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TNO report

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Evaluation of particulate filtration efficiency of retrofit particulate filters for light duty vehicles

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Summary

Background and objective

In the light of the currently running subsidy programme for particulate filters in the Netherlands, the Dutch ministry of spatial planning and environment (VROM) asked TNO to execute a desk study to evaluate the particulates filtration efficiency of retrofit particulate filters for light duty vehicles (passenger cars and vans).
The typical retrofit particulate filters for light duty vehicles are also called “open” or “half-open” filters, because a part of the exhaust gas can pass through the particulate filter unfiltered. From design point they are very different from the majority of the factory installed particulate filters, which are also called wall-flow or “closed “ particulate filters. Due to these differences there is a large difference in filtration efficiency. Whereas the “closed” particulate filters show a filtration efficiency of larger than 90%, the filtration efficiency of “open” particulate filters is generally lower (type approval minimum 30%) , and strongly dependent on the conditions of use.

The objective of the current project was to assess the average filtration efficiency of retrofit (open) particulate filters on light duty vehicles in real world day to day driving, based on available literature data. Also, the reasons of a possible deviation with the type approval test results (minimum filtration efficiency of 30%) was investigated.

Approach

The project carried out consisted of four parts: a) collecting information, b) analysis of the collected information, c) reporting of results both in writing and in a stakeholders meeting and d) a review by international experts.

The study focused on the collection of experimental data. Information of about eight experimental programs was available from which three were carried out by TNO. The programs are summarized in Table 1. Overall test results were available of about 32 retrofit particulate filters from 10 different brands and tested on about 19 different cars. The number of kilometres the filters were used on vehicles ranges from 0 (new filters) to 17000 km or more. This is a low value, taking into account that the yearly average driving distance for diesel passenger cars is about 37.000 km. The test cycles included the New European Driving Cycle (NEDC, type approval test cycle), the Common Artemis Driving Cycle (CADC), the USA Federal test procedure (FTP-75), the New York City Cycle (NYCC) and the Bundes AutoBahn (BAB). The test cycles other than the NEDC are often seen as more representative for real world conditions, because of the low dynamics and low average load of the NEDC. It should be noted however, that the NEDC tests were generally with a cold engine at the start (20° - 30°C lubricant temperature according to type approval) while the other cycles were generally run with a warm engine at the start of the test.

Table 1: Overview experimental programs

Experimental Program	# Vehicles	# Filters	# test cycles
VROM toxicity 2007 (TNO)	**3**	**3**	**2**
VROM delivery van 2007 (TNO)	**4**	**4**	**3**
Supplier evaluation 2008 (TNO)	**6**	**5**	**1**
EMPA passenger car 2006	**1**	**1**	**2**
Hyundai-Kia evaluation 2006	**2**	**2**	**1**
UBA investigation 2007	**1**	**4**	**5**
VW evaluation 2007	**1**	**4**	**1**
ADAC evaluation 2008	**1**	**9**	**2**

Results; filtration efficiencies of retrofit particulate filters

The results of the particulates reduction capability (filtration efficiency) are summarized in Table 2. Table 2 lists the average filtration efficiency, the total number of test results and the percentage of test results with a filtration efficiency lower than 20%.

Table 2: Overview of filtration efficiencies with retrofit open particulate filters for light duty vehicles

Test cycle	**Average filtration efficiency**	**Total number of test results**	**% of test results with filtration efficiency ≤ 20%**
Type approval test: New European Driving Cycle with cold start (20°C)	30%	38(1)	21%
Other test cycles: mostly warm start (including NEDC with warm start)	40%	87(2)	17%
All test cycles cold and warm start	37%	125	18%

(1) about 30 different vehicle-filter combinations

(2) about 50 different vehicle-filter-test cycle combinations

The following can be concluded from Table 2:

a. The collected experimental data shows that the average filtration efficiency during the type approval test cycle is about 30%. This is the same value as the type approval requirement (30%). The variation in test result is however large, i.e. with 21% of the tests, the filtration efficiency was lower than 20%.
b. Based on the data collected, the average real world filtration efficiency could be between 30% and 40%. The performance in real world however will be lower because of two effects which are not sufficiently investigated: 1) sudden blow-off of stored soot in the retrofit filter and 2)

aging of the retrofit filter. Because of this the exact real world filtration efficiency remains uncertain.

Large variation in test results.

The experimental data shown in Figure 1 show a large variation in filtration efficiencies depending on the test cycle. In real world driving similar large variations are expected with (open) retrofit particulate filters. The following reasons have been found for the large variation in test results:

- High sensitivity to the driving conditions of the vehicle during the days and weeks before the test. From the design point, the filtration efficiency is very sensitivity to the amount of soot stored in the filter. The amount of soot within the filter is dependent on the driving conditions.
- High sensitivity to the precise engine-filter combination, also within the formal “family” definition of a specific filter type.

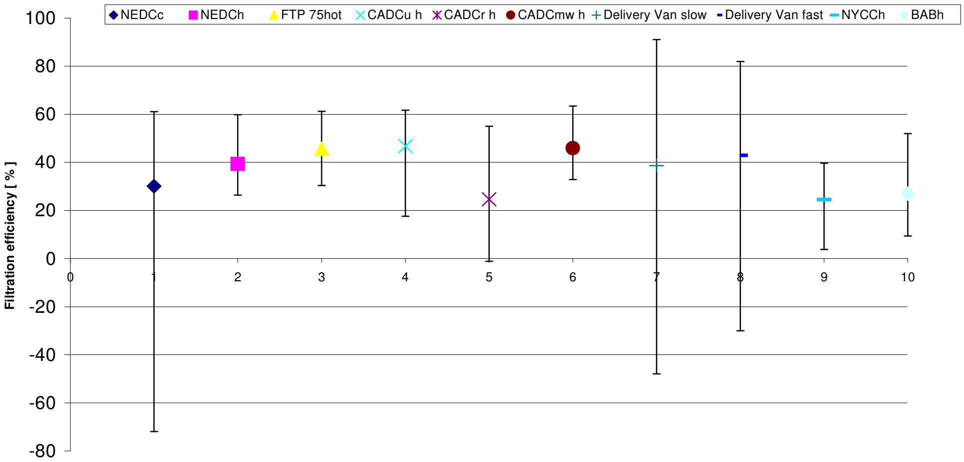


Figure 1: Range in filtration efficiencies of retrofit particulate filters found for different test cycles

Conclusions and Recommendations

There is no hard evidence that the average real world filtration efficiency of retrofit particulate filters on light duty vehicles in practice (real world) is lower than the type approval requirement of 30%. It has however been demonstrated that a significant percentage of the vehicles (indication 20%) have a filtration efficiency of lower than 20%, including negative efficiencies (release of stored particulates). Possible blow-off of stored soot is seen as the most serious draw back of retrofit open particulate filters.

A better confirmation of the average real world filtration efficiency can be obtained by additional testing with retrofit particulate filters which are mounted for a longer period on the vehicle (1 year or longer). The following approach is recommended:

a) select vehicles from which the retrofit filters were mounted for a longer period on the vehicle (1 year or longer).
b) do extensive real world conditioning of the filter (without special preconditioning or “cleaning”) just prior to the formal tests.
c) include several test cycles including engine power dependent parts and full load accelerations.

d) investigate a number of different vehicle types to obtain data with a better statistical coverage of the vehicle fleet.

It is believed that the particulate filter type approval test can be improved by incorporating these same items (b, c, d).

There is no indication that the average NO_2 emission will rise due to the installation of the retrofit filters.

The study was reviewed by two international specialists. They are less optimistic about the filtration efficiency than TNO and emphasize the unacceptability of the blow-off phenomenon because of health and legal aspects.

Samenvatting

Achtergrond en doel

Het ministerie VROM heeft in het kader van de huidige stimuleringsregeling voor retrofit roetfilters, TNO gevraagd een literatuurstudie uit te voeren naar het filtratierendement van “retrofit” roetfilters voor personenauto’s.
De toegepaste retrofit roetfilters voor personenauto’s (en bestelwagens) worden ook wel “open” of “half-open” roetfilters genoemd, omdat een gedeelte van het uitlaatgas door het roetfilter kan stromen zonder dat het wordt gefilterd. Vanuit de constructie bezien, is dit type filter totaal anders dan de affabriek gemonteerde roetfilters, die ook wel gesloten roetfilters worden genoemd. Vanwege dit verschil is er een groot verschil in filtratierendement tussen de 2 type filters. De gesloten roetfilters hebben een filtratierendement van meer dan 90%, terwijl dat van de open filters veel lager is (type goedkeuringseis minimaal 30%) en ook nog afhankelijk is van de gebruikscondities in de praktijk.

Het doel van het project is het bepalen van het gemiddelde filtratierendement van retrofit (open) roetfilters voor personenauto’s in het dagelijks gebruik, gebaseerd op data die in de literatuur beschikbaar is. Indien er een verschil geconstateerd wordt tussen type goedkeuringswaarden en praktijkwaarden, dan zal naar de mogelijke oorzaken gezocht worden.

Aanpak

Het project bestond uit vier onderdelen: a) informatie verzamelen, b) analyse van de verzamelde informatie, c) rapporteren van de resultaten, zowel schriftelijk als mondeling aan de stakeholders en d) het laten evalueren door internationale experts.

De literatuurstudie concentreerde zich op het verzamelen van experimentele data. Er was informatie beschikbaar van acht experimentele programma’s, drie hiervan zijn uitgevoerd door TNO. De verschillende programma’s zijn samengevat in Tabel 1. In totaal waren testgegevens beschikbaar van ongeveer 32 retrofit roetfilters van 10 verschillende merken, getest op 19 verschillende voertuigen. De hoeveelheid kilometers dat de filters gebruikt zijn op de voertuigen varieert van 0 (nieuwe filters) tot ruim 17.000 km. Dit zijn relatief weinig kilometers vergeleken met een jaarlijks gemiddeld kilometrage van 37.000 km voor een dieselvoertuig. De gebruikte experimentele gegevens omvatte data gebaseerd op de volgende testcycli: de New European Driving Cycle (NEDC, type goedkeuring testcyclus), de Common Arthemis Driving Cycle (CADC), the USA Federal test procedure (FTP-75), de New York City Cycle (NYCC) en de Bundes AutoBahn (BAB). De testcycli anders dan de type goedkeuringscyclus (NEDC), worden vaak gezien als meer representatief voor praktijkgebruik, vanwege de beperkte dynamiek en de lage gemiddelde belasting van de NEDC. Wel moet opgemerkt worden dat de testen uitgevoerd met de NEDC in het algemeen zijn gestart met een koude motor (olietemperatuur 20-30^{o}C volgens type goedkeuringsvoorschrift), terwijl de andere cycli in het algemeen zijn uitgevoerd met een warme motor aan het begin van de test.

Tabel 2: Overzicht experimentele programma's

Experimenteel Programma	Aantal voertuigen	Aantal roetfilters	Aantal testcycli
VROM toxiciteit 2007 (TNO)	**3**	**3**	**2**
VROM bestelwagen 2007 (TNO)	**4**	**4**	**3**
Toeleverancier evaluatie 2008 (TNO)	**6**	**5**	**1**
EMPA personenauto 2006	**1**	**1**	**2**
Hyundai-Kia evaluatie 2006	**2**	**2**	**1**
UBA onderzoek 2007	**1**	**4**	**5**
VW onderzoek 2007	**1**	**4**	**1**
ADAC onderzoek 2008	**1**	**9**	**2**

Resultaten; filtratierendement van de retrofit open roetfilters

De resultaten zijn samengevat in Tabel 2. Deze tabel geeft het volgende weer: het gemiddelde filtratierendement, het totaal aantal uitgevoerde testen en het percentage van testen dat een lager filtratierendement heeft dan 20%.

Tabel 2: Overzicht van filtratierendementen van retrofit roetfilters voor personenauto's

Test cycle	**gemiddeld filtratierendement**	**Total aantal testen**	**% van de test resultaten met filtratierendement ≤ 20%**
Type goedkeuringstest: New European Driving Cycle met koude start (20°C)	30%	38[1)]	21%
Andere testcycli: meestal met warme start (inclusief NEDC met warme start)	40%	87[2)]	17%
Alle test cycli koude en warme start	37%	125	18%

[1)] ca 30 verschillende voertuig-filter combinaties

[2)] ca 50 verchillende voertuig-filter-testcyclus combinaties

Conclusies die volgen uit Tabel 2 zijn:

a. De verzamelde experimentele data laat zien dat het gemiddelde filtratierendement tijdens een type goedkeuringscyclus uitkomt op 30%. Dit is de zelfde waarde die geldt als eis voor goedkeuring (30%). De variatie in testresultaten is echter groot: 21% van de testen heeft namelijk een lager filtratierendement dan 20%.

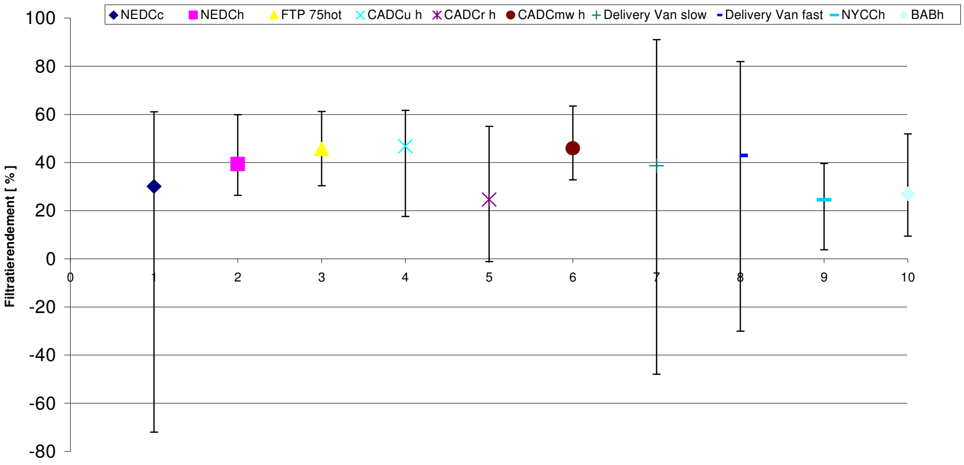
b. Op basis van de verzamelde data, komt het gemiddelde "praktijk" filtratierendement uit tussen de 30 en 40%. Het werkelijke rendement in de praktijk zal lager zijn vanwege twee effecten die niet voldoende zijn onderzocht:

1) onverwachte uitstoot (blow-off) van opgeslagen roet in het roetfilter en 2) veroudering van het roetfilter. Vanwege deze effecten blijft de exacte praktijkwaarde van het filtratierendement onzeker.

Grote variatie in de test resultaten

De experimentele data weergegeven in Figuur 1, laat de grote variatie in filtratierendementen van de retrofit roetfilters zien afhankelijk van de testcyclus. Ook tijdens het gebruik in de praktijk mag verwacht worden dat grote variaties plaatsvinden. De volgende redenen voor de grote variaties zijn gevonden:

- Grote gevoeligheid voor de rijomstandigheden die met het voertuig in de dagen en weken voorafgaand aan de daadwerkelijke test hebben plaatsgevonden. Bezien vanuit de filterconstructie is het filtratierendement erg gevoelig voor de hoeveelheid opgeslagen roet in het filter. De hoeveelheid opgeslagen roet in het filter is sterk afhankelijk van de rijomstandigheden.
- Grote gevoeligheid voor de juiste motor/roetfilter combinatie, ook binnen de officiële voertuig “familie”definitie van een specifiek filtertype.



Figuur 1: Variatie in filtratierendement van retrofit roetfilters voor verschillende testcycli

Conclusies en aanbevelingen

Er zijn geen harde bewijzen dat het gemiddelde filtratierendement van retrofit (open) roetfilters voor personenauto’s in de praktijk lager is dan type goedkeuringswaarde van 30%. Het is echter aangetoond dat een significant percentage van de voertuigen (indicatie 20%) een lager filtratierendement heeft dan 20%, waaronder zelfs negatieve rendementen (loslaten van opgeslagen roetdeeltjes). Het mogelijk loslaten (blow-off) van opgeslagen roet wordt gezien als grootste nadeel van retrofit open roetfilters.

Een betere onderbouwing van het gemiddelde filtratierendementen in de praktijk kan verkregen worden door het uitvoeren van aanvullende testen met retrofit roetfilters die voor een langere periode gemonteerd zijn onder een voertuig. Aanbevolen wordt de volgende aanpak:

a) selecteer voertuigen waar een retrofit roetfilter al voor een langere periode gemonteerd is (1 jaar of langer).

b) voer een uitgebreide conditionering van het filter onder praktijkomstandigheden uit, voorafgaand aan de officiële testen (pas zeker geen speciale conditionering toe zoals schoonbranden van het filter).
c) neem verschillende testcycli op, inclusief motorvermogen afhankelijk testen en vollast acceleraties.
d) neem in het onderzoek een aantal verschillende voertuigtypen mee om een beter statistische dekking van het voertuigpark te verkrijgen.

Het is te verwachten dat de type goedkeuringstest voor roetfilter verbeterd kan worden door het rekening houden met de bovenstaand genoemde punten (b, c, d).

Er zijn geen aanwijzingen gevonden dat de NO_2 emissie toeneemt vanwege de montage van retrofit open roetfilters.

De studie is beoordeeld door enkele internationale specialisten. Deze specialisten zijn minder optimistisch over het filtratierendement dan TNO en benadrukken het onacceptabel te vinden van het fenomeen “blow-off”, vanwege de gezondheid- en wettelijke aspecten.

Contents

1 Introduction

Background

In the past few years a great number of retrofit particulate filters are mounted on Euro 2 and Euro 3 heavy duty trucks and passenger cars in the Netherlands, due to a stimulation arrangement since 2006 of the Dutch ministry of spatial planning and environment (VROM). The retrofit soot filters are all so-called “open or half-open” types. This means that not the total exhaust gas flow is filtered. Parts of the flow can pas the filter element without being filtered. This type of filters are also referred to as PM-cat, flow through filter or oxy-cat filter. The advantage of this type of filters is that due to the filter construction it can’t be blocked. This advantage is at the same time a disadvantage. The disadvantage is that filter efficiency is not guaranteed. The efficiency of the filters in-use will mainly depend if and how fast the collected soot will be regenerated, which in turn depends strongly on filter history and driving behaviour.

In the type approval test, a flow through filter has to reduce PM10 emission by at least 50% for heavy duty vehicles, and by at least 30% for light duty vehicles. There are a number of reasons why the average filtration efficiency in the real world can deviate from the filtration efficiency during the type approval test. The most important reasons are:

- The load pattern of the type approval test cycle deviates from the load pattern in day to day real world driving.
- The particulates filter ages in real world (more than accounted for during the type approval test procedure) due to which the performance deteriorates.
- There can be an engine problem with a certain percentage of the vehicles leading to a too high particulate load of the filter.

Objective

The objective of the program was to use available literature to assess the average filtration efficiency of retrofit particulate filters on light duty vehicles in real world day-to-day driving and to investigate the reasons of a possible deviation with the type approval test results (minimum filtration efficiency of 30%).

Plan of approach

The following activities were carried out in this desk study:

- Collecting information
- Analysis of the information
- Review of the results with specialists
- Reporting

This report is structured as follows:

Chapter 2 gives a general background on the operation principles of open particulate filters. In chapter 3, an overview is given of the results of the various experimental studies. In chapter 4 an overall overview is given of the results. In chapter 5, the results are discussed in the light of the principal question of this study, and conclusions are drawn regarding the expected average efficiency and the main factors influencing this. Chapter 6 lists the main conclusions and recommendations.

2 Theoretical background open diesel particulate filters

2.1 Introduction

Diesel particulate filters are devices that physically capture diesel particulates to prevent their release to the atmosphere. A diesel particulate filter can quickly accumulate considerable volumes of soot. The collected particulates would eventually cause excessively high exhaust gas pressure drop in the filter, which would negatively affect the engine operation. Therefore, diesel filter systems have to provide a way of removing particulates from the filter to restore its soot collection capacity. This removal of particulates, known as the filter regeneration, can be performed either continuously, during regular operation of the filter, or periodically, after a pre-determined quantity of soot has been accumulated. In either case, the regeneration of filter systems should be "invisible" to the vehicle driver/operator and should be performed without his intervention. In most cases, thermal regeneration of diesel filters is employed, where the collected particulates are removed from the filter by oxidation to gaseous products, primarily to carbon dioxide (CO_2). Thermal regeneration is schematically represented in Figure 2.

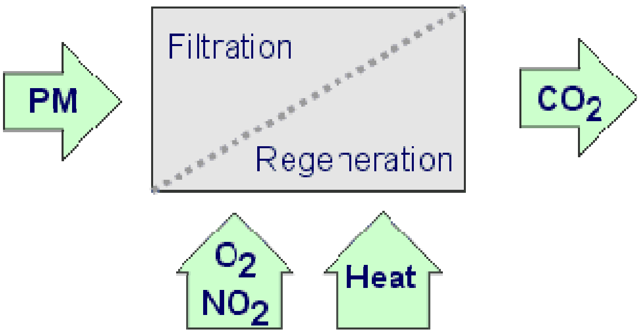


Figure 2. Schematic of Particulate Filter with Thermal Regeneration [10]

To ensure that particulates are oxidized at a sufficient rate, the filter must operate at a sufficiently high temperature and oxidizing gases, such as oxygen or nitrogen dioxide, must be supplied to the filter. In some filter systems, the source of heat (as well as of the oxidizing gases) is the exhaust gas stream itself. In this case, referred to as the passive filter, the filter regenerates continuously during the regular operation of the engine.

2.2 Operation of an open diesel particulate filter

An open or semi-open diesel particulate filter consists in principle of two parts: an oxidation catalyst and a semi-open diesel particulate filter. These filters are so-called passive filters, where the word 'passive' relates to the nature of the activation of the diesel particulate filter's 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. Owing to the semi-open structure, however, the filtration efficiency is limited. Some of the exhaust gas can flow through unimpeded.

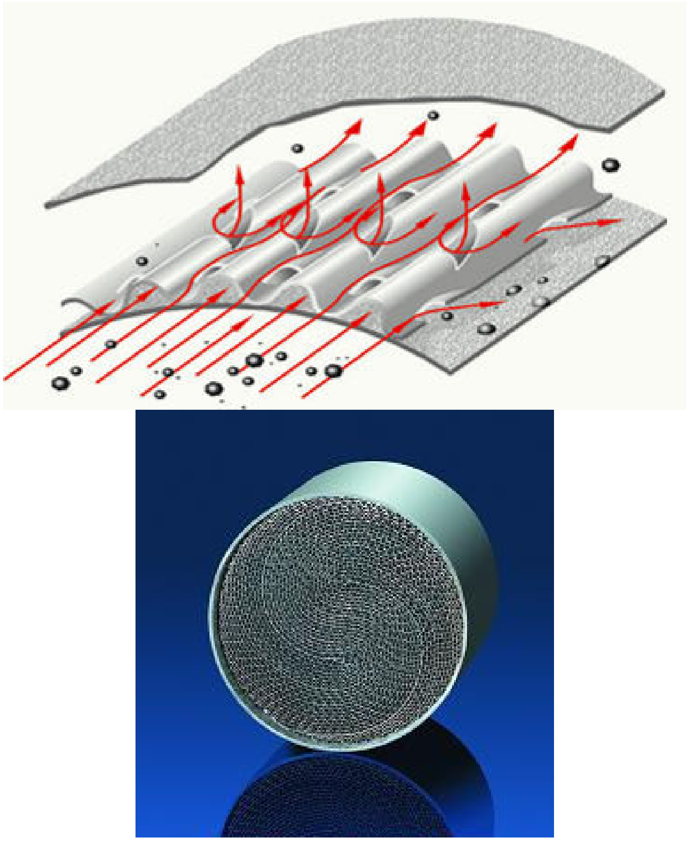


Figure 3. Semi-open structure of a passive particulate filter

When the vehicle is in operation any one of four situations can occur in a open diesel particulate filter; these can also occur simultaneously [10]:

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 filter efficiency or conversion efficiency of the diesel particulate filter, also referred to simply as the efficiency.

During the regeneration of a diesel particulate filter diesel particulates are oxidised. This can occur in the following two ways [8]:

- 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 reaction with 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 slowly 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 particulates react with the oxygen present and burn 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 particulates will react with NO_2 and oxidise. 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 occur.
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.

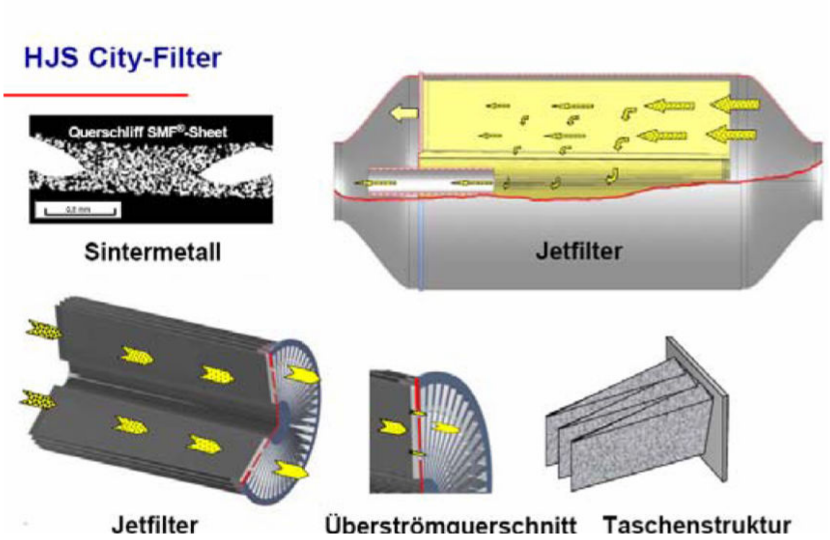


Figure 4. HJS City-Filter is formally an open filter type due to openings at the end of the filter package

2.3 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 oxidized. In general, regeneration commences at 250 ºC and will continue to completion at temperatures in excess of 300 ºC.

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 particulate; this happens when temperatures exceeding 350 ºC are maintained for an extended period.

3 Results of the literature study

For this study, a total of 8 different experimental studies on particulate filters for light duty vehicles was used. The experimental studies chosen are all fairly recent, having been carried out in the period 2006-2008. The key information from all the studies was collected in a data sheet, which is depicted in Table 3. The results of the various studies are described in some more detail below, and results of particular interest to the current study are highlighted.

Table 3: Overview of results of experimental programs with retrofit particulate filters for light duty vehicles and vans

Program	Number of PM filters/cars	Filter driving distance	Share of test results with filtration efficiency		Average efficiency	Test cycle
		[km]	≤ 20%	> 20%	[% }	
VROM toxicity 2007 (TNO)	3 filters / 2*Euro3 & 1 Euro4	>10.000	33%	67%	37.7	NEDC
			0%	100%		CADC
VROM urban delivery van 2007 (TNO)	4 filters (4 brands) / 4*Euro3 (3 brands)		25%	75%	27.5	UDV slow
			0%	100%	49.8	UDV slow*)
			25%	75%	30.3	UDV fast*)
			0%	100%	55.5	UDV fast
			50%	50%	14.8	NEDC *)
Supplier evaluation 2008 (TNO)	5 filters (1 brand) / 6*Euro 3	4000 – 17000	14%	86%	29.3	NEDC
	1 filter / 3*Euro3	12.000	0%	100%	27.7	NEDC
EMPA passenger car 2006	1 filter / 1 vehicle				~40	NEDC
					~40	CADC
Hyundai-Kia evaluation 2006	1-f, Euro 3				40	NEDC
	1-f, Euro 3				39	NEDC hot
	1-f, Euro 3				83	NEDC
VW evaluation 2007	4 filters (4 brands)	New&	0%	100%	46.0	NEDC
		5.000	75%	25%	14.8	NEDC
ADAC evaluation 2008	9 filters (4 brands) / 1*Euro3	New	25%	75%	25.3	NEDC
		1500	25%	75%	23.5	NEDC
		New	0%	100%	55.3	ADAC
		1500	0%	100%	55.0	Autobahn
UBA investigation 2007	4 filters (4 brands) / 1*Euro3	2000 endurance cty cycle	0%	100%	41.0	NEDC
			0%	100%	39.4	NEDC hot
			0%	100%	45.6	FTP 75 hot
		4000 endurance city cycle	12%	88%	45.1	CADCu hot
			75%	25%	17.9	CADCr hot
			0%	100%	45.0	CADCm hot
			25%	75%	24.5	NYCC hot
			50%	50%	27.0	BAB hot

*) after regeneration

The characteristics of the test cycles from Table 3 are presented in Appendix A.

3.1 VROM toxicity 2007 (TNO)

Experimental programme

Here an investigation into the effect of Retrofit Particulate Filters on the Exhaust Gas Emissions of Diesel Passenger Cars[2] took place. The research comprised identical measurements of three vehicles with three different types of retrofit particulate filters. The tests were conducted on a chassis dynamometer on which every vehicle was tested over a standardized driving cycle. This cycle begins with a cold start, following by segments that represent driving in urban environment, on rural roads, and on a motorway. The measurements contained standard emission measurement equipment, a particle size measurement system and different sampling systems for chemical components.

The number of vehicles was restricted to three, two Euro 3 vehicles, a VW Golf and Passat and a Euro 4 VW Passat. The retrofit particulate filters had been in service for at least 10,000 km.

Main observations relevant to the current study

The following conclusions regarding the application of retrofit particulate filters on passenger cars with diesel engines were drawn:

1) The particulate mass emission was reduced by 37% on average over the NEDC cycle (Type Approval test cycle), and by 44% on average over the more real-world oriented CADC cycle. It should be mentioned that the regeneration of the trapped particulates within the retrofit particulate filter was not investigated. Part of the filtered particles may only be stored temporarily, to be released another time.

2) An increase in the total number of particulates could not be proven. The measurements results indicated a decrease in the total number of particles due to application of an open particulate filter, and a more or less constant number for the ultrafine particle fraction (<100 nm). However, for one vehicle the ultrafine particle number increased slightly, at a smaller average particle size.

3) The alleged higher NO_2 emission could not be proven; the measurement results rather indicated a decrease of NO_2 emission.

3.2 VROM urban delivery van 2007 (TNO)

Experimental programme

The project “Efficiency of retrofit diesel particle filters on urban delivery vans”[3] which was carried out for VROM consisted of 2 parts: a) recording of driving characteristics and development of urban delivery van test cycles, and b) emission measurement with 4 vans (2 Ford Transits, a Mercedes Benz and a VW Transporter) with and without retrofit particulate filters (also 4 different types of filters).

Driving characteristics of urban delivery vans were recorded in 3 Dutch cities (Zoetermeer, Leiden and Amsterdam). It appeared that the driving characteristics in the 3 cities were similar.

Parameters like average speed, average acceleration and duration of stops were very close to each other. From the driving data a “slow” and a “fast” urban delivery van cycle were developed. The average speeds are respectively 9.4 and 21.3 km per hour.

The emission measurements with 4 vans were performed during 3 test cycles: the NEDC cycle, urban delivery van slow and urban delivery van fast. In addition during the urban delivery van cycles the vans were tested with “loaded” and with “regenerated” particulate filter. “Loaded” is representative for vans which generally used under urban driving conditions.

Main observations relevant to the current study
The chassis dynamometer emission measurements with 4 vans lead to the following conclusions:

1) With “loaded” particulate filter, the particulate emission reduction with installation of the retrofit particulate filter was about 30% (average of urban delivery van “slow” and urban delivery “fast” cycles).
2) With “regenerated” particulate filter, the particulate emission reduction was about 40% (average of NEDC cycle, urban delivery van slow and urban delivery fast cycles).
3) The results are strongly influenced by one van with negative filtration efficiency (release of particulates stored in the filter) with the “loaded” filter. These results are most likely strongly influenced by the historic engine behaviour (particulate filter loading conditions).
4) One van exceeded the emission limits by 54% to 185% depending on the exhaust gas component. However, this vehicle showed a consistent particulate emission reduction with the retrofit particulate filter. The emissions of the other 3 vans were well below the limits.
5) The retrofit particulate filter also leads to a reduction in NOx, HC and CO emissions. The NOx emission reduction ranged from a few to about 15% depending on the vehicle and test cycle.

One of the 4 delivery vans had with a “loaded” particulate filter negative filter efficiency in NEDC, urban slow and urban fast test cycle.

After an interview with a participant a remark was made of one delivery van when collected and transported to the test lab. This vehicle showed a blow-off when the vehicle accelerated from the urban area onto the motorway.
During the test program no special issues with the vehicle were noted.

3.3 Supplier evaluation 2008 (TNO)

Experimental programme
In a retrofit filter program of a Tier 1 supplier four passenger cars (a SEAT Toledo, a VW Golf and 3 VW Passat’s) were used for emission measurements and to determine open soot filter efficiency[1]. According to the definition all vehicles belong to the same family.
The six Euro 3 vehicles were a randomly selection from cars owners. The cars were equipped with the retrofit filters between 4000 till 17000km driving range before they were collected for testing.
One filter is tested on 3 vehicles of the family. Before an official NEDC test was performed the filters were pre-conditioned. The pre-conditioning programs imply execution of 10 NEDC cycles.

Main observations relevant to the current study

The particulate mass emission was reduced by 29% on average over the NEDC cycle (Type Approval test cycle). The efficiency range measured over the NEDC was 14 till 40%. The tests with a PM reduction of more than 30% showed also a reduction in CO and THC emission. The NOx emission and fuel consumption didn't change.

In this program one filter seems to have a strong degradation. The filter efficiency went to 14%. Also the vehicle emission components CO and THC with the open filter increased compared to the original configuration with only the DOC. The reason of the fast degradation of the filter after only 12000km is not known.

The type approval of a vehicle family with a retrofit open filter, demands from the supplier a thorough technical knowledge from vehicles and open filters. The different results within the formal "family" definition of a specific filter type on several vehicles shows high sensitivity to the precise engine-filter combination.

3.4 EMPA passenger car 2006

Experimental programme

The goal of the project "Retrofit particulate filter for diesel personal vehicles"[9] was to determine to what extent particulate emission with retrofit particulate filters will be reduced and what will be the influence the filter will have on the fuel consumption. For this purpose VW Touran Euro 3 diesel vehicle was measured on a chassis dynamometer with and without particulate filter. To qualify the filters the following tests, NEDC cycle, CADC cycle and constant vehicle speeds at 50 km/h, 80 km/h and 120 km/h are performed.

Main observations relevant to the current study

The results in NEDC show a particulate emission reduction of around 40%. The fuel consumption increased by about 0.1%. In the CADC cycle also a particulate emission reduction of 40% was achieved. A higher fuel consumption of 0.9% was observed in the motorway part of the CADC. In the urban part and rural part the fuel consumption was within the measurement reproducibility.

The particulate emission reduction for the constant vehicle speeds is between 20% and 50%. The fuel consumption increased at 50 km/h with 1.8%, at 80 km/h with 2.2% and at 120 km/h with 3%. Under dynamic conditions such as in the NEDC test, PM efficiencies observed are slightly higher (~40%)

There was a suspicion that mainly the larger PM particles would be collected and the more dangerous smaller particles could pass the filter without hindrance. This wasn't confirmed during the test measurements. The size distribution of particles after the filter measured from 10 to 260 nm is constant.

They concluded that an open filter system is a cost efficient PM reduction device to retrofit diesel engines without any engine H/W changes and additional regeneration calibration application.

3.5 VW evaluation 2007

Experimental programme

Volkswagen Wolfsburg compared 4 open retrofit filters[5], one regarded as VW-original and 3 other brands. The filter efficiency is determined on a chassis dynamometer. The engine out emissions was compared with the emissions after the open filter in the NEDC test.
First the filter efficiency is determined with new filters, than an endurance test is performed. The endurance test consisted of repeated NEDC tests during 5000km. During the endurance test the filter efficiency is measured from time to time.

Main observations relevant to the current study

- The four filters showed a filtration efficiency of 39% to 53% during the NEDC with cold start.
- Only one open filter type showed a filtration efficiency of 30% after 5000 km endurance testing. The other filters show efficiencies around 10% after endurance testing. One filter still didn't reach equilibrium in filtration efficiency.
- The lower filtration efficiency measured during the endurance test for some filters was apparently not found anymore in the NEDC after a blow-off.
- One filter out of four had a somewhat higher NO_2 emission.

3.6 ADAC evaluation 2008

Experimental programme

The German consumers' association ADAC performed a program with a VW Golf Euro 3 vehicle and four open retrofit filters types[6]. The background for this investigation was the discussion about the filter efficiency.
Nine open filters were measured in new state and after 1500km loading during driving in a city. After pre-conditioning the emissions were determined in the NEDC and ADAC BAB (Bundes AutoBahn) cycle.

Main observations relevant to the current study

- To judge the filtration efficiency of a retrofit open filter the NEDC cycle is considered inadequate.
- The open filters show an efficiency in NEDC after loading between 18% and 60% with one supposed blow-off. In the ADAC BAB the average filter efficiency is around 45%.
- The NOx emission is equal with or without open filter. The NO_2 emission is 30% lower after the filter.

3.7 UBA investigation

Experimental programme

Four open filters were tested on a passenger car sponsored by UBA[7]. The standard German filter test procedure for open filters was performed, but moreover, the response to various operating conditions was tested including worse case situations.

Main observations relevant to the current study

The filtration efficiency ranged from about 0% to 65% depending on filter type and test cycles.

Comparing the differences of the four concepts, one filter has so much particulate storage capacity that it never needed to be regenerated during the actual testing program of less than 2000km. The overall performance of this filter was the best in the different driving cycles. The other three filter concepts had a calculated particulate storage between 400km and 1500km.

The filtration rate scatter indicates that conditionings change from test to test.
These observations indicate that filter conditioning is unsuitable for systems evaluation. During conditioning, deposits are removed. Thus the filter is restored to a better state than after a period of city use. Without assessing the conditioning phenomena, the results are unrealistically distorted.

All systems attain or exceed the required range of 30% in the NEDC cycle. Other cycles very often show worse efficiencies, due to greater dynamic, much lower load or very high motorway speeds. These operation conditions are realistic, too. Hence, system evaluation based on NEDC alone is considered to be inappropriate. In some cases measured efficiencies are extremely low, especially for the particulate mass evaluation. The only explanation is blow-off phenomena, which occur in these cycles and appear as emitted mass.

NO_2
If the load varies at a constant vehicle speed of 85 km/h, the NO_2 emission (as % of NOx) is affected as follows due to the installation of the particulate filter:
- Filter A: slight degrease at lower load: NO_2 from 35% to 25% (of NOx).
- Filter B: decrease of NO_2 over the whole load range from approx 40% to approx 20%.
- Filter C: quite an increase at higher loads. Above an exhaust temperature of 275ºC, NO_2 increases from approx 5% to approx 25%.
- Filter D: increase of NO_2 at lower loads from approx 37% to approx 45% and at higher loads from approx 15% to approx 27%.

Recommended test methods

This program suggest that fundamental rethinking is needed of the following two test aspects. Firstly, the testing of retrofit filters in standard driving cycles. Secondly, the conditioning routine of expelling the accumulated particles. More suitable test procedures or worse-case protocols, which scrutinize the extreme operating situations at lighter loads, at high space velocities, and in dynamic operating conditions.

They concluded that tested retrofit systems which attained the minimum 30% efficiency in the new state, deteriorated substantially in driving cycles comprising lower loads, higher dynamics or higher space velocities. Moreover, these open filters tend to particulate deposition and stochastic release, which cause high smoke emissions unacceptable in traffic situations. The test procedure must be enhanced to include those aspects. That would provide the guidelines for a retrofit technology, which ensure sustainable emissions curtailment.

3.8 Blow off of stored particulate mass

Several cases of high visible smoke are reported with (full load) accelerations. This is probably "blow-off" of stored particulates within the filter. Apparently the particulates come lose and are emitted.
Several sources report this sudden blow-off of particulates in practice under circumstances with high accelerations. One delivery van of the "VROM delivery vans 2007" [3] program had a blow-off when it was collected at the client and drove to TNO for testing. Also Dipl. Ing A.Mayer has looked at the phenomenon and reported about the blow-off/ store-and-release [7]. In the paper he mentioned the video clips taken during the vehicle was run at 40km/h on the chassis dyno and suddenly accelerated. Photographs from the video clip are shown in Figure 6. The test was repeated three times with the same result.

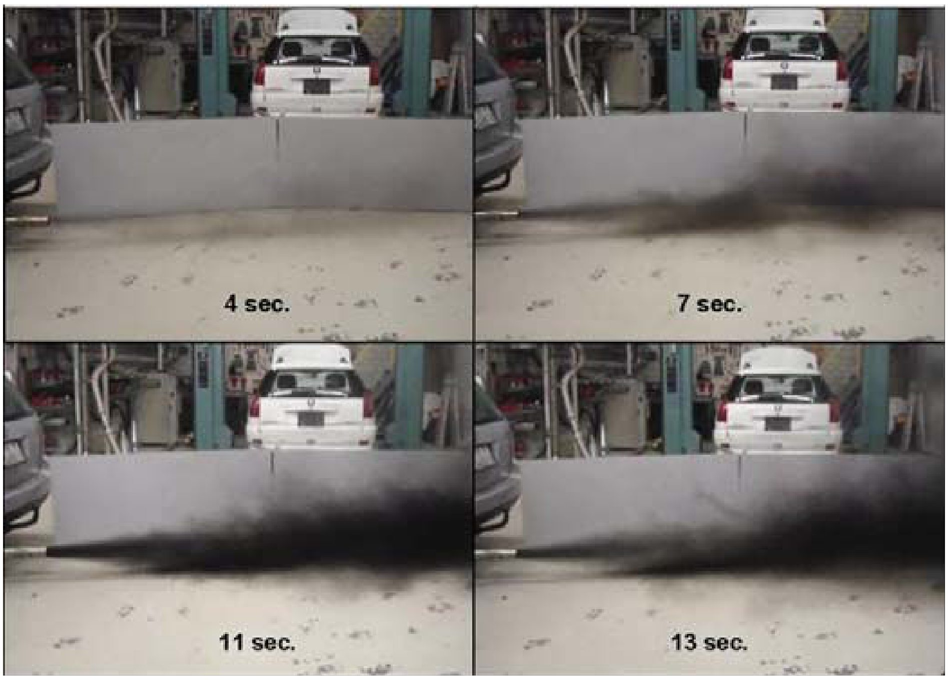


Figure 6. Blow-off during full load acceleration after 5000km city driving at average speed of 30km/h [7]

ADAC did an extensive program with 9 filters. Refer to [6] and pg 3.6. This included extensive loading of the filter during 1500 km under city conditions (max speed 60 km/h). After this loading 6 out of 9 filters (4 different types) 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. 1500 km under city conditions is an extreme case which would only happen in the Netherlands for example with certain delivery vehicles or other vehicles which rarely leave the city. On the other hand it does show that most, if not all, of these filters cannot be safeguarded against a sudden release of stored particulates.

During a discussion, which rose after the presentation of a QualityControl and In Search of Conformity (ISC) programme by a big European car manufacturer, it appeared that at the execution of its ISC programme the car manufacturer takes special measures for preconditioning the cars in advance of the emission test procedure in some cases.

The manufacturer performs a special preconditioning schedule for its diesel cars in the case the selected cars have driven more than 50% under urban driving conditions. The share of urban driving is determined by means of a questionnaire in which the owner, next to urban driving share, has to fill in a long list of technical information about the car and its maintenance history.
The special preconditioning consists of a few fast accelerations in 3rd and 4th gear in the case a highway is in the vicinity of the test facility. If there is no highway nearby the accelerations are done as fast as they are allowed/possible on the chassis dynamometer. The special preconditioning is said to stabilize the emission behaviour of the vehicle in question. After the special preconditioning, the normal preconditioning is performed on the chassis dynamometer (3 x EUDC + soak at 20ºC) before the actual MVEG-B cycle is driven and emissions are sampled. This means if this is common practice the chance that a blow-off will take place during a test cycle will be minimized.

Regeneration:

The only remedy against blow off is sufficient regeneration. For open filters guidelines of continuously regenerating wall flow filters can be used. Sufficient NO_2 and exhaust gas temperature is needed to regenerate the stored particulate mass. The rules of thumb vary from 50% of the time above 250°C to 20% of the time above 275°C. To some degree this is also dependent on the NOx / PM ratio. The higher the ratio the more NO_2 in relation to the PM mass.

In the Netherlands the km distribution for diesel passenger cars between different road types is as follows:
- 28% city
- 31% rural / local roads
- 41% motorway

Looking at publications with exhaust gas temperatures of diesel passenger cars, we came to the following (underfloor) exhaust gas temperatures [11, 12, 13]:
- 80 km/hr: around 250°C
- 90 km/h: around 275°C
- 100 km/h: around 300°C
- US FTP cycle: 20 – 350°C (average 200 - 230°C)
- European NEDC: 20 – 350°C (average 200°C)

Taking into account the Dutch mix of city, rural and motorway driving distances, regeneration conditions are reasonable: probably during about 50% of the kilometers, regeneration can take place. It can also be concluded that regeneration during city driving is generally insufficient.

4 Overview of results of particulate filter efficiency

An overview of the average filtration efficiencies is presented in Table 4 and 5. Table 4 shows the range of efficiencies reported in the different studies, whereas Table 5 gives the average efficiencies for the type approval test cycle and the other test cycles These are calculated based on the information in Table 2.

Table 4: Efficiency range indication per program

Program	Eff. range indication %
VROM toxicity 2007 (TNO)	20 to 56
VROM delivery van 2007 (TNO)[1]	-72 to 91
Supplier evaluation 2008 (TNO)	14 to 40
EMPA passenger car 2006	40
Hyundai-Kia evaluation 2006	39 to 83
UBA investigation 2007	-1 to 63
VW evaluation 2007	7 to 53
ADAC evaluation 2008	-23 to 70

[1] Fluctuation of engine out emission may be part of the reason, for wide range

Table 4 shows that there is a very large range of reported efficiencies in many of the studies. Note that many of these extremes do not reflect steady state conditions.

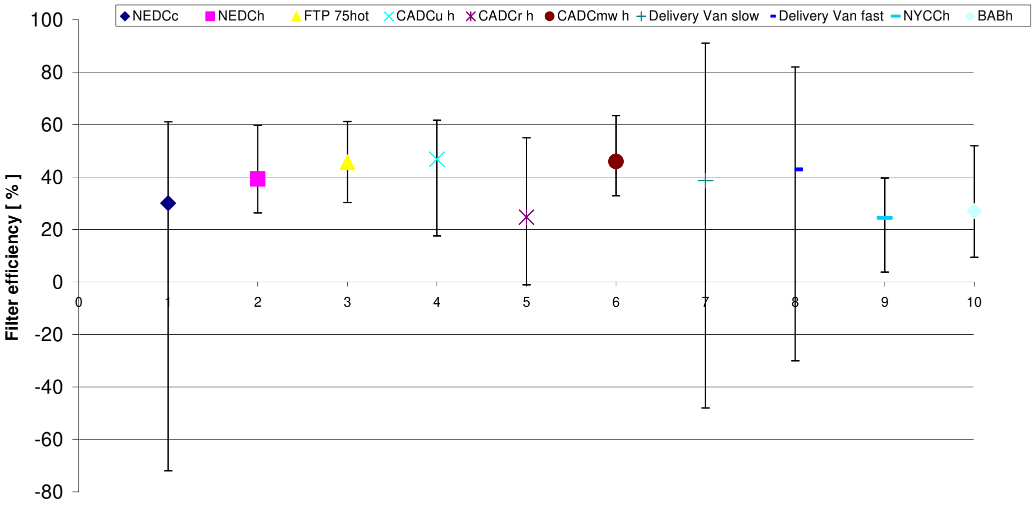


Figure 5: Range in filtration efficiencies of retrofit particulate filters found for different test cycles

The experimental data shown in Figure 5 shows a large variation in filtration efficiencies depending on the test cycle. In real world driving similar large variations are expected with these types of retrofit filters.

Table 5: Overview of filtration efficiencies with retrofit open particulate filters for light duty vehicles

Test cycle	Average filtration efficiency	Total number of test results	% of test results with filtration efficiency < 20%	% of test results with filtration efficiency < 30%
Type approval test: New European Driving Cycle with cold start (20°C)	30%	38$^{1)}$	21%	42%
Other test cycles: mostly warm start (including NEDC with warm start)	40%	87$^{2)}$	17%	30%
All test cycles cold and warm start	37%	125	18%	34%

1) about 20 different vehicle-filter combinations

2) about 50 different vehicle-filter-test cycle combinations

From Table 5 it can be concluded that the average filtration efficiency during the type approval test cycle is 30%. This is equal to the minimum type approval requirement. The variation in test result is however large, i.e. with 21% of the test, the filtration efficiency was lower than 20%.

Other test cycles used were mainly performed with a hot engine at the start of the test. The average efficiency during these tests (including NEDC with hot start) is 40%, which is substantially higher than during the type approval test (NEDC with cold start).

5 Discussion

5.1 Relation between real world and type approval filtration efficiency

In this study, data has been collected and average efficiencies have been calculated. The question is to whether the calculated numbers are really representative for the efficiency that is obtained in real world day to day driving. Two potentially important mechanisms that can lead to lower efficiencies in real world than estimated based on the literature, are blow-off and ageing. These are discussed below.

Blow-off

In real world driving, there can be driving conditions which are not sufficiently represented by the test cycles used. This is because the test cycles are generally a representation of an average driver in an average vehicle. For example the cycles do not taken into account that cars can have very different maximum power ratings, also relative to the weight of the vehicle. A highly powered car never has a full load acceleration during the test cycle developed for an average vehicle and driver. In reality these full load accelerations do of course (frequently) happen for example when a car enters the motorway. Several sources report sudden blow-off of particulates in practice If this only happens with full load accelerations, this would be missed by most of the stronger than average powered vehicles during most of the test cycles. However if this would be a serious problem, you would expect to see a difference in results between the more gentle and more aggressive test cycles. The CADC, NYCC and to a lesser extend the FTP-75 are the more aggressive test cycles. This is partly the case, mainly for the urban and road part of the CADC cycle. In these parts of the cycle some filters show efficiencies of less than 10%. Of course it is still likely that a certain percentage of vehicles which do have this blow-off problem would not show this problem to the same extent during the test cycles. Also when the blow-off takes place, it is not certain this will be measured correctly by the normal measuring systems. This is because blown-off particles can be larger agglomerated particles (>1 µm) above the cut-off point of the measuring system. It can be concluded that many uncertainties remain. There is no easy way of quantifying which percentage of vehicles would (regularly) encounter this blow-off problem and to what extent this would affect the average filtration efficiency of those vehicles. The possibility of blow-offs is seen as one of the main draw backs of these filter types.

Preconditioning prior to testing

Another issue is the preconditioning that is generally done just prior to the formal test(s). The type of preconditioning cycle and the number of repetitions vary. Examples are MVEG-B (just once), ten times MVEG-B (this is according to the type approval for the retrofit filters) and three times EUDC. The higher the load during the preconditioning test, the “cleaner” the filter and the higher filtration efficiency that can be expected. It is important that the preconditioning reflects the average type of load pattern, which is normally seen in real world driving. When started with a new filter, the preconditioning should be long enough such that the particulate mass stored within the filter is stabilized. Depending on the type of filter, this may take days or weeks.
If a filter from the field is taken, it should be considered to skip any preconditioning and start right away with formal tests. The tests can be repeated in order to judge the repeatability and/or stabilisation on a certain level.

It is also recommended to include several different test cycles including a test cycle with engine power or power divided by vehicle mass dependent parts and full load accelerations.

Ageing

Another possible difference between the collected data and real world is the number of kilometres the filters are mounted on vehicles. A longer distance can lead to aging of the catalyst and to a collection of relatively difficult to regenerate particulates and ash (i.e. ash from lubricant additives). The aging can also result in a lower NO_2 concentration which affects the regeneration and consequently the average quantity of particulates stored within the filter. This can result in a lower average filtration efficiency. The filters used for the test programs were from new state till 17000 km or more on the vehicle. It is however a relatively short distance compared to the yearly average driving distance of diesel passenger cars (about 37.000km).

Because of the phenomena described above (especially blow-off and possible influence of driving distance or aging of the filter), it can be concluded that the presented efficiencies should be seen as the most optimistic value of what happens in practice. In reality the average values can be lower.

Large variation in test results

The individual test results (presented in Appendix B) on which the tables 2 and 4 are based show a large variation in filtration efficiency depending on the vehicle-filter combination and test cycle. Also before and after a “regeneration” (high load period) results in large differences.
It is believed that the large variation in test results reflects what is happening in practice. This is because of the many indications that the filtration efficiency is dependent on the average soot load within the filter with these type of filters. The soot load within the filters is –such as with all continuously regenerating filters- dependent on the historic load pattern and the equilibrium between the amount of soot emitted by the engine and the amount of soot regenerated per second. This regeneration is a function of temperature. The average temperature is dependent on the load pattern but also on the temperature level of the engine and the temperature loss between engine and particulate filter. This means that also within one family of cars for which one filter type can be applied, there will be differences in regeneration, in average soot load and consequently also in filtration efficiency. As a result, it is advised to pay considerable attention to find the worst case configuration within the family definition.

Driving cycles

Another question is which driving cycle would best represent the real word driving. The test cycles other than the NEDC are often seen as more representative for real world conditions than the NEDC. This is because of the low dynamics and low average load of the NEDC. It should be noted however, that the NEDC tests were generally with a cold engine at the start (20°C) while the other cycles were generally run with a warm engine at the start of the test. A cold start is a realistic driving condition which is missed with the other test cycles. The best possible conclusion at this stage is that the real world efficiency is probably somewhere in the range between the result of the NEDC (type approval) and the average results of the other test cycles. This is in the range of 30% tot 40%. Of course taking notice of the earlier remarks that there are issues (possible blow off and driving distance/aging) which will influence this in a negative way.

In general it can be concluded that there is no proof, that the average filtration efficiency of retrofit open particulate filters for light duty vehicles in practice (real world) is substantially lower than the type approval requirement of 30%. It has however been demonstrated that a significant percentage of the vehicles (20%) will have a filtration efficiency of lower than 20% (table 5).

Note on test methods

It is recommended to update the test methods for (open) retrofit particulate filters, also for type approval of these filters. This is primarily because of the storage an release phenomenon of particulates within the filter structure (due to the specific design of open filters).

In order to obtain realistic filtration efficiencies for real word driving, it is recommended to develop a test procedure which would include the following:

- sufficient aging and stabilisation of the particulate mass stored in the filter under normal engine load conditions.
- No preconditioning just prior to the formal tests, especially no preconditioning that would release stored particulates.
- Several test cycles including parts with engine power dependent and full load accelerations.

NO_2

The diesel passenger cars are standard equipped with diesel oxidation catalyst (DOC), which generally lead to an increase of NO_2 emission compared to engine out. Some of the particulate filters use this same oxidation catalyst and others come with there own (integrated) oxidation catalyst. This may lead to a difference in NO_2 formation (from NO). Also the particulate filter part will consume some of this NO_2 for the particulate oxidation.

Looking at the results, information on NO_2 is limited. Some filters show a reduction in NO_2 compared to the standard configuration, while others showed an increase. In general a reduction is seen more frequent than an increase. This leads to the conclusion that there is no indication that the average NO_2 emission will rise due to the installation of the retrofit filters.

5.2 Review of the report by specialists

Dipl.Ing. A. Mayer and Professor Dr. J. Czerwinski have reviewed the report.

Mr Mayer and Mr Czerwinski have more than 15 years experience with the application of retrofit particulates filters including retrofit open particulates filters.

They both have the opinion that the conclusions of the report are too mild. In reality phenomena such as the blow-off of stored soot is a more serious problem and some other draw backs are not mentioned.

Mr Mayer and Mr Czerwinski emphasise the following:

- There is no way to safeguard against stochastic particulate blow-off.
- Blown-off particulates may not be included in the measurements because of their possible larger size and cut-off points of the usual test equipment. I system which can blow off should not be allowed at all and is illegal.
- The time of measurement in the test cycle is much shorter than the storage time of soot in the filter (1000 – 10000 km storage capability). So with a relatively clean filter, you will not detect a problem in the normal test procedure.

- Regeneration of stored PM takes place above 100 km/h with the Passat TDI tested at the University of Applied Sciences Biel-Bienne.
- Metal oxides are not trapped within the filter. These are smaller than 30 nm and may be 100 times more toxic than soot particles.
- Indicated PM reduction is close to the PM reduction of the diesel oxidation catalyst (which is about 25%). But this is only a reduction of condensates (condensed hydrocarbons), which is useless. Objective should be a reduction of black carbon (elementary carbon).
- NO_2 will go up while PM reduction is uncertain. NO_2 has a negative health impact.
- Many applications of open particulate filters on trucks and buses were not successful and the filters were even removed from the vehicles. This was the case with bus fleets in Munich and Graz and with fleets in Japan (3000 vehicles) and China (EPA test fleet in Beijing).

TNO sees some contradictions with the collected data. The data does not show an increase in NO_2 on the average (refer to paragraph NO_2 above). Also an oxidation catalyst is present on all standard vehicles. Still the data indicates a reduction in particulate emission with installation of the retrofit DPF.

6 Conclusions

Real world and type approval filtration efficiency

A literature study has been conducted with respect to the filtration efficiency of retrofit open particulate filters for light duty vehicles. This leads to the following conclusions:

a. Experimental data shows that the average filtration efficiency during the type approval test cycle is about 30%. This is the same value as the type approval requirement (30%). The variation in test result is however large, i.e. with 21% of the tests, the filtration efficiency was lower than 20%.
b. Based on the data collected, the average real world filtration efficiency could be between 30% and 40%. The efficiency will however be lower because of two effects which are not sufficiently investigated: 1) sudden blow-off of stored soot in the retrofit filter and 2) aging of the retrofit filter.
c. Blow-off of stored soot is seen as the most serious draw back of retrofit open particulate filters. It is expected that most filter types will show this problem if driven for a long time (>1000 km) at low average speeds such as city driving.

Following these points, the average real world efficiency remains uncertain. There is however no hard evidence, that the average real world filtration efficiency in practice (real world) is substantially lower than the type approval requirement of 30%. It has however been demonstrated that a significant percentage of the vehicles (indication 20%) have a filtration efficiency of lower than 20% including negative efficiencies with blow-offs of stored soot.

Large variation in test results

The experimental data show a large variation in filtration efficiencies depending on the test. In real world driving similar large variations are expected with these types of retrofit filters.

The following reasons have been found for the large variation in test results:

- High sensitivity to the driving conditions of the vehicle during the days and weeks before the test. From the design point, the filtration efficiency is very sensitivity to the amount of soot stored in the filter. The amount of soot within the filter is dependent on the driving conditions.
- High sensitivity to the precise engine-filter combination, also within the formal “family” definition of a specific filter type.

NO_2

There is no indication that the average NO_2 emission will rise due to the installation of the retrofit filters. The available data indicates more frequent a reduction in NO_2 than an increase.

Recommendations

A better confirmation of the average real world filtration efficiency can be obtained by additional testing with retrofit particulate filters which are mounted for a longer period on the vehicle (1 year or longer). The following approach is recommended:

a) select vehicles from which the retrofit filters were mounted for a longer period on the vehicle (1 year or longer).

b) do extensive real world conditioning of the filter (without special preconditioning or “cleaning”) just prior to the formal tests.
c) include several test cycles including engine power dependent parts and full load accelerations.
d) investigate a number of different vehicle types to obtain data with a better statistical coverage of the vehicle fleet.

It is believed that the particulate filter type approval test can be improved by incorporating these same items (b, c, d).

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8 Signature

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A Additional characteristic data of test cycles

Table A: Characteristics of test cycles. Source A. Mayer [7] and TNO [3]

test cycle	full name	overall length	average speed	max. speed
		[m]	[km/h]	[km/h]
NEDC, ECE part		4073	18.8	50.0
NEDC, EUDC part		6955	62.6	120.0
NEDC, complete		11028	33.6	120.0
FTP-75, 1st part		5777	41.2	91.2
FTP-75, 2nd part		6209	25.8	55.2
FTP-75, 3rd part		5777	41.2	91.2
FTP-75, complete		17763	34.1	91.2
CADC urban	Common Artemis Driving Cycle - Urban	4870	17.7	57.7
CADC road		17272	57.5	111.5
CADC motorway		28736	97.0	131.8
NYCC	New York City Cycle	1896	11.4	44.6
BAB, 1st part	Bundes AutoBahn, 1st part	12963	106.8	124.2
BAB, 2nd part		9554	114.6	138.6
BAB, 3rd part		10112	138.4	162.0
BAB, complete		32628	117.5	162.0
Delivery van:				
Urban slow		3152	9.4	44.2
Urban fast		7111	21.3	69.4

Table B: Characteristic data of used driving cycles

	max accel.	max decel.	% of accel.	% of decel.	% of idle
	[m/s²]	[m/s²]	[%]	[%]	[%]
NEDC, ECE part	1.042	-0.992	18.5	17.4	30.8
NEDC, EUDC part	0.833	-1.389	25.8	10.5	10.0
NEDC, complete	1.042	-1.389	20.9	15.1	24.8
FTP-75, 1st part	1.806	-1.500	34.3	35.4	19.6
FTP-75, 2nd part	1.889	-1.806	35.9	34.5	19.5
FTP-75, 3rd part	1.806	-1.500	34.3	35.4	19.6
FTP-75, complete	1.889	-1.806	35.0	35.0	19.6
CADC urban	2.861	-3.139	33.5	32.5	30.3
CADC road	2.361	-4.083	39.8	39.8	3.3
CADC motorway	1.917	-3.361	39.9	34.7	1.7
NYCC	2.682	-2.637	28.1	31.6	40.3
BAB, 1st part	0.750	-1.000	32.0	29.7	0.0
BAB, 2nd part	0.750	-1.250	58.7	25.7	0.0
BAB, 3rd part	0.250	-1.250	51.0	21.7	0.0
BAB, complete	0.750	-1.250	45.0	26.4	0.0
Delivery van:					
Urban slow	2.200	-2.800	23.0	22.0	53.0
Urban fast	1.790	-2.830	33.0	31.0	30.0

B Test cycle data

# Tests	1	2	3	4	5	6	7	8	percentage		**Average**	percentage	
UBA investication 2007									≤ 20%	> 20%	[%]	< 30%	≥ 30%
NEDCc	42,0	47,2	55,7	55,0	38,1	33,3	31,3	25,0	0,0	100,0	**41,0**	13,0	87,0
NEDCh	37,9		59,8		26,4		33,3		0,0	100,0	**39,4**	25,0	75,0
FTP 75hot	42,1	46,8	60,5	61,2	37,9	40,3	30,3	45,9	0,0	100,0	**45,6**	0,0	100,0
CADCu h	26,4	47,1	60,5	61,7	17,6	52,9	44,4	49,9	12,00	88,00	**45,1**	25,0	75,0
CADCr h	2,9	13,3	49,6	43,9	10,8	-1,1	17,3	6,8	75,00	25,00	**17,9**	75,0	25,0
CADCmw h	37,6	40,8	63,4	59,9	32,8	33,4	44,3	48,1	0,00	100,00	**45,0**	0,0	100,0
NYCCh	3,8	27,7	39,6	27,2	22,6	17,0	25,0	33,2	25,00	75,00	**24,5**	75,0	25,0
BABh	16,5	28,4	41,2	51,9	18,9	9,4	19,2	30,8	50,00	50,00	**27,0**	63,0	37,0
Supplier evaluation 2008													
NEDCc	13,7	21,7	24,9	31,3	36,4	37	40,2		14	86	**29,3**	43	57
VROM Toxicity 2007													
NEDCc	48	20	45						33	67	**37,7**	33	67
CADCu h	55	52	47						0	100	**51,3**	0	100
CADCr h	51	55	22						0	100	**42,7**	33	67
CADCmw h	50	56	39						0	100	**48,3**	0	100
CADC total	51	54	38						0	100	**47,7**	0	100
VROM urban delivery van 2007													
NEDCc	-72	14	56	61					50	50	**14,8**	50	50
Urban slow Loaded	-48	79	21	58					25	75	**27,5**	50	50
Urban slow after regen	43	91	21	44					0	100	**49,8**	25	75
Urban fast Loaded	-30	77	52	22					25	75	**30,3**	50	50
Urban fast after regen	43	82	52	45					0	100	**55,5**	0	100
VW evaluation 2007													
NEDCc	53	44	48	39					0	100	**46,0**	0	100
NEDCc endurance	30	10	12	7					75	25	**14,8**	75	25
ADAC evaluation 2008													
NEDCc	57	25	42	-23					50	50	**25,3**	50	50
NEDCc endurance	19	24	24	27					25	75	**23,5**	100	0
ADAC	59	70	37	?					0	100	**55,3**	0	100
ADAC endurance	42	52	70	56					0	100	**55,0**	0	100
EMPA passenger car 2006													
NEDC	40										**40,0**		
ADAC	40										**40,0**		
VKM Hyundai-Kia evaluation 2006													
NEDCc	40	83									**61,5**		
NEDCh	39										**39,0**		