamometer testing is 13% while this is 26% for the chassis dynamometer testing (Table 30). For the city cycle the 24 ton weight is selected for the comparison, because then the temperature is the closest.

There are two reasons which are most likely mainly responsible for the difference in average filtration efficiency:

- The average exhaust gas temperature during the chassis dynamometer is about 30°C lower. With the chassis dynamometer testing, a trend can be seen that efficiency goes down when the average temperature goes up. Refer to Figure 25. The city cycles show a steeper decline than the average decline. With the chassis dyno city cycle, the efficiency goes down from about 45% to about 26%, between 160 to 190°C. The value 13% at 220°C of the engine tests follows that decline linearly.
- With the chassis dynamometer tests, the city cycle tests were more frequently alternated with motorway tests (once and three times per hour). Most likely during the motorway tests, the stored particulates are regenerated and the city cycle is started with a relatively clean filter. The filtration efficiency with a cleaner filter is generally higher than with a filter containing more particulates.

Heavy hydrocarbons, which are normally (when diluted and cooled down) a part of the particulates, possibly play a role in the two phenomena described above. These hydrocarbons can be adsorbed and desorbed from the oxidation catalyst and particulate filter and in that way account for a relatively high efficiency during the relatively cold (city) test, especially when it was preceded by a higher loaded test. A confirmation of this phenomenon is also found in the relatively high filtrations efficiencies with tests with a cold start. This was seen both during the engine and chassis dynamometer programmes. Also refer to the description at the end of paragraph 4.2.

In the lower part of Table 30, for completeness, the ranges of exhaust gas temperatures and filtration efficiencies are given for all chassis dynamometer tests. The upper side of the range corresponds to the average filtration efficiency with the tests with the low,14 ton vehicle weight. This is actually the case for each truck, refer to Table 25, and not only the heavy truck evaluated in this paragraph.

Finally differences in the historic load pattern (months before the tests) can play a role and influence the average efficiencies during the chassis and engine dynamometer programmes. During the engine dynamometer programme six identical filters were tested. The differences in average filtration efficiencies (of all tests) between the filters ranged from about 0% to about 30%, which is of course an enormous difference.

Noted should be that the test programmes of the individual filters on the engine dynamometer were not identical, which may account for some of the difference.

Table 30. Comparison of exhaust gas temperature and filtration efficiency of chassis dynamometer test results and engine test results

	vehicle weight	Temperature (℃)		Filtration efficiency (%)	
	ton	chassis dyno	engine dyno	chassis dyno	engine dyno
Corresponding tests					
City / WHTC city part	24	190°	220°	26%	13%
ETC			320°		28%
International motorway	41-47	325 to 350°	365°	19%	19%
All tests					
City	14-24	160 to 190°		26 to 44%	
National motorway	14-24	250 to 290°		15 to 31%	

5.4 Conclusions comparison engine and chassis dynamometer tests

Two key points are of importance:
- What is the cause of the differences in reported filtration efficiencies between the engine dyno series and the chassis dyno series?
- What are the implications of this for estimating real-world efficiency of particulate filters?

Specific test types of the chassis dynamometer tests were selected, which correspond to the engine tests with respect to load pattern and average exhaust gas temperature.
From this analysis the following is concluded:
- There is a good correlation of engine-out PM emissions for the two test sites under similar testing conditions
- There is a good correlation for the tests simulating motorway driving with a vehicle weight of 41 to 47 ton.
- There is a considerable difference between the tests simulating city driving; average filtration efficiency is 13% and 26% for respectively engine dynamometer and chassis dynamometer testing. The main reasons for this difference are most probably
  1) a difference in average exhaust gas temperature and
  2) the difference in test sequence. The more frequent alternations between motorway and city cycle test is thought to have a positive influence on the city cycle efficiency during the chassis dynamometer tests.

The chassis dynamometer tests cover a wider range of driving conditions and vehicle weights. The driving conditions, vehicle weights and test sequence have been studied extensively and agreed upon with the stakeholders.
For this reason the chassis dynamometer test result should give the best indication for the real-world filtration efficiencies. The broader, real world focused, test programme also leads to differences in results compared to the phase 1 programme . Due to that, average filtration efficiencies during city driving and national motorway driving are higher than concluded at the end of phase 1.

6 Discussion

Influence of test cycle and test sequence

It was already demonstrated in other programmes, that it is difficult to do a reproducible measurement of filtration efficiency with open particulate filters. On top of that it appears to be very difficult to measure and determine a filtration efficiency which is representative for real-world driving conditions. This programme and also the engine dynamometer programme carried out in 2008 confirmed this. In both programmes a large number of tests were carried out (200-300 tests) and still it is difficult to correlate the results. Basically you can get any result depending on how the tests are carried out. Conditioning, precise exhaust temperatures, probably transients, and sequence of testing all have a strong influence on the measured filtration efficiency. Also wall-flow diesel particulate filters show some variation in efficiency due to adsorption of heavy (semi-volatile) hydrocarbons, but with open filters these effects seem much larger. Either the quantity of adsorbed hydrocarbons is much larger and/or the particles come lose and are emitted due to the open structure of the filter. The blow-off phenomenon has been demonstrated several times with passenger cars, yet it seemed less of a problem with this chassis dynamometer programme. A possible explanation for this is the relatively high engine out particulates level of passenger car diesel engines compared to truck engines. The exhaust gas temperatures on the motorway are comparable: for both passenger cars and trucks 250-350°C (80-120 km/hr for passenger cars refer to [4]).

Figure 25, where engine and chassis dynamometer results are compared, displays the sensitivity towards the test cycle and probably also the test sequence. Especially at low temperatures the efficiency varies strongly with temperature and engine efficiency is lower during the engine tests than during the chassis dynamometer tests. The possible phenomena are discussed at the end of paragraph 4.2. At higher temperatures the results of the engine and chassis dynamometer testing are very similar, but also the sequence of testing was in that case more similar.
It should be noted that only two filter are used (and also can be used) for the comparison with the engine dynamometer results. Due to possible variation in filter performance, the results can change when more filters are tested. Especially during the engine dynamometer testing the filter to filter variations were sometimes large. Positive for the chassis dynamometer testing is that filtrations efficiency responds similarly towards test cycle conditions such as vehicle weight. Generally low vehicle weight leads to a higher efficiency than with high vehicle weight and city cycle was better than motorway. Refer to 4.2, Table 25.

Blow-off of stored particulates

The phenomenon of blow-off of stored particulates has been regularly reported with passenger car retrofit open particulates filters [1], [4] and [5]. ADAC had carried out tests which included extensive loading of the filter during 1500 km under city conditions. After this loading 6 out of 9 filters showed a release of stored particulates during a motorway test cycle (130 km/h). Emission could be up to a factor of three higher than without the filter [5].

The current test programme consisted of mix of low load and high load test conditions. It was made certain that the filters, which were used in practise, were not specially regenerated prior or during the test programme.

The test programme was organised in such a way that the release of particulates during blow-off would most probably be measured. This was done by avoiding any conditioning or pretesting and to always have the dilution tunnel and particulates sampling system operational when the truck was running. Also the first test of the day with cold engine was always a normal test with the particulates sampling system operational. It was labelled as a test with cold start.
The particulates sampling system at VTT did not have a cyclone or a Chinese hat to prevent larger particulates from entering the sampling system. So also possible larger particles, which break lose from the soot filter, would be measured.
Only with the heavy truck, there was one test with apparently a release or blow-off of stored particulates, which was indicated by a particulates emission increase of 100% compared to engine out level. In addition there were two tests with 0% efficiency and one test with an efficiency of 5%. With these tests it is likely that there is a release of particulates during a part of the test and storage/regeneration during another part.
Consequently it can be concluded that during the measuring programme of in total about 300 tests, there was one event with a most likely blow-off of stored particulates and three events with a possible blow-off (filtration efficiency lower than 10%).

Test method

Testing of open particulate filters is particularly difficult because of the large storage capacity, the possibility of release of particulates under certain conditions and the influence of stored particulates quantity on the filtration efficiency.
However, the current work has shown that with sufficient testing insight into the main mechanisms can be obtained and a relatively complete picture of particulate filter behaviour can be drawn. The carried out test method seems to lead to good results.
Important aspects of the methodology are:

- use particulate filters which are sufficiently aged under real-world conditions
- closely simulate real world conditions during measurements
- frequent repetition of several standard tests
- avoidance of any conditioning prior or in between the measurements

It is recommended to implement these elements into the type approval test procedure, not only for partial flow particulate filters, but basically for any emission control device which may be sensitive to (cumulative/historic) engine load conditions such as exhaust gas temperature and flow rate.

7 Conclusions

A test programme was conducted which was focussed on measuring the real-world filtration efficiencies of retrofit open particulate filters of medium heavy and heavy trucks. In the first part of the programme a considerable effort was undertaken in order to correlate the test cycles and test sequence with real world conditions for city and motorway driving. The test programme consisted of in total more than 300 measurements with 9 filters, tested on 4 trucks.

The measuring programme leads to the following conclusions:

- The filtration efficiency for half-open particulate filters on both medium heavy and heavy trucks with a total vehicle weight in the range of 11 to 24 ton is:
  - around 40% during city driving
  - around 35% during motorway driving

- For heavy trucks with a total vehicle weight between 40 and 47 tons, the efficiency is around 20% during motorway driving.

- Possible blow-off of stored particulates happened only a few times during the phase 2 program (with medium and high vehicle weights > 18 ton).

- The precise load pattern and load pattern history have a large impact on the filtration efficiency. This explains the difference with the phase 1 results. The efficiency is higher with relatively low vehicle weights and after driving conditions which are favourable for regeneration.

The 20% filtration efficiency during motorway driving is based on motorway driving during about 2.5 hours (7 tests per filter). Based on the engine dynamometer tests in 2008 (phase 1), it is possible that with continuous motorway driving (longer than about 3 hours) the filtration efficiency would go up to a value in the range of 30% to 40%.

8 References

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Signature

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List of abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conformity Of Production
CSF	Closed Diesel particulate Filter
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
ELPI	Electric Low Pressure Impactor
ELR	Engine Load Response test
ESC	European Steady State Cycle
ETC	European Transient Cycle
FAME	Fatty Acid Methyl Ester
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen monoxide + Nitrogen dioxide
PM	Particulate Matter
RDW	RDW (the Dutch vehicle authority)
THC	Total HydroCarbons
VROM	Ministry of Housing, Spatial Planning and the Environment
WHTC	World Heavy Duty Transient Cycle

Appendix 1: Fuel specifications

NESTE OIL 1.1.2009

TUOTETIEDOTE	PRODUKTDATA	PRODUCT DATA SHEET
NESTE GREEN-DIESEL -5/-15 RIKITÖN LYHENNE: DIG-5/-15	NESTE GREEN-DIESEL -5/-15 SVAVELFRI FÖRKORTNING: DIG-5/-15	NESTE GREEN DIESEL -5/-15 SULPHUR FREE ABBREVIATION: DIG-5/-15

	Yksikkö Enhet Unit	Laaturaja Kvalitetskrav Specification		Tyypillinen arvo Typvärde Typical analysis	Määritysmenetelmä [1] Testmetod [1] Test method [1]
		min.	max.		
Rikki [2] Svavelhalt [2] Sulphur content [2]	mg/kg		10,0	5	EN ISO 20846 D 3120
Tislaus, Destillation, Distillation Haihtunut, Förångat , Evaporated 180 °C:ssa, vid 180 °C, at 180 °C	til.-% vol.-% % v/v		10	1	EN ISO 3405
250 °C:ssa, vid 250 °C, at 250 °C	til.-% vol.-% % v/v		65	< 21	
350°C:ssa, vid 350 °C, at 350 °C	til.-% vol.-% % v/v	85		> 97	
95 % piste	°C		360	< 340	
Leimahduspiste [3] Flampunkt [3] Flash point [3]	°C	60		65	EN ISO 2719
Tiheys, 15 °C Densitet vid15 °C Density at 15 °C	kg/m³	820	845	835	EN ISO 12185
Viskositeetti, 40 °C Viskositet vid 40 °C Viscosity at 40 °C	mm²/s	2,00	4,50		EN ISO 3104
Samepiste [4] Grumlings temperatur [4] Cloud point [4]	°C		-5		EN 23015 D 5773
Suodatettavuus [5] Filterbarhetstemperatur [5] CFPP [5]	°C		-15		EN 116
Setaani-indeksi Cetanindex Cetane index		46,0		> 55	EN ISO 4264
Setaaniluku Cetantal Cetane number		53,0		> 56	EN 15195 EN ISO 5165 D 6890
Hiiltojäännös 10 % pohjasta Kokstal av 10 % återstod Carbon residue on 10 % distillation residue	p-% mass-% % m/m		0,30	< 0,01	EN ISO 10370
Kuparikorroosio Kopparkorrosion Copper strip corrosion			1	1	EN ISO 2160
Vesi Vatten Water content	mg/kg		200	50	EN ISO 12937
Tuhka Askhalt Ash content	p-% mass-% % m/m		0,01	< 0,001	EN ISO 6245

Käännä Vänd See overleaf

DIG-5/-15	Yksikkö Enhet Unit	Laaturaja Kvalitetskrav Specification		Tyypillinen arvo Typvärde Typical analysis	Määritysmenetelmä [1] Testmetod [1] Test method [1]
		min.	max.		
Sedimentti Sediment Particulate matter	mg/kg		24	< 5	EN 12662
Hapetuskestävyys Oxidations stabilitet Oxidation stability	g/m³		25	< 5	EN ISO 12205
Polyaromaatit Polyaromater Polyaromatics	p-% mass-% % m/m		9	2	EN 12916
Voitelevuus / HFRR Smörjbarhet / HFRR Lubricity / HFRR	µm		460	350	EN ISO 12156-1
NExBTL -diesel NExBTL -diesel NExBTL -diesel	til-% vol-% % v/v	10		> 10	
Väri ja ulkonäkö Färg och utseende Appearance	Värjäämätön, kirkas, ei kiinteitä epäpuhtauksia Ofärgad, klar och blank Undyed, clear and bright				D 4176-2

[1] D-numero viittaa ASTM-menetelmään

[2] Laki nestemäisten polttoaineiden valmisteverosta 1472/1994, 1159/1998 ja 394/2004

[3] Asetus 59/1999

[4] 1.5. - 31.8. 0 °C

[5] 1.5. - 31.8. -10 °C

Tuote sisältää voitelevuus- ja sähkönjohtavuutta parantavan lisäaineen.

Tuote täyttää Vna:n 767/2003:n ja SFS-EN 590 kylmäominaisuusluokan E (A-D) vaatimukset sekä direktiivin 2003/17/EY.

Spesifikaation tulkinnassa käytetään ISO 4259:n mukaista käytäntöä

Käyttöturvallisuuden osalta viittaamme Neste Oil Oyj:n julkaisemiin käyttöturvallisuustiedotteisiin sekä tuotteiden käyttöä koskeviin oppaisiin.

TIEDUSTELUT
Neste Oil Oyj
Öljytuoteneuvonta
PL 310
06101 PORVOO

Puhelin 0800 1 9696

[1] D-nummer hänvisar till ASTM-metod

[2] Lag om accis på flytande bränslen 1472/1994, 1159/1998 och 394/2004

[3] Förordning 59/1999

[4] 1.5. - 31.8. 0 °C

[5] 1.5. - 31.8. -10 °C

Produkten innehåller smörjbarhet och additiv, som förbättrar konduktivitet.

Produkten uppfyller förordningen 767/2003 och SFS-EN 590 klass E (A-D) samt direktiv 2003/17/EG.

Produktspecifikationen tolkas i enlighet med proceduren beskriven i ISO 4259.

Angående skyddsinformation hänvisar vi till skyddsinformationsblad publicerade av Neste Oil Oyj samt till produkternas bruksanvisningar.

FÖRFRÅGNINGAR
Neste Oil Oyj
Nordic Sales
PB 95
FIN-00095 NESTE OIL, Finland

Telefon 010 458 5651 eller
+358 10 458 5651

[1] D- number refers to ASTM-method

[2] Product meets the act for sulphur free diesel fuel set by Finnish authorities

[3] Regulation 59/1999

[4] 1.5. - 31.8. 0 °C

[5] 1.5. - 31.8. -10 °C

The product contains lubricity and additive, which improves conductivity.

The product meets regulation 767/2003, SFS-EN 590 grade E (A-D) and directive 2003/17/EC.

The product will comply with the spesification according to the procedures described in ISO 4259.

Concerning safe use of the products, we refer to the Safety Data Sheets and User's Guides published by Neste Oil Oyj.

INQUIRIES
Neste Oil Oyj
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POB 95
FIN-00095 NESTE OIL, Finland

Phone +358 10 458 5651

Käännä Vänd See overleaf

Appendix 2: SO_4 test results

Motorway cycle PM samples											
Test			PM mass	SO4	SO4/PM	SO4	H2O + H2SO4	SO4/PM	H2O + H2SO4		corr. PM mass
						blank corr.	blank corr.	blank corr.	blank corr.		H2SO4 corr.
			[mg]	[μγ]	[%]	[μγ]	[μγ]	[%]	[%]		[mg]
210	Truck 1	DPF 2	2.032	47.8	2.35	40.3	88.7	2.0%	4.4%		1.943
246	Truck 1	DPF 3	2.421	46.5	1.92	39.0	85.7	1.6%	3.5%		2.382
251	Truck 1	DPF 3	2.249	41.0	1.82	33.5	73.7	1.5%	3.3%		2.215
293	Truck 2	DPF 4	2.115	53.7	2.54	46.2	101.5	2.2%	4.8%		2.069
297	Truck 2	DPF 4	2.099	52.9	2.52	45.4	99.8	2.2%	4.8%		2.054
317	Truck 2	DPF 5	1.945	100.0	5.14	92.5	203.5	4.8%	10.5%		1.852
126	Truck 3	DPF 6	0.637	13.8	2.16	6.3	13.8	1.0%	2.2%		0.631
128	Truck 3	DPF 6	0.645	12.4	1.92	4.9	10.7	0.8%	1.7%		0.640
149	Truck 3	DPF 7	1.954	20.8	1.07	13.3	29.4	0.7%	1.5%		1.941
151	Truck 3	DPF 7	2.032	18.9	0.93	11.4	25.1	0.6%	1.2%		2.021
443	Truck 4	DPF 8	2.526	52.0	2.06	47.0	103.4	1.9%	4.1%		2.479
463	Truck 4	DPF 9	3.054	19.0	0.62	14.0	30.8	0.5%	1.0%		3.040
472	Truck 4	DPF 9	0.515	33.0	6.41	28.0	61.6	5.4%	12.0%		0.487
473	Truck 4	DPF 9	0.486	26.0	5.35	21.0	46.2	4.3%	9.5%		0.465
Blank reference for test 443 - 473			7.5								
Blank reference for test 126 - 318			5								
detection limit: 5 µg /sample											

Appendix 3: NO_2 test results

Truck		Low Weight				High weight			
		City Cycle 11.5tons		Motorway 11.5tons		City Cycle 18.5tons		Motorway 18.5tons	
		NOx g/km	NO2 %	NOx g/km	NO2 %	NOx g/km	NO2 %	NOx g/km	NO2 %
1	Muffler	10.61	5.8	5.15	4.1	11.46	7.2	5.92	3.7
	DPF1,2&3	10.62	6.3	5.10	21.1	11.28	15.4	5.98	20.1
2	Muffler	5.49	3.4	4.45	-0.1	6.92	-1.5	4.09	-0.2
	DPF1&2	5.81	12.0	4.38	12.3	7.11	12.9	5.03	9.0
3	Muffler	8.89	6.6	5.74	1.9	10.61	6.7	6.25	0.6
	DPF1	7.44	7.6	5.98	38.8	10.61	21.6	6.51	42.3
	DPF2	8.97	6.7	6.24	19.3	10.63	10.7	6.80	21.7
Average	muffler	8.33	5.2	5.12	2.0	9.66	4.1	5.42	1.3
	DPF	8.21	8.1	5.43	22.9	9.91	15.2	6.08	23.3

Appendix 4: Graphical representation of real-world data of delivery trucks

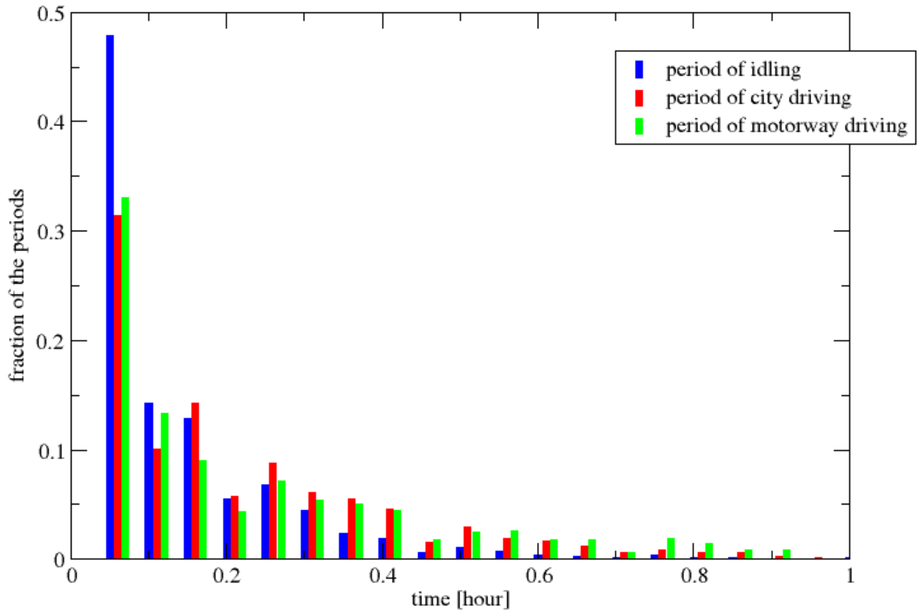

Figure: Distribution duration of driving conditions

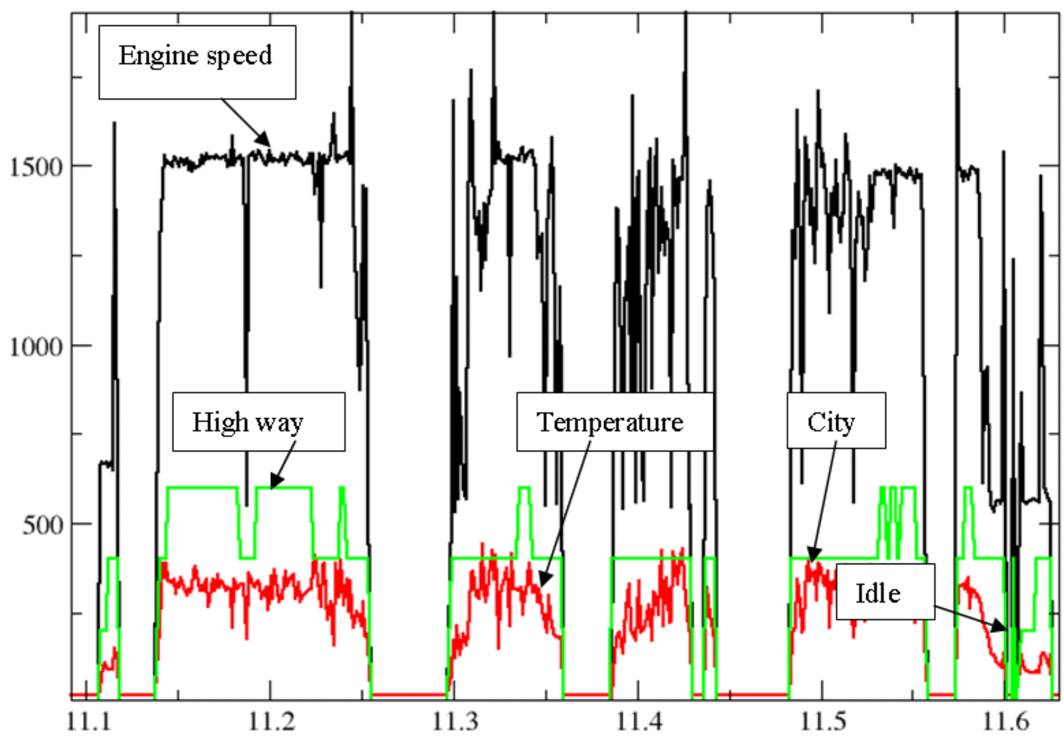

Figure : Example of the (driving) conditions analysis. Analysis is done with once per 100 s data. A software routine selects the driving condition.
Green line represents the driving condition:

- highest level is highway
- second highest is city
- second lowest is idle
- lowest (0) is engine off

Appendix 5: VTT test equipment

VTT, Technical Research Centre of Finland

Measurement Equipment The following measurement equipment was used for testing:

Heavy-Duty chassis dynamometer:

Manufacturer:	Froude Consine
Maximum power:	± 300 kW (54 – 110 km/h)
Excess capacity:	120 % / 300 s.
Maximum traction force:	± 20 000 N (0 – 54 km/h)
Inertia simulation:	2 500 – 60 000 kg
Diameter of the rolls:	2 500 mm
Maximum axle load:	20 000 kg

Emission measurement system:

Manufacturer: Pierburg

Model: CVS-120-WT

- Multiple (3) CFV-venture system
- Maximum flow 120 m3/min
- Dilution tunnel size 8000 * 450 mm
- Secondary tunnel VT-458
- Particle collector PS2000C

Analyser system AMA 4000

- HFID THC 0-1000 ppm
- HFID CH_4 0-3000 ppm
- HCLD NO_x 0-10 000 ppm
- NDIR CO_2 0-20 %
- NDIR CO 0-2500 ppm
- NDIR CO_2 tracer 0-20 %

Dynamometer settings Chassis dynamometer settings used for the distribution vehicles.

load	Inertia	F0	F1	F2
low load	11500	200	4.726	0.2028
high load	18500	470	12.352	0.1503

Chassis dynamometer settings used for the Long haul vehicle.

load	Inertia	F0	F1	F2
low	14000 kg	349	4.098	0.2154
medium	24000 kg	974	-1.252	0.2916
high	41000 kg	2009	-7.024	0.3739
steady state	47500 kg	2389	-7.024	0.3739

F0, F1 and F2 stand for road load model Ftotal = (F0) + v(F1) + v(F2)^2, where v is the vehicle speed in km/h.

Steady state load was used with reference measurements to engine dynamometer testing performed in earlier project by TNO.

Dynamometer settings for the vehicles are derived from actual coast down tests performed with a typical model representing the vehicle class in question. Repetitive coast-down testing using precise road profile resulted in very accurate basic road load model. This road load model was then adjusted by eliminating the effect of tyre used on dynamometer according to axle weight. Road load was also adjusted by simulated load. This method assumes uniform aerodynamic performance within vehicle classes, justified with similar frame design and construction among most of the vehicles.