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Properties of Partial-Flow and Coarse Pore Deep Bed Filters proposed to reduce Particle Emission of Vehicle Engines

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ABSTRACT

Four of these Particulate Reduction Systems (PMS) were tested on a passenger car and one of them on a HDV. Expectation of the research team was that they would reach at least a PM-reduction of 30% under all realistic operating conditions. The standard German filter test procedure for PMS was performed but moreover, the response to various operating conditions was tested including worst case situations. Besides the legislated CO, NOx and PM exhaust-gas emissions, also the particle count and NO_2 were measured. The best filtration efficiency with one PMS was indeed 63%. However, under critical but realistic conditions filtration of 3 of 4 PMS was measured substantially lower than the expected 30 %, depending on operating conditions and prior history, and could even completely fail. Scatter between repeated cycles was very large and results were not reproducible. Even worse, with all 4 PMS deposited soot, stored in these systems during light load operation was intermittently blown-off. Due to these stochastic phenomena the behavior of these systems is hardly predictable. Furthermore the provision of NO_2, through catalysis ahead of the filter or in the filter matrix, is inherent in these systems. Some of this secondary NO_2 is emitted. Cost/benefit ratio is high compared to full-flow filters and Diesel engines equipped with partial-flow filters are inferior to SI engines regarding global warming potential. Based on these findings it is concluded that the sustainable performance of partial-flow filters is not yet determined.

INTRODUCTION

Full-flow filters (FFF) have become a standard. Wall flow honeycomb filter media, used in this concept are reaching filtration efficiencies exceeding 99.9% [1]. These are fitted ex-factory to European passenger cars and USA trucks [2,3]. Retrofitting onroad heavy-duty (HD) vehicles and offroad construction machines is also very successful [4]. Retrofit filter systems with active regeneration, a prerequisite for dependable operation, are however still rather complex, bulky and costly and therefore prohibitive for retrofitting in-use passenger cars. Nevertheless to diminish emissions, in countries with a high Diesel car population, environmental policy requires simpler and less costly retrofit systems. These shall enable at least 30% curtailment of the particle mass (PM) emission, and correspondingly benefit air quality in the Low Emission Zones. The German [5] specification, which the Netherlands and other countries have adopted, is based on a weighted average PM emission reduction measured over 3 New European Driving Cycles (NEDC) in the as new state, after 2000 km, and after 4000 km operation.

This paper describes the investigation of 4 commercially available partial-flow filters. These were tested according to the German NEDC based criteria. Moreover, since the NEDC is regarded as not reflecting real world city driving conditions [6], tests were performed in various other driving cycles and at other realistic operating conditions. In addition to PM, the investigation also measured the emission of solid nano-particles in the size range 10 nm – 400 nm, and of the systems inherent NO_2 emissions.

BASIC PROPERTIES OF FULL-FLOW (FFF) AND PARTIAL FLOW FILTERS (PFF)

The filtration response of the full-flow [7,11,21] filter and the partial-flow filter [8,9,10] is very extensively published. Fig. 1 shows schematically the basis concept of the full-flow filter and the partial-flow filter.

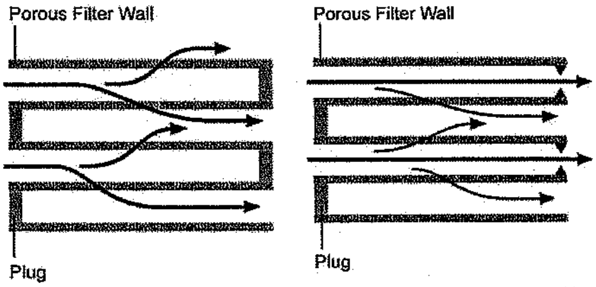

Fig. 1: Schematic of full-flow Filters FFF (left) and partial flow filters PFF (right).

Whereas in FFF [11] all exhaust gas has to pass through the fine porous walls of the filter, in the PFF [10] some flow is allowed to pass unfiltered. The ratio of the two flows PFF/FFF may be designed to be 0.5, when clean but will vary with soot deposition and may reach very low values when the filter wall gets plugged, resulting in corresponding low overall filtration.

Figure 2 shows some of the basic characteristics of the FFF and PFF concepts. Figure 2a shows the characteristics of the FFF, with this design filtration is improved with soot loading, approaching nearly 100% after a few minutes of operation. Back-pressure also increases thus continuous or discontinuous regeneration is required. Figure 2b shows the characteristics of the PFF; these are clearly different. In the PFF design filtration efficiency decreases with soot loading and sudden blow off can happen where all stored material is lost. Backpressure however remains low.

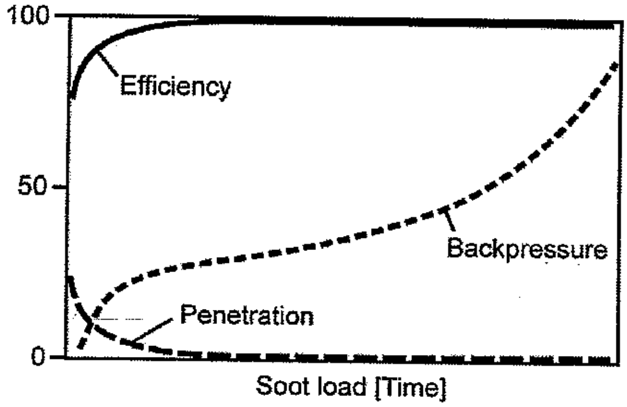

Fig. 2a Basic properties of full-flow filters (FFF)

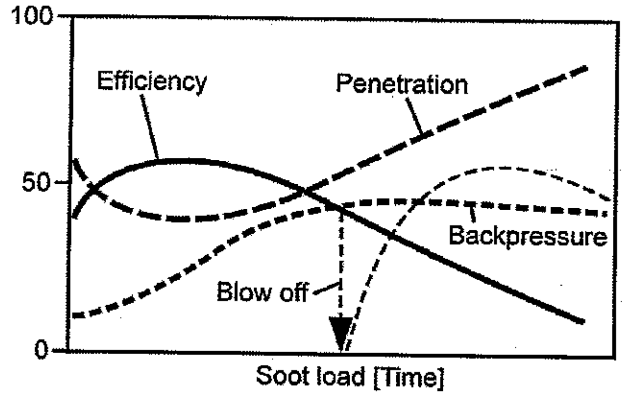

Fig. 2b Basic properties of partial flow filters (PFF)

With the FFF backpressure increases when soot loading and can become plugged if not regenerated properly while backpressure with PFF levels out with decreasing filtration efficiency. The PFF can clean itself by releasing stored soot to avoid plugging – which is undesirable from an environmental point of view.

The well-established full-flow filters, of the wall through-flow type, have porous cell walls, through which the exhaust gas passes at very low velocities (a few cm/s). Thus diffusion effects occur in the very small pores (about 10 µm). Such filters attain filtration efficiencies above 99.9% for all particle sizes prevalent in the exhaust-gas. The large surface area of these filters facilitates catalyst coating. The filtration efficiency of full-flow filters usually increases from 70-80%, in the new state, to the maximum value within minutes of engine operation. The maximum filtration rate is sustained during the filter life. The regeneration process periodically combusts the deposited soot particles. The full-flow filter also dependably intercepts incombustible ash particles from engine wear and combustion of lubricating oil. The back-pressure initially increases rapidly, due to particle deposition in the filter walls; the back-pressure then increases linearly during soot-cake build up and finally rises rapidly if the filter becomes fully loaded. The consequent high back-pressure is not permissible. Hence, the filter must be regenerated before the back-pressure exceeds about 200 mbar (approx. every 1,000 km). Subsequently, after 2 - 3,000 operating hours the filter must be cleaned of ash. The filter is then fully reusable.

Prerequisites for effective regeneration are monitoring the back-pressure and initiating the regeneration through raising the temperature until ignition of the deposited soot is triggered. Engine management (delayed fuel injection, diminishing air through-flow) can raise the exhaust temperature. Other possibilities are heating after the engine, e.g. burner, catalytic combustion or electrical heating. These methods are expensive and relatively complex but they are required unless the exhaust temperature is high enough to guarantee continuous regeneration supported by catalysis [11,35].

Partial-flow filters are essentially open cell systems, whose walls, too, are porous materials. Part of the inlet gas exits the system directly, without surrendering particles. The main channel flow has a very high velocity. The partial-flow through the filter walls is at a reduced flow rate, so that filtration can occur within the porous walls and on their surfaces. Here, too, soot deposition occurs that supports the filtration of ultrafine particles. The soot deposition in the filter medium however inevitably shifts the ratio of partial-flow to full-flow, i.e. more gas exits unfiltered. Thus the filtration efficiency decreases. The claimed advantage is that such a construction tends not to clog. Increasing soot deposits on the walls narrows the channels thereby raising the flow forces, until the deposited soot is blown off in a short but intensive smoke puff. That process then reiterates - an effect which is well known and described as store-and-release [12]. Any actual curtailment of particle emissions only occurs when the intercepted soot is converted to CO or CO_2. The temperature in a passenger car exhaust is too low for oxygen to react with the soot. The only possibility is to utilize NO_2 for regeneration, a process, which may start at temperatures as low as 230 °C if sufficient NOx is available. Hence, a very effective oxidation catalytic converter, coated with platinum, must be mounted ahead of the filter. This oxidation catalyst converts part of the engine NO into NO_2. NO_2 will be decomposed again and will release an oxygen atom, which can combust soot above 230°C. This is a slow process and therefore only oxidizes deposited soot. The stoichiometric mass ratio of for this process is at $NO_2/C = 7.6$ if CO_2 shall be formed. Experience indicates a 2-3 times higher NO_2 production is necessary, since not all NO_2 can react with soot [35]. The four critical parameters of partial-flow filters therefore are: filtration response, NO_2 availability, adequate temperature and storage capacity.

ON-ROAD TEST

The German test procedure was performed as per Annex 26 [5] of the German traffic certification directive. The filtration performance is assessed during the NEDC test in the as new state, then after 2000 km of light load city operation and then again after further a 2,000 km. Depending on the emission level of the vehicle, the distance can be extended to 2,500 km. The mileage accumulation can be performed on the road, or on the chassis dynamometer. The average speed is between 25 and 35 km/h but never exceeding 70 km/h. The idling time is > 7% of operating time. The duration between 50 and 70 km/h is <10% of operating time. The highest exhaust temperature is < 300°C. The measurements on the chassis dynamometer are done after conditioning (2-3 times, Part 2 of the NEDC). A weighted average, which overweights the results after the city driving period, decides the approval. This value must be more than 30% filtration efficiency. After the actual test, a so-called worst-case test is performed at engine full load: as soon as exhaust temperature reaches values above 550 °C an oxygen regeneration is initiated. This fast regeneration with high heat release is used to verify the thermo-mechanical dependability of the system. The test is supplemented with a smoke measurement during free acceleration.

This standard test was performed on two of the systems, here designated system A and system C, i.e. an actual partial-flow filter and a foam deep filter. Fig. 3 shows the results. In the figure "C" denotes the conditioning phase (3 times NEDC without measurement), "T" denotes the emissions testing phase (NEDC) and "WC" denotes the worst case test. How the system behaves in between the test points "T" is not known.

The baseline is the filtration efficiency in the as new state, which complies with the limits. Compared to the baseline, the filtration decreases substantially for both systems after the first city driving period. This deterioration continues in the second stage but is mostly corrected through regeneration during the so-called worst case test (WC). The weighted average filtration efficiencies are: system A 3.1%, and system C 8.2%. Both systems do not attain the objective.

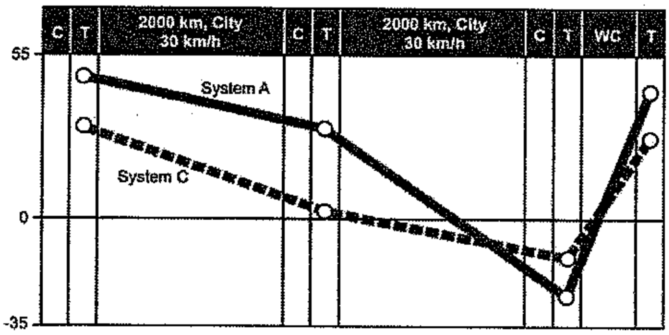

Fig. 3: Performance of system A and system C.

The soot puff, during free acceleration from idling engine speed to governed engine speed, was verified after the defined test runs. System B emitted 17% less soot than the base-line; system G emitted double the baseline value.

These tests clearly indicate the deficiency of these partial-flow filters. The filtration deteriorates, due to soot deposition, and thus the danger of soot puffs when the deposits are blown-off.

The filtration efficiency scatter indicates that conditions change from test to test. Possibly, other higher values might have been recorded, had the filter shed soot just before measurement, i.e. a stochastic phenomenon. These observations indicate that filter conditioning is unsuitable for system evaluation. During conditioning, deposits are removed. Thus the filter is restored to a more effective state than after the city driving period. Without assessing the conditioning phenomena, the results are unrealistically distorted. Hence, the results of this standard test are misleading, overestimating the real world efficacy of these devices.

In 2008 the German automobile club ADAC [13] tested 9 marketed partial-flow filters, types A and B. However, the city driving phase was only 1,500 km. The measurements before and after the city driving showed an average deterioration of the filtration efficiency from 39% to 21% with individual cases of –51%, despite conditioning before measurement. During a so-called "ADAC Autobahn-cycle" 8 of 9 filters candidates showed blow-off, emitting on average 110% PM above engine baseline, in one case 370%.

CHASSIS DYNAMOMETER TESTS

In 2006 the Exhaust-Gas Test Center AFHB of the Swiss University of Applied Sciences, Biel investigated such devices. The tests comprised the following:

INFLUENCE OF SOOT BURDEN AND BLOW-OFF PHENOMENA

Constant speed	35 km/h from cold start 4th gear Exhaust temperature < 200°C
Test duration:	210 minutes

Constant speed	65 km/h from warm start 4th gear Exhaust temperature ≈ 300°C
Test duration:	210 minutes

Load variation to investigate temperature dependence
Constant speed 85 km/h in 6th gear
Wheel load incremented in 5 steps from 0 – 1600 N chassis dynamometer setting i.e. until full load

EMISSIONS AT CONSTANT SPEED

Setting the chassis dynamometer, which simulates roll resistance on a horizontal road; driven in 5th gear at constant speeds of 45 – 120 km/h.

EMISSION FACTORS IN VARIOUS DRIVING CYCLES

The following driving cycles were tested twice on two different days:

- New European Driving Cycle NEDC, cold and warm
- Federal Test Procedure FTP75, warm
- CADC (so-called ARTEMIS cycle [6]) warm
- New York City Cycle NYCC, warm
- German Autobahn Cycle BAB, warm

This program is based on over 10 years experience in testing and certification of full-flow particle filters deployed in Switzerland. It also considers results of prior investigations [1, 14, 15, 16, 17]

The test vehicle details are given below.

VW Passat TDI (on the chassis dynamometer)

Manufactured in year :	2005
Vehicle type:	3BG
Engine displacement :	1.9 dm^3 (1896 cm^3)
Power rating:	96 kW at 4000 RPM
Torque:	310 Nm at 1900 RPM
Engine type:	AVF
Engine:	TDI 2V VTG
Injection system :	Pump nozzle
Exhaust after-treatment :	DOC close coupled
Emission level:	EURO 3
Gear box:	6 gear manual
Odometer at start:	23,700 km

The test fuel used throughout this work was Shell Formula Diesel, compliant to EN-SN-590 with a sulfur content of less than 10 ppm. Details of the test lubricant are given below.

Lubrication oil: SAE OW/30

Sample analysis of fresh oil :

Sulfur:	5000 ppm
Calcium:	2847 ppm
Iron:	171 ppm
Phosphorous:	1078 ppm
Zinc:	1243 ppm

The baseline emissions results over the different test cycles are given in Table 1 and the baseline emissions values at the different load settings at 85km/h in 6th gear are given in Table 2.

Table 1: Emissions baseline of the test vehicle over the different driving cycles

g/km	Limit value EURO 3	NEDC cold	NEDC warm	FTP 75 warm	CADC urban warm	NYCC warm	BAB warm
CO	0.64	0.21	0.05	0.04	0.24	0.27	0.02
HC	-	0.06	0.02	0.03	0.02	0.03	0.02
NOx	0.5	0.35	0.35	0.40	0.72	0.75	0.8
PM	0.05	0.03	0.025	0.033	0.07	0.07	0.025

Table 2: Emissions baseline of the test vehicle in load steps at 85 km/h, 6th gear

Load	Exhaust Temp. °C	PM g/km	Particle Count x 10^6 10-400nm #/cm^3	P Ø nm	NOx ppm	NO_2/NOx %
3 N	230	0.007	35.7	60	50	41
400 N	330	0.019	21.1	70	196	39
800 N	390	0.033	10.6	80	461	23
1200 N	435	0.046	4.4	80	856	15
1600 N	465	0.055	4.5	80	1099	8

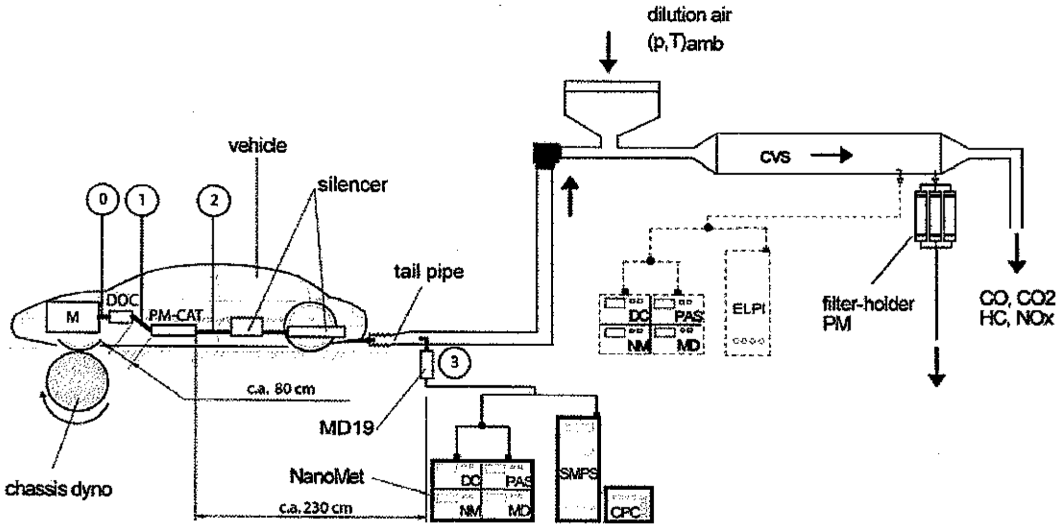

Fig. 4: Sampling points and instrumentation for exhaust-gas and nanoparticles on the chassis dynamometer

The measurement of the emitted gaseous components and the particle mass PM is performed according to EU-legislation for passenger car emission measurement. The measurement system is shown schematically in Figure 4. The nanoparticle analysis was done using the heated rotary diluter MD 19, the instruments CPC for the total particle count, SMPS for the particle size analysis 10-400 nm, and the sensors DC and PAS for the online determination of the particle surface and the overall elemental carbon (EC) in the size range 10 – 1000 nm. The equipment was deployed at various test locations. For measurements in the CVS-Tunnel, the instrumentation was enhanced with the Electrical Particle Impactor (ELPI), which provides information on count and mass in 12 size classes 30-10,000 nm. Details of the instrumentation are given in [18]. Sampling was according to Particulate Measurement Protocol (PMP) [36] with 300 °C preheated sampling lines and dilution range (DR) > 100 to guarantee that only solid particles were counted.

A specialty of this investigation is the sample extraction before and after the test object. This segregates the influence from other parts of the exhaust system on the investigated emissions and permits a proper evaluation of the properties of each single device e.g. the filtration of the filter and the conversion of the DOC. It also identifies any trends in the engine emissions during the testing period. The sampling points are "0" before the DOC, "1" between DOC and filter, and "2" immediately after the filter, for nanoparticles and NO_2. The sampling lines are instrumented for pressure and temperature.
The sampling points are connected to the instrumentation chain through a heated switching valve. In some cases a DOC was integrated in the device and then unfortunately there was no access to the point between the integrated DOC and the filter unit.

Test candidates

Filter "A" is actually a partial-flow filter [19, 20]. The design features are a metallic substrate of corrugated and perforated foils and a fleece of very fine metallic fibers acting as the actual filter medium. Deflection blades in the channels create flow conditions, which intensify momentum cross-transfer between the channels and flow through the filter fleece. This PMS used the existing closed coupled DOC of the vehicle for the necessary NO_2-formation and an integrated DOC immediately upstream of the PFF in addition.

Filter "B" [10) is derived from a VERT-certified full flow sintered metal filter. This filter provides a high filtering surface and excellent ash storage by a filter pocket design instead of a cellular filter structure. The filter medium itself consists of a fine metal grid covered with sintered metal powder. It attains a filtration efficiency of > 98 % according to the VERT verification protocol [1]. For the application as partial-flow filter each filter pocket has received two exit holes, providing an overall section of about 400 mm^2, through which the exhaust-gas can escape unimpeded and unfiltered. This PMS also used the vehicle DOC for the necessary NO_2 formation, but the existing was replaced by a new one.

The other two test candidates "C" and "D" are coarse-pored deep filters of ceramic and metallic foams, This concept goes back to the early days of exhaust filter development [22,23], when filtration efficiencies up to 90% were attained with well engineered foams. However, the store-and-release problem, i.e. the occasional soot blow-off, was never adequately mastered. The pore size of these filters is in the range 1–3 mm, i.e. almost two orders of magnitude larger than the usual pore size of ceramic wall flow filters. Since filtration efficiency of ultrafine particles is proportional to the filter depth / pore diameter x flow velocity [24] the disadvantage of large pore size and large flow velocity must be compensated for by a greater filter depth, which is basically detrimental to the pressure loss. An acceptable trade-off is not easy to achieve. C uses an integrated DOC and was placed close coupled replacing the vehicle DOC. D again used the existing vehicle DOC but in addition some Pt coating inside the PMS-structure. The different filter technologies are shown in Figure 5.

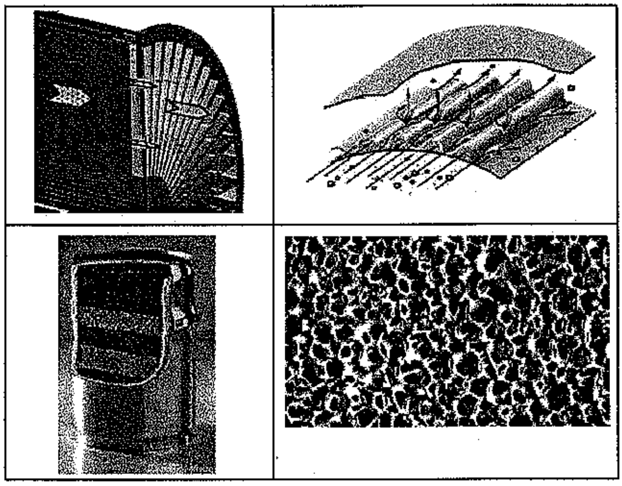

Fig 5: System A above right; system B above left, system C below left; the picture below right shows the typical structure of an open pore ceramic foam from [23]

Table 3 shows some of the physical properties of the test systems. Some of the dimensions are estimated. The velocities are based on an average engine flow 0.076 m^3/s. The storage volume of A, C and D was calculated assuming that agglomerates larger than 10 µm will be blown off, since aerodynamic forces exceed adhesion forces.

Table 3: Basic properties of the 4 candidates.

	A	B	C	D
Diameter [m]	0.115	0.150	0.118	0.145
Length [m]	0.150	0.170	0.076	0.180
Inflow Section [m^2]	0.010	0.018	0.011	0.016
Filter Volume [ltr]	1.56	3.00	0.84	2.97
Inflow Velocity [m/s]	7.6	4.3	6.9	4.8
Filtration Surface [m^2]	1.0	1.0	0.4	1.5
Space Velocity [1000/h]	175	91	326	97
Face-Velocity [cm/s]	3.8	3.8	730	480
Pore Size [µm]	25	25	3000	3000
Storage Volume [ltr]	0.1	1.0	0.04	0.15
Storage distance [km]	1'000	10'000	400	1'500
Part.Flow Section [m^2]	0.005	0.0004	-	-

The comparison demonstrates the large differences of these concepts. Filter B has so much volume-storage capacity that it will never need to clean itself during the actual chassis dynamometer testing period of less than 1500 km while all other systems, which can only store soot on their flow exposed surfaces must blow off if they do not regenerate during the 1500 km testing period. This means that the quality of Filter B will be overestimated during short time testing as performed here.

The NO_2, needed for the regeneration, can be obtained through various methods. The B filter substitutes the vehicle's DOC with another DOC. The A filter integrates a DOC in its own casing and uses the original DOC in addition. The very compact close coupled C filter contains catalytic coated foam elements and the original DOC is unnecessary. The metallic foam D filter, too, contains catalytic coated elements but uses the original DOC in addition.

For these tests the manufacturers matched the filters to the test vehicle. To identify manufacturing scatter, a further example was purchased from the market and compared. No major difference was found.

Influence of the soot burden

The soot loading of the filters was done at two operating conditions:

- Cold start and acceleration to 35 km/h in 4th gear. Subsequently, constant operation during 210 mins at exhaust temperature before filter < 200°C.
- Constant speed, after warm-start, at 65 km/h in 4th gear at exhaust-gas temperature of about 300°C.

At intervals of 10 minutes, the limited components CO, HC, NOx and PM were extracted from the CVS-Tunnel. Additionally, the ELPI instrument was used. The nanoparticle analysis was connected to the sampling locations 1 and 2.

The particle concentration as measured size-specific by SMPS was integrated over the size range 10 nm to 400 nm and the comparison of results from sampling point 1 and 2 was used to determine the filtration efficiency. The filtration efficiency determined at some of these 10 minute intervals is shown in Table 4.

Table 4: Filtration efficiency at 35 km/h

	A [%[	B [%]	C [%]	D [%]
cold start	53.02	60.37	31.34	20.72
10 min.	55.75	61.05	7.76	ND
30 min.	50.20	56.37	8.99	ND
60 min.	43.18	57.56	9.51	23.96
120 min.	36.49	54.39	10.38	26.65
180 min.	31.72	55.00	12.56	24.55

The A filter is a classical partial-flow filter with limited deposition capability in the filter fleece. It performs as anticipated: the ratio of partial-flow/main-flow shifts and decreases the filtration efficiency from the initially 55% to 31%, i.e. the filtration efficiency is almost halved. Unfortunately the test was not continued to observe the probable continuation of this trend. The second partial-flow filter B has a substantially higher deposition capability in the filter body. The efficiency decreases from 61% to 55%. Here, the degradation obviously is slower. The deep-filters C and D exhibit, as expected, an inverse trend. The filtration efficiency slightly increases with deposition of particle matter. Deposited soot raises the available deposition surface inside the filter matrix and thus improves the filtration efficiency. This trend always occurs in deep filters [25]. Eventually, saturation will occur and the trend will reverse because the adhesion locations are occupied. The high flow velocity in such filters then expels the agglomerates [26].

This second test variant has the higher exhaust-gas temperature of 300°C. An intensive regeneration can be expected, because the peak NO_2 generation usually happens around 300°C [27]. The test results indeed indicate a more sustained filtration. The results of this testing are shown in Table 5, again the particle concentration as measured size-specific by SMPS was integrated over the size range 10 nm to 400 nm and the comparison of results from sampling point 1 and 2 was used to determine the filtration efficiency.

Table 5: Filtration efficiency at 65 km/h

	A [%[	B [%]	C [%]	D [%]
Warm start	35.30	59.70	29.48	6.20
10 Min.	21.65	51.89	15.33	8.58
30 Min.	20.79	51.99	20.35	11.27
60 Min.	18.43	52.68	23.45	16.72
120 Min.	23.28	52.14	24.12	21.86
180 Min.	20.11	54.97	25.38	25.66

The A filter indeed sustains a filtration efficiency of about 20 % - however far below expectations. The explanation may be that at 65 km/h, which is above city driving speeds, the designs space velocity is exceeded. The B filter sustains acceptably high filtration efficiency. But the deep filters C and D interestingly are reaching the 25% rate, reaching higher values than the A filter.

Blow-off / store-and-release

The Store-and-Release phenomena in exhaust systems have been extensively investigated [12,13]. The observed response is usual in exhaust systems with mufflers. It is very similar to the physical behavior in catalytic converters and the open filter systems discussed here.

The investigation of blow-off phenomena is technically difficult. It is a stochastic event, which occurs sporadically and unpredictably depending on deposition burden, prior events and space velocity.

In order to provoke this store-and-release phenomenon, after 5000 km controlled city driving according to [5] – and after conditioning and EUDC-cycle-measurement – the vehicle was run at 40 km/h on the chassis dyno and suddenly accelerated - see photographs from video clips taken during this testing are shown in Fig 6. The time at the bottom of each frame indicates the time after the start of the sudden acceleration.

Fig 6: Typical blow-off during full load acceleration after city driving according to [5].

A systematic investigation of the blow-off phenomena was done at free acceleration as specified above in the section on the influence of the soot burden.

The soot puff was logged twice as follows:

- Online CPC recording, directly at the tailpipe
- Online recording with ELPI, at the CVS tunnel

The Tables 6 and 7 summarize the peak values from the two instruments.

Table 6 Peak values of solid particle number emissions during free acceleration, measured with CPC at the tailpipe.

	CPC			
	A	B	C	D
Basis	9.8×10^7	9.8×10^7	9.8×10^7	9.8×10^7
With filter	8.6×10^7	4.5×10^7	9.8×10^7	9.0×10^7
Reduction	12.2%	53%	2%	8.2%

Table 7: Peak values of solid particle number emissions at the CVS tunnel during free acceleration, measured with ELPI at the CVS tunnel.

	ELPI			
	A	B	C	D
Basis	4.5×10^5	4.5×10^5	4.5×10^5	4.5×10^5
With filter	10×10^5	6.6×10^5	27.7×10^5	9×10^5
Reduction	- 122%	- 47%	- 515%	- 100%

The CPC data shows a respectable result for the B filter, but very modest values for the A, C and D filters. At first sight the comparison of the ELPI data to CPC is surprising. The emission peaks measured by the ELPI are consistently much higher with the filter systems compared to the baseline without filter.

This observation, too, is not new [17] and can be explained as follows: the CPC only detects very small particles.. But the ELPI detection range is up to 10,000 nm. The particles expelled from open systems, during the free acceleration, are previously deposited soot particles, i.e. agglomerated and substantially larger than the engine emitted particles. Hence, the CPC will just not "see" many of them but the ELPI will. So it is not surprising at all that the ELPI registers higher values for open systems during acceleration. It is clear proof of blow-off.

Comparing the visual impression (Fig 6)), even the ELPI might be underestimating the extent of blow-off, because many particles may be much larger than the 10 µm ELPI detection limit.

This blow-off hypothesis was further investigated. The particle mass PM was measured during 10 minutes, within which three free accelerations were performed. This measurement is presumably not very precise; because the mass is so small. Nevertheless, in these measurements all four systems emitted a higher mass with filter than without filter.

Load variation at 85 km/h

The load variation at 85 km/h was performed to discover the system dependence of the filtration efficiency and the NO_2 emissions. Again the number count is measured size-specific by SMPS and then integrated in the size range 10 nm – 400 nm to determine filtration efficiency. The filtration efficiency results are presented in Table 8.

Table 8: Particle filtration efficiency at 85 km/h, 6th gear.

	A	B	C	D	Temp. °C
0 N	18.72	48.18	3.15	21.82	244
400 N	23.86	56.06	16.52	13.93	345
800 N	13.06	56.58	19.44	-5.65	409
1200 N	15.24	60.59	19.19	-31.85	472
1600 N	33.44	63.52	33.44	-29.63	519

The system B apparently exhibits sustained filtration efficiency at relatively high level, although due to the higher capacity of this filter this may in fact be merely soot storage. The system A deteriorates with increasing load, probably because the ratio main-flow/partial-flow increases and regeneration is still weak. Once regeneration becomes active at high load then the efficiency improves. A similar pattern is observed for system C. System D is blowing off at increasing flow.

The last column shows the exhaust-gas temperatures upstream of the filter. At the last operating point, oxygen based regeneration may occur. That might explain the step improvement of systems A and C, and also the clear improvements in system B.

The load variations were also used to scrutinize the systems' NO_2 emissions. The emissions of NO_2 are very temperature dependent because of the equilibrium reaction NO - NO_2 [27]. Diesel engines without exhaust-gas after-treatment only have elevated NO_2 emissions at very low exhaust-gas temperatures in the idling range. As the temperature increases, the equilibrium shifts towards NO and only 5 – 8% NO_2 is measured. Oxidation catalysis using Pt, when the fuel is sulfur free, creates a completely different situation, which is fully described in the cited publication [27].

NO_2 is measured hot [28], so that no loss of the easily water soluble NO_2 in condensate occurs. Table 9 shows, for all four systems, the concentration of NO_2 in the ratio to total NOx, before and after each filter system.

System A has high NO_2 values before the filter system, as a result of the vehicle catalytic converter, decreasing at high temperatures because of the equilibrium shift. Within the PMS some NO_2 seems to be used for regeneration thereby lowering the slip of this toxic gas compound to some extend.

B has an even higher inlet value, because a new catalytic converter was used. Also here some NO_2 is used for soot oxidation.

System C replacing the vehicle DOC shows upstream the typical Diesel engine-out NO_2 emission characteristic and downstream the effect of the integrated DOC. System D, using 2 DOC's, the vehicle DOC and coatings inside is clearly strengthening the emission effect.

Table 9: NO_2 emissions relative to total NOx, before and after particle filter, with load variations at 85 km/h

NO_2/NOx	Before PMS			
[%]	A	B	C	D
Idle	35.8	49.2	27.1	36.7
398 N	33.5	40.6	4.8	34.5
798 N	23.4	26.0	3.2	22.4
1198 N	14.4	12.8	3.2	15.0
1598 N	5.9	6.3	3.7	8.9

NO_2/NOx	After PMS			
[%]	A	B	C	D
idle	21.6	36.6	20.5	44.0
398 N	25.5	21.7	27.0	49.3
798 N	22.3	11.0	22.8	36.0
1198 N	17.5	3.6	16.2	26.9
1598 N	7.2	0.4	10.6	19.1

Varying the vehicle speed

This test focuses on the influence of space velocity. The temperature varies simultaneously with the speed. Table 10 shows the influence on filtration efficiency. Again the number count is measured size-specific by SMPS and integrated over a size range of 10 nm – 400 nm to determine the filtration efficiency. In the table Tv corresponds to the temperature upstream the filter, and Tn corresponds to the temperature downstream of the filter.

Table 10: Filtration efficiency from the integrated particle counts 10 – 400 nm, at increasing speed in 5th gear.

Km/h	A	B	C	D	Tv [°C]	Tn [°C]
45	39.27	55,43	16.19	25.16	195	150
60	29.39	50.27	9.48	19.21	250	200
80	27.62	57.01	15.98	17.54	295	230
100	32.19	58.95	19.65	18.32	350	285
120	36.45	62.76	15.90	23.00	350	290

The data do not identify a clear influence of increasing space velocity. Apparently, the simultaneously higher temperature increases conversion and hence better efficiency for all systems. The systems C and D are nevertheless below expectation.

The temperatures, logged before and after the filter, do not indicate a significant chemical reaction. The distance of the thermocouples from the filter, approx. 10 cm, may explain the difference since the pipes were not insulated.

Driving cycles

The NEDC cycle is no longer considered to mirror real driving conditions [6]. Hence, further driving cycles were tested. These were the FTP 75 and CADC (which are both more dynamic driving cycles), the New York City Cycle NYCC (which has very low loads) and the German Autobahn cycle BAB (for high driving speeds). Table 11 provides characteristic data comparing these driving cycles

Table 11: Characteristic data of the used driving cycles

	overall length	average speed	max. speed	estimated engine work
	[m]	[km/h]	[km/h]	[kJ]
NEDC, ECE part	4073	18.8	50	1779
NEDC, EUDC part	6955	62.6	120	3583
NEDC, complete	11028	33.6	120	5362
FTP-75, 1st part	5777	41.2	91.2	3117
FTP-75, 2nd part	6209	25.8	55.2	3010
FTP-75, 3rd part	5777	41.2	91.2	3117
FTP-75, complete	17763	34.1	91.2	9244
CADC, urb.	4870	17.7	57.7	3644
CADC, road	17272	57.5	111.5	9388
CADC, Mw.	28736	97.0	131.8	20890
NYCC	1896	11.4	44.6	1398
BAB, 1st part	12963	106.8	124.2	7998
BAB, 2nd part	9554	114.6	138.6	7543
BAB, 3rd part	10112	138.4	162.0	9823
BAB, complete	32628	117.5	162.0	25318

	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, urb.	2.861	-3.139	33.5	32.5	30.3
CADC, road	2.361	-4.083	39.8	39.8	3.3
CADC, Mw.	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

Table 12 shows the integrated filtration efficiency for the 4 system based on particulate mass PM and overall particle number CPC when tested during these driving cycles. All tests were repeated once on the following day to provide information on repeatability.

The big span of measured filtration efficiencies is typical for these systems. The results are not reproducible, because they are so heavily dependent on prior events and the operating conditions. All systems attain or exceed the required range of 30% in the NEDC cycle. Other cycles very often show worse efficiencies, due to greater proportion of transients, much lower load or very high motorway speeds. These operating conditions are realistic, too.

Hence, system evaluation based on the NEDC alone is inappropriate. In some cases measured efficiencies are extremely low, especially for the particle mass evaluation. The only explanation is the blow-off phenomena, which occur in these cycles and appear as emitted mass.

The particle-count evaluation before/after the filter, at the same operating points, shows completely different values. This is because particle counting does not detect the large blow-off particle agglomerates.

Fuel consumption

The fuel consumption was measured during all tests. Minor improvements and minor deterioration were recorded. These are in the scatter band. No definitive statement can be made about the influence of these open filter systems on the engine fuel economy.

This is consistent with the measured back-pressures of the filters. The pressure loss, even at the highest speeds and loads was a maximum of 100 mbar more than the baseline with muffler. This 100 mbar, compared to the indicated mean pressure of the passenger car engine at the operating points, represents an increased engine pumping work of 1 – 2%. This should cause a small fuel penalty but could not be experimentally confirmed.

Table 12: Filtration efficiency based on particulate mass PM and the particle count measured by CPC in the driving cycles. Sampling from the CVS-Tunnel. Conditioning between cycles was 3 mins at 80 km/h 4th gear.

	Filter A			
	1st day [%]		2nd day [%]	
	PM	CPC	PM	CPC
NEDC c.	42.0	40.6	47.2	41.3
NEDC w.	37.9	31.0	ND	ND
FTP 75 w.	42.1	31.9	46.8	35.6
CADC Urb w.	26.4	28.9	47.1	32.2
CADC Rd w.	2.9	23.8	13.3	25.0
CADC Mw w.	37.6	35.9	40.8	36.6
NYCC w.	3.8	58.2	27.7	60.0
BAB w.	16.5	24.6	28.4	28.8
	Filter B			
	1st day [%]		2nd day [%]	
	PM	CPC	PM	CPC
NEDC c.	55.7	56.1	55.0	50.8
NEDC w.	59.8	50.2	ND	ND
FTP 75 w.	60.5	55.2	61.2	53.4
CADC Urb w.	60.5	54.9	61.7	50.0
CADC Rd w.	49.6	49.8	43.9	48.1
CADC Mw w.	63.4	61.7	59.9	58.0
NYCC w.	39.6	67.0	27.2	61.8
BAB w.	41.2	45.8	51.9	46.8
	Filter C			
	1st day [%]		2nd day [%]	
	PM	CPC	PM	CPC
NEDC c.	38.1	30.6	33.3	26.6
NEDC w.	26.4	19.8	ND	ND
FTP 75 w.	37.9	20.7	40.3	24.8
CADC Urb w.	17.6	29.3	52.9	24.9
CADC Rd w.	10.8	22.3	-1.1	14.5
CADC Mw w.	32.8	30.9	33.4	27.9
NYCC w.	22.6	27.2	17.0	20.8
BAB w.	18.9	18.3	9.4	14.1
	Filter D			
	1st day [%]		2nd day [%]	
	PM	CPC	PM	CPC
NEDC c.	31.3	32.5	25.0	35.6
NEDC w.	33.3	29.9	-	-
FTP 75 w.	30.3	31.1	45.9	38.9
CADC Urb w.	44.4	35.9	49.9	38.3
CADC Rd w.	17.3	32.0	6.8	35.5
CADC Mw w.	44.3	37.1	48.1	42.3
NYCC w.	25.0	34.2	33.2	38.0
BAB w.	19.2	32.5	30.8	37.6

Risk of clogging

No clogging occurred during these investigations. Clogging of "open" systems however cannot be excluded, as reported elsewhere [29]. Filters may clog when the vehicles are operated at low loads, so that no regeneration occurs, and simultaneously there is high lubricating oil consumption. In such systems, sticky layers can block the fine cells.

Consequently, the back-pressure and therefore the exhaust-gas temperature increases and may trigger a hazardous uncontrolled regeneration. Heat release during this event can destroy the underfloor catalytic converter and may be a risk of fire.

Ash accumulation

The manufacturers of most open filters claim that ash particles cannot clog the filter and are emitted into the atmosphere If this is true then ash particles which are probably orders of magnitude more toxic than the soot particles [30] will be released to the atmosphere - not a desirable attribute. Filtration of exhaust-gas should also comprise the filtration of ash particles.

If it is not true then there is a danger that fine ash particle can irreversibly accumulate in the partial-flow filter. The low storage capacity of these filter media causes an irreversible shift in the ratio of partial-flow/ main-flow, and consequently to lower the filtration efficiency. An investigation of ash accumulation requires long test times but is highly desirable.

To clarify the basic processes, a test was run with metallic fuel additive, which forms oxide clusters in the size range 20 – 30 nm. Figure 7 shows that the filter system A was indeed not very effective in curtailing soot emissions. But when a Fuel Borne Catalyst (FBC) was used, some of the additive particles were trapped in the filter system, many however were emitted, which would never be acceptable in full-flow filters.

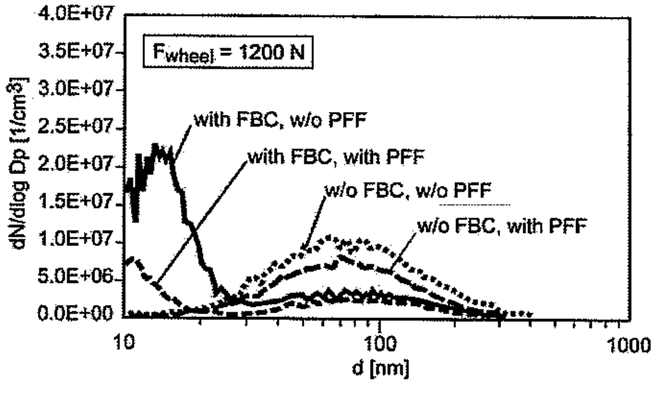

Fig. 7: Penetration and accumulation of small ash particles in the filter system A

Repercussion on the engine

In European passenger car Diesel engines of emission category EURO 3, NOx emissions are usually controlled through Exhaust-Gas Recirculation (EGR). If this EGR is not backpressure controlled the engine may become very sensitive if back-pressure rises due to filter soot loading. Also in these tests, the raw emission of the engine increased with back-pressure, despite the modest back-pressures. This is shown in Table 13.

Table 13: Influence of back-pressure on the raw emission of the engine. Load variation at 85 km/h.

	Particle concentration X 10^7	
	Without filter	With filter
0	3.6	3.3
400 N	2.1	2.6
800 N	1.05	1.16
1200 N	0.44	0.53
1600 N	0.48	0.55

If the back-pressure rises, due to filter clogging, then the raw emission of the engine increases. This diminishes the overall filter efficacy.

PARTIAL FLOW FILTER IN HD-VEHICLES

The effect of partial-flow filters in HD onroad vehicles is extensively reported by the authors in [17]. Unlike the results reported in this paper, conditions in heavy duty road vehicles are more favorable because the exhaust-gas temperatures are usually higher. Also the NOx level is higher in vehicles of EURO III and earlier.

It is indeed possible to design partial-flow filters for HD-vehicles so that it can have a filtration efficiency of 50% and more, provided continuous regeneration is ensured. If not, the partial-flow filter will be soot burdened and the filtration efficiency will drift to lower values [17] and all the negative effects as they were observed here with LDV will happen as well.

Furthermore it has to be noted that while passenger cars usually already have a DOC prior to filter retrofit, HD vehicles have not. They must first be equipped with a DOC in order to permit the use of such a partial-flow filter unless the part flow filter will have an integrated DOC. Thus NO_2 created for regeneration is a new pollutant in the exhaust-gas of the HDV. The toxicity of this NO_2 must be scrutinized for certain locations.

COST/BENEFIT – ANALYSIS OF PARTICLE FILTER RETROFIT

Retrofit plans have no business justification. They cause substantial investment and operating costs. The cost-benefit ratio, i.e. the ratio of the invested funds to particle emission curtailment, is expressed as Euro/kg soot.

As an example: consider the retrofitting of a passenger car having an anticipated rest-of-life of 100'000 km, an average PM emission of 0.04 g/km and a filtration efficiency of 30% on average: the retrofit will prevent an emission of 1.2 kg of soot. The purchase price and retrofitting costs of the filter may be about Euro 750 for a midsize car. Hence, the cost/benefit factor is Euro 625 per kg soot. This is illustrated in Table 14.

Table14: Cost/Benefit for HD-truck with a full flow filter compared to a passenger car equipped with so-called "low-cost" partial-flow filter

	HDV	LDV
PM-Emission	0.1 g/kWh	0.04 g/km
Mileage	500 hrs/y	10'000 km/y
Average Performance [kW]	100	10
PM Emission [kg/year]	5	0.4
Overall vehicle life [year]	20	10
Emission [kg/vehicle life]	100	4
Filter type	wall flow	partial flow
Filter efficiency [%]	99.9	30
Filter Cost [EUR]	7500	750
Total prevented soot [kg/vehicle life]	100	1.2
Cost/Benefit [EUR/kg soot]	75	625

The cost/benefit analysis of HD road vehicles with full-flow filters yields substantially better value:

The emission of 0.1 g/kW/h is eliminated from a EURO III vehicle. Assuming a life of 10,000 operating hours and average performance of 100 kW, the emission of 100 kg soot is prevented. Retrofit costs plus operating costs may be Euro 7,500 for individual retrofits. The cost/benefit factor is 75 Euro/kg soot.

This factor improves to <50 Euro/kg for older vehicles of larger production volume [31] and higher production volumes.

Maximum environmental benefits therefore require highly efficient filters on long-life HD-vehicles, instead of low efficiency filters on either HD or LD vehicles to provide high benefit at low cost for the society.

GLOBAL WARMING POTENTIAL GWP

Diesel's share in the European passenger car fleet is increasing rapidly. It is justified on the Diesel engines' better thermodynamic efficiency, hence smaller CO_2 footprint. This facilitates achieving the automobile industry's self-imposed objective to reduce global warming.

However, atmospheric soot particles also have a very high potential for global warming. These particles absorb sunlight and radiate heat, in the infrared range, thus warming the atmosphere. Acc.to [32, 33] the global warming potential of black carbon (BC) particles finely dispersed in the atmosphere is enormous: per kg, BC causes 360,000 – 840,000 times higher global warming than CO_2

Spark ignition (SI) engines emit much less particles. Table 15 presents a simplified comparison:

Table15: Relative Global Warming Potential (GWP) of Diesel-engines including black carbon effects on GWP with and w/o filters compared to SI engines

	LDV SI without filter	LDV Diesel w/o filter	LDV Diesel with FFF	LDV Diesel with PFF
CO_2-Emission [g/km]	SI/CI=1.15 184	160	160	160
Soot-Emission [g/km]	0.002	0.04	99.9% 0.00004	30% 0.028
rel. GWP due to CO_2	normalized 1	0.87	0.87	0.87
rel.GWP due to Soot	6,5	130	0.13	91.3
Total rel GWP	7.5	130.87	1	92.2

To restrict global warming potential at the SI engine level, and assuming a CO_2-difference of 15 % between Diesel and SI, average Diesel engines must be fitted with particle filters having a filtration efficiency of at least 98 %. Only filters with better efficiencies enable Diesel technology to cause less global warming than SI engines.

RECOMMMENDED TEST METHODS

A test method to curtail particle emissions, who's only metric is the particulate mass, does not adequately reflect the health aspects [30,36]. The alveoli penetrating particles are smaller than 1 µm and their influence culminates in the size range of about 20 nm [1]. If the attributes of particle filters are not determined size-specific to this toxic range, then statements on filtration efficiency have no relevance. The larger particles dominate the particulate mass. Hence, the PM metric is inappropriate for toxicity evaluation and curtailment.

Beside ozone, lead and sulfur respiratory air quality legislation also limits particulate mass PM2.5 and NO_2, which both mostly originate from road traffic. Methods to curtail particle emissions must therefore simultaneously ensure that the NO_2 emissions do not increase.

Fundamental re-thinking is needed of the following two test aspects. Firstly, the testing of retrofit filters in standard driving cycles. Secondly, the conditioning routine of expelling accumulated particles. More suitable test procedures are worst-case protocols, which scrutinize the store-and-release phenomena, the extreme operating situations at lighter loads, at high space velocities, and under transient operating conditions.

OVERALL PENETRATION

Filtration means that soot is intercepted and stored in a filter substrate. Not to reach the atmosphere requires in addition that this soot is converted to CO_2 . Clearly these are two processes with different prerequisites. Mastering both only guarantees that soot does not penetrate into the environment. The overall penetration P of engine soot reaching the atmosphere is calculated from the product of filtration efficiency AG and regeneration efficiency RG to P = 1 - AG x RG

Full-flow filters have filtration efficiencies > 0.99. The regeneration efficiency is almost 1, otherwise the filter would soon clog and become ineffective. Overall penetration into the atmosphere is < 0.01 or 1 % of engine emitted soot. Prerequisites are complex regeneration equipment, and on-board diagnostics. Regeneration does not eliminate ash and other inert substances. These accumulate in the filter, and may only partially escape at the tail-pipe when the filter pores are too coarse (> 20 μm).

Partial-flow filters can be designed for 50% filtration efficiency. The actual filtration rate is often worse, as reported in this paper. So even in favorable circumstances, 50 % of the engine originated soot directly reaches the atmosphere. Some of the intercepted and stored soot also later escapes into the atmosphere. The quantity depends on the regeneration efficiency integrated over the driving cycle. Regeneration in partial flow filters is exclusively NO_2 enabled. The NO_2 is formed on platinum catalysts and subsequently can release an oxygen radical in the soot cake. The regeneration is thus a two-stage chemical process. The two stages (catalytic oxidation of NO and oxidation of C) are sequential, disparate and partially follow opposing chemical dynamics. The catalytic formation of NO_2 has its maximum at about 350 °C and, for equilibrium reasons, rapidly decreases at higher temperatures [35]. The oxidation of C begins at 250 °C, proceeds very slowly and only attains higher reaction rates above 400 °C. Thus, the engine generated NO_2 during idling (approx. 25% of NOx) is useless for soot burn-off. Moreover, the availability of NO_2 is limited. Depending on the driving cycle, only 30-50 % of the engine originated NO is converted into NO_2. The gravimetric stoichiometric ratio NO_2/ C is 7.6. Experience shows that twice this ratio is actually needed.

The data for the tested EURO3 engine: particle emission limit in NEDC is 50 mg/km and the NOx limit is 500 mg/km. The maximum available NO_2 per km is therefore 150 mg/km to 250 mg/km, which at double stoichiometry can oxidize 9.8 to a maximum of 16.4 mg soot per km. Regeneration is thus constraining the performance of such partial-flow filters. Assuming 50 % filtration, the calculated regeneration rate is thus 39 to 65 %, which is close to the 45 % measured in [13], the rest of the intercepted soot must be blown-off. The combined best case with 50% filtration and 65 % regeneration reaches an overall penetration rate of 1- 0.5 x 0.65 = 67 %. If filtration is only 30% [5] and 45 % of the intercepted soot are regenerated [13], the overall penetration will be 86 %, only 14 % of the engine emitted soot will be converted to CO_2. Penetration of 86% must be compared to the penetration 0.1 % of a good wall flow filter – leading to a quality comparison of 86/0.1 which means that PMS releases 860 times more particles to the atmosphere, which is the real effect on the environment [34].

CONCLUSIONS

Three of the four tested retrofit systems, for curtailing particle emissions from Diesel passenger cars, did not fulfill the expectations in the short duration tests that were performed. Filters 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, all four partial-flow filters tend to soot deposition and stochastic release, which cause high smoke emissions unacceptable in traffic situations.

Test procedures must be enhanced to include these aspects. That would provide the guidelines for a retrofit technology, which ensures sustainable emission curtailment. Simultaneously, the cost/benefit ratios must reach an acceptable range and also the global warming potential. Finally the emitted number of particles must become the decision criterion and not the reduced mass.

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ACRONYMS

Euro	Currency EUR (approx. 1.39 US$)
AG	Filtration rate
BAB	German Autobahn Cycle
CADC	Common Artemis Driving Cycle
CPC	Condensation Nucleus Counter
CVS	Dilution tunnel
DC	Diffusion Charging
DR	Dilution Ratio
DOC	Diesel Oxidation Catalyst
ELPI	Electrical Particle Impactor
FTP	Federal Test Procedure
NEDC	New European Driving Cycle
NYCC	New York City Cycle
PAS	Photoelectric Aerosol-Sensor
PM	Particulate mass
PMP	Particle Measurement Program; an UN-ECE-program 2003-2007 to develop a number based particle measurement protocol, leading to [36]
PMS	«Partikelminderungssystem» - particle reduction system reaching at least 30 % reduction of PM
VERT	Verification of Emission Reduction Technology; a particle filter verification protocol used by Swiss authorities SUVA and BUWAL since 1998 [1]

REFERENCES

[1] Mayer et al.; Quality standards and test procedures for particle filters to retrofit utility vehicles; MTZ 00//2009

[2] Belot G. et al.; Passenger Car Serial Application of a Particulate Filter System on a Common Rail Direct Injection Diesel Engine, SAE 2000-01-0473, Detroit 2000

[3] Eckerle W.A.; Technology for Advanced Heavy Duty Diesel Engines, 12th ETH Conference on Combustion Generated Nanoparticles, Zürich, 2008

[4] Mayer A., et al.; Reliability of DPF-Systems: Experience with 6000 Applications of the Swiss Retrofit Fleet; SAE 2004-01-0076, Detroit 2004

[5] Massnahmen gegen die Verunreinigung der Luft durch Partikel von Kraftfahrzeugen mit Selbstzündungsmotor, Anhang zu Artikel 1 Nr. 4, Anlage XXVI, zu § 47 Abs. 3a der Strassenverkehrszulassungsordnung der Bundesrepublik Deutschland

[6] Rexeis M, Hausberger S: ARTEMIS, Assessment and Reliability of Transport Emission Models in Inventory Systems. Final Report of the WP400-Heavy Duty Vehicles Emission; Institut für Vkm and Thd, TU-Graz 2003

[7] Rembor H.J.; Hot Gas Filtration of Fine and Ultra Fine Particles, Particle Filter Retrofit for all Diesel Engines, Expert Verlag ISBN 978-3-8169-2850-8

[8] Okawara S. et al.; Soot trapping and continuously oxidizing behaviour by flow-through Metallic PM filter, Toyota Motor Corp., Emitec, JSAE Annual Congress Sept. 2005, paper No. 20055824

[9] Koltsakis G.C. et al.; Filtration and Regeneration Performance of a Catalyzed Metal Foam Particulate Filter, Aristotle Univ. Thessaloniki, Inco Special Products, SAE 2006-01-1524, Detroit 2006

[10] Kolke R. et al.; Einsatz wechselnder Filtersysteme und Regenerationsverfahren für die Nachrüstung von PKW, LKW, Baumaschinen. „Dieselabgasnachbehandlung", München 11.-12. Juli 2006, CTI Car Training Institute www.iir-verlag.de; info@iir-verlag.de; www.car-training-institute.com

[11] A.Mayer and 50 co-authors; Particle Filter Retrofit for all Diesel Engines; published by Expert-Verlag, 2008, ISBN 978-3-8169-2850-8

[12] Andrews G.E. et al.; Particulate Mass Accumulation and Release in Practical Diesel Engine Exhaust Systems under Cold Start conditions, SAE 2000-01-0508, University of Leeds, Ford Research, 2000

[13] Kolke R. et al.; ADAC Verbraucherschutztest an Nachrüstfilter für PKW, 6. FAD-Konferenz, Herausforderung – Abgasnachbehandlung für Dieselmotoren, November 2008 in Dresden

[14] Rüdy C. et al.; Nachrüst-Partikelfilter für Diesel-Personenwagen, EMPA Untersuchungsbericht Nr. 441179, Dezember 2006, EMPA, Überlandstrasse 129, CH 8600 Dübendorf

[15] Hausberger St. Et al.; Testverfahren und Optimierung für Partikelkatalysatoren, Bericht des Instituts für Verbrennungskraftmaschinen und Thermodynamik, TU Graz, Inffeldgasse 21A, A-8010 Graz, Februar 2006

[16] Nylund N.O. et al.; Heavy-duty Vehicles : Safety, Environmental Impacts and new Technology, VTT Annual report 2006

[17] Mayer A. et al.; Nanoparticle-Emission of EURO 4 and EURO 5 HDV Compared to EURO 3 with and without DPF, SAE 2007-01-1112, Detroit 2007

[18] Mohr M. et al.; Conventional and New Methods of Particle Measurement, Elimination of Engine Generated Nanoparticles, expert verlag ISBN 3-8169-2552-9

[19] Rice M. et al., Innovative Substrate Technology for High Performance Heavy Duty Truck SCR Catalyst Systems, SAE 2007-01-1577, Detroit 2007

[20] Brück, R and Reck,A.; Retrofit with Particulate Traps – the first Step; Experience and Outlook into the Future; 6.FAD-Conference Dresden, Nov.2008

[21] Schrewe K. et al.; SMF – AR Autarkes Partikelfiltersystem für Nach- und Erstausrüstung von LDV und Industriemotoren, 6. FAD-Konferenz, Herausforderung – Abgasnachbehandlung für Dieselmotoren, November 2008 in Dresden

[22] Bykowski B.; Formulation and Evaluation of Alternate Diesel Particulate Trap Media, Southwest Research Institute, The American Society of Mechanical Engineers, 87-ICE-36

[23] Mizra T. et al., Open-Pore Ceramic Foam as Diesel Particulate Filter, SAE 890172

[24] Van Basshuysen, Schäfer; Handbuch Verbrennungsmotor, published by Vieweg&Sohn, ISBN 3-528-03933-7; page 633

[25] H.Jodeit; Partikelabscheidung in technischen Tiefenfiltern; VDI-Fortschrittsberichte Verfahrenstechnik Nr.108, VDI-Verlag 1985

[26] Mayer A. et al., Pre-Turbo Application of the Knitted Fiber Diesel Particulate Trap, SAE 940459, Detroit 1994

[27] Allansson R. et al.; The use of the Continuously Regenerating Trap (CRT ™) to Control Particulate Emissions: Minimising the Impact of Sulfur Poisoning, SAE 2002-01-1271, Detroit 2002

[28] Stationary source emissions – Determination of mass concentration of nitrogen oxides (NOx) - Reference method: Chemiluminescence; European Standard, EN 14792, June 2005

[29] Payne S. et al.; Fundamental Studies of Soot Deposition Using Flow-through Substrates, 12th ETH Conference on Combustion Generated Nanoparticles, Zürich, 2008

[30] Gojova A. et al.; Induction of Inflammation in Vascular Endothelial Cells by Metal Oxide Nanoparticles: Effect of Particle Composition, Environmental Health Perspectives – Volume 115, Number 3, March 2007

[31] U.S.EPA : The Cost Effectiveness of Heavy-Dutydiesel Retrofits and Other Mobile Source Emission Reduction Projects and Programs; EPA 420-B-07-006; May 2007

[32] Jacobson M.Z.; Testimony for the Hearing on Black Carbon and Global Warming, Stanford University, United States House of Representative, October 2007

[33] Waxman H.A.; Hearing on Black Carbon and Global Warming, US House of Representatives, October 2007

[34] Leutert, G. Quality Criteria, Test Methods and Test Standards for Particle Filter Systems; chapter 7 of [11]

[35] Görsmann, C.; Catalytic Coatings for diesel Particulate Trap Regeneration; chapter 5.1 of [11]

[36] Regulation (EC) No. 715/2007 for the European Parliament and the Council of 20.June 2007 on type approval of motor vehicles ...

Experimental program with retrofit open particulate filters for diesel trucks

TNO: René van Asch, **Gerrit Kadijk,** Ruud Verbeek
VROM: Henk Baarbé

TNO | Knowledge for business

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2. Objectives
3. Experimental set up
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1. Introduction

- In The Netherlands from 2006 onwards installation of HD retrofit soot filters (semi-open and closed) have been subsidized by the Dutch government
- HD retrofit soot filters

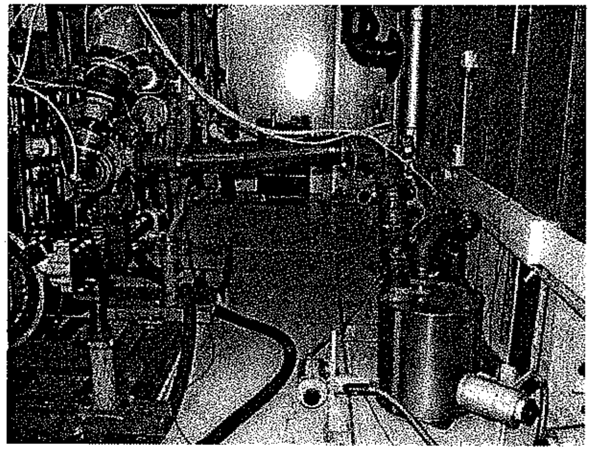
Type/Name	Req.eff. [%]	Subsidy [€]		Number installed
		150-225 kW 2006 / 2009	> 225 kW 2006 / 2009	2006 - 2009
Open / PM-cat	> 50%	4250 / 0	6250 / 0	15000
Closed / DPF	> 90%	7000 / 5500	9000 / 0	8000

2. Objectives

- Determination of the efficiency of used retrofit open particulate filters (PM-cat) for trucks in **real world** conditions

- PM-cat efficiency in urban areas?
- Effect of 1 hour motorway use on efficiency in urban areas?
- Aging effects?
- Soot loading versus efficiency?
- Regeneration behaviour

3. Experimental set up



Part 1:

- 1 HD-engine 355 kW Euro III on **engine dynamometer** (TNO-The Netherlands)
- 6 used PM-cats (open)

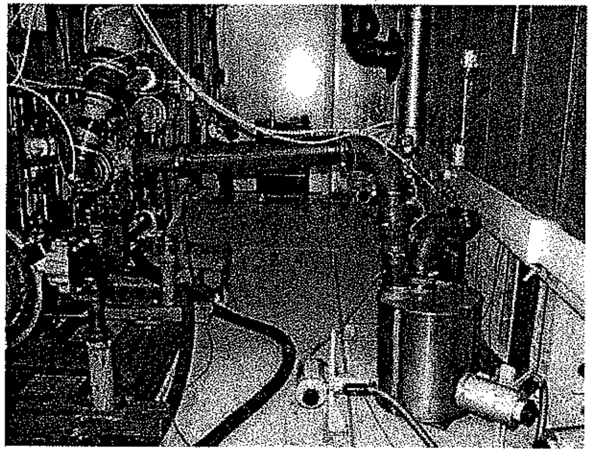
Part 2:

- 3 different Euro III delivery trucks on **chassis dynamometer** (VTT-Finland)
- 7 used PM-cats (open)

3. Experimental set up engine dyno

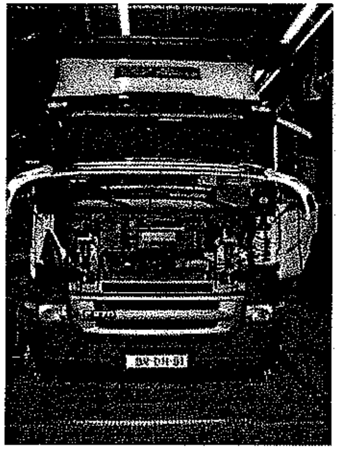
- 12 litre Euro III engine, 355 kW
- Full flow dilution tunnel + CVS
- AVL 439 smoke meter
- EN590 fuel (S<10 ppm)

- 6 used PM-cats of 1 type (pre oxicat + filter element)
- 65 emission tests engine out
- 130 emission tests PM-cat 1 - 6



3. Experimental set up chassis dyno

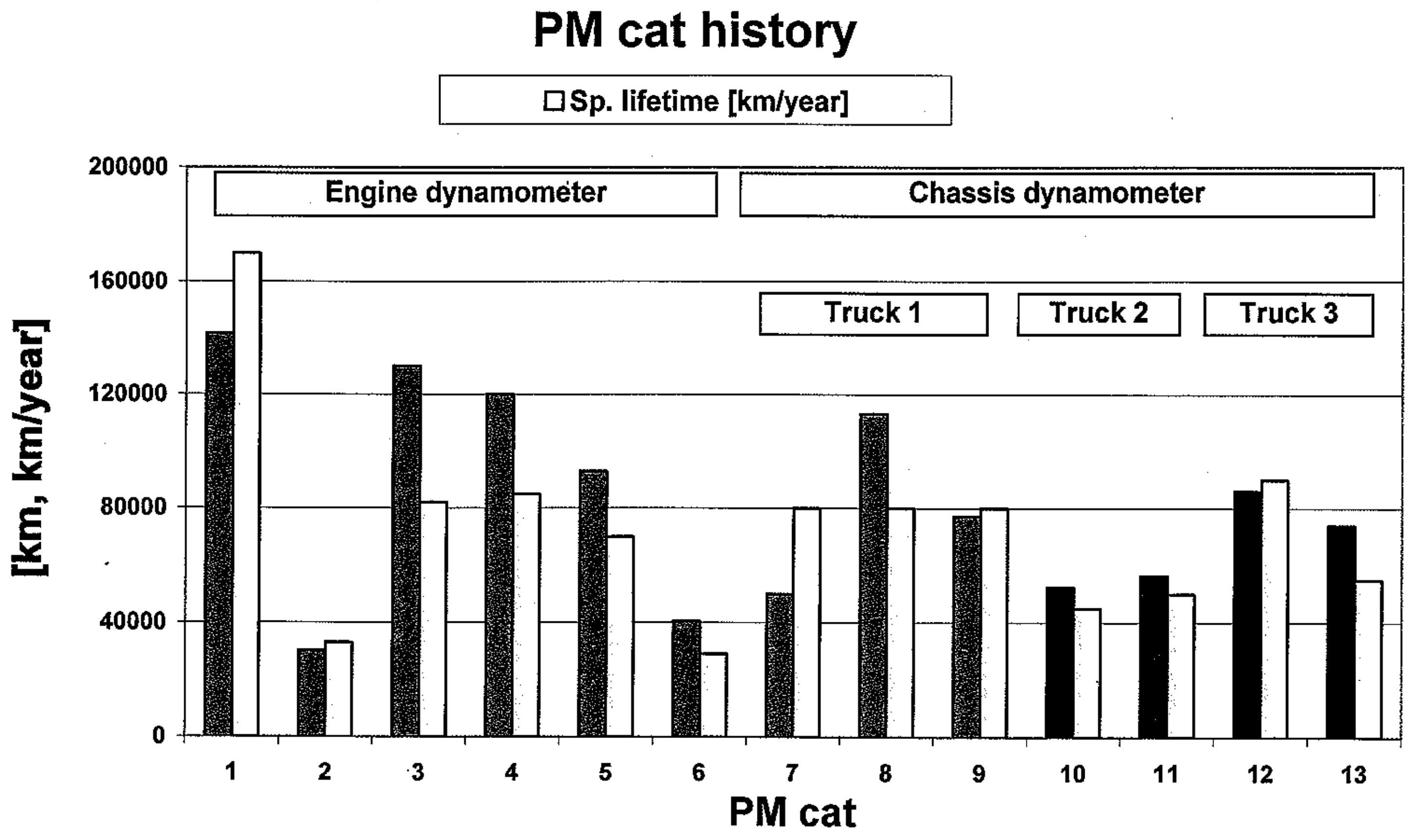
- 3 different delivery trucks Euro III
- Chassis dynamometer
- Full flow dilution tunnel + CVS
- EN590 fuel (S<10 ppm)



- 7 used PM-cats of 4 types
- 70 emission tests engine out
- 145 emission tests with PM-cat

Number of emission tests		
	Engine out	PM-cat
Truck 1	21	61
Truck 2	25	42
Truck 3	24	42

3. History and use 13 PM-cats



- 10 PM-cats 80.000 – 140.000 km and 3 PM-cats 30.000 – 50.000 km
- Most PM-cats have run 1 – 1,5 year

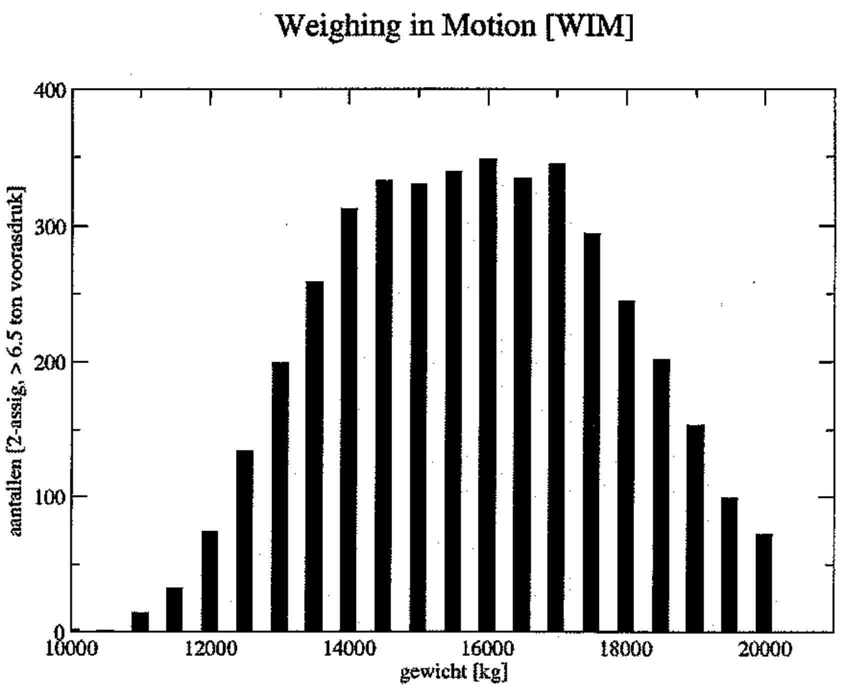
4. Test cycles

Engine dynamometer	**Chassis dynamometer**
WHTC urban part cold 900 s	City Cycle 11,5 tonne 1234 s
WHTC urban part hot 900 s	City Cycle 18,5 tonne 1234 s
ETC (Type approval PM-cat) 1800 s	Motorway 11,5 tonne 1272 s
Motorway (85 km/h)	Motorway 18,5 tonne 1272 s

Do the test cycles cover real world conditions?

4. Motorway total vehicle weight distribution truck

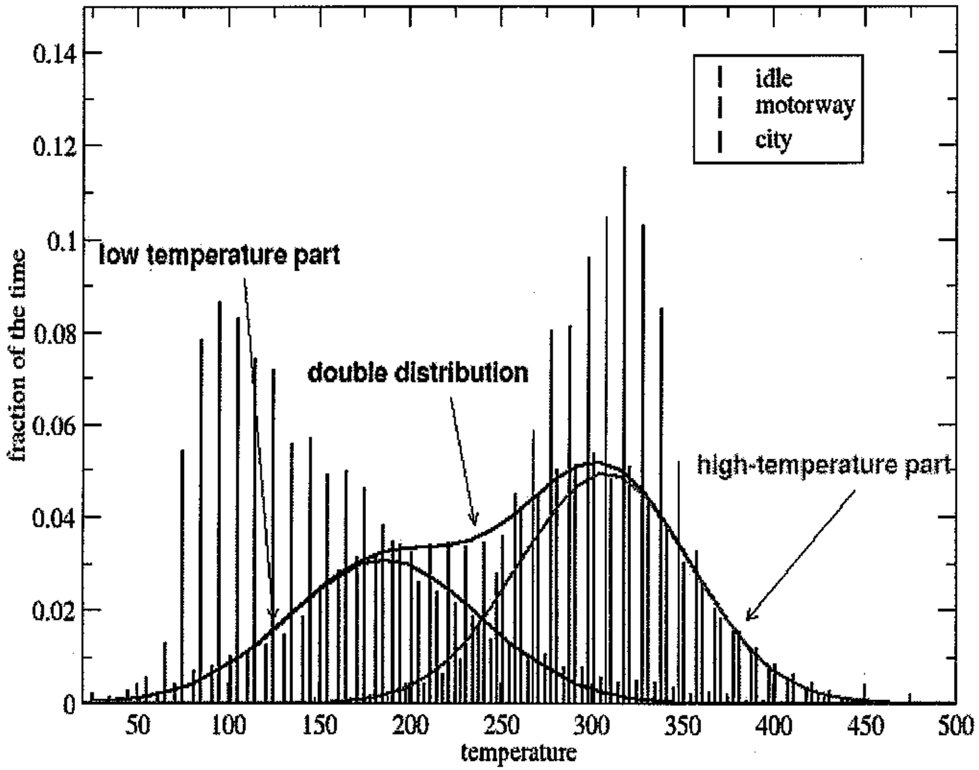
(real world)



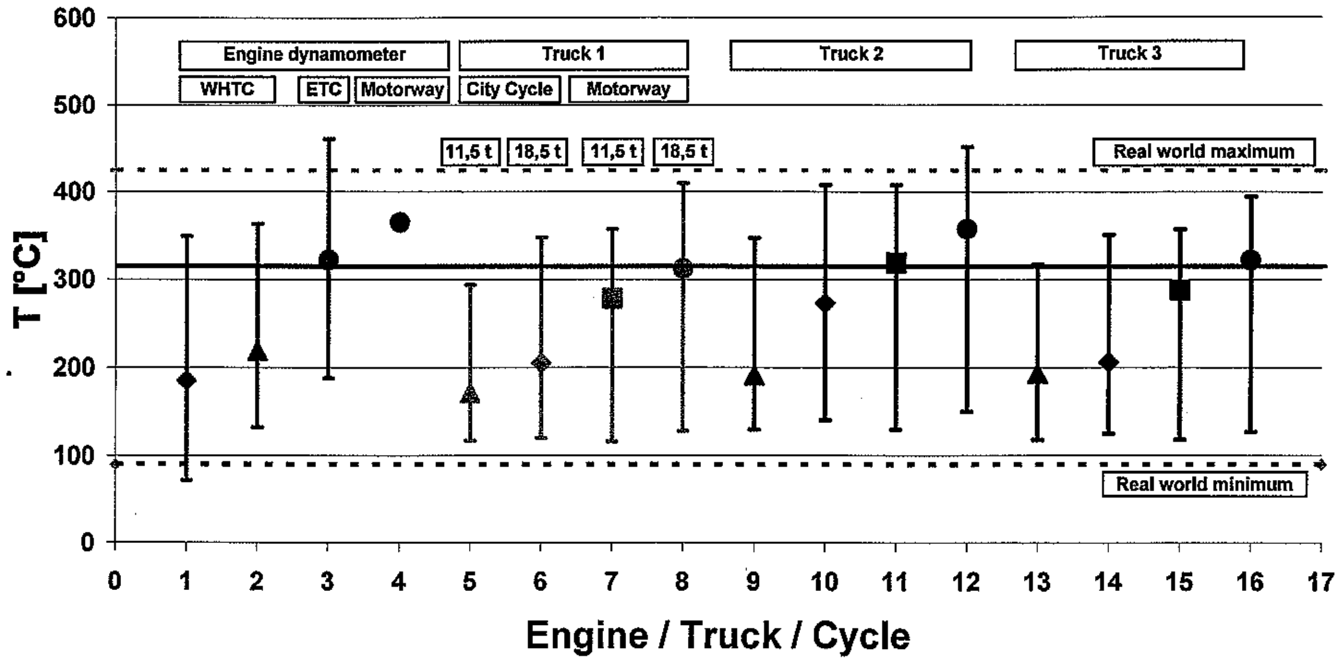
- **Minimum truck weight 11 tonne, Maximum truck weight 20 tonne**
- (source: highway automatic truck weighing system, 4000 trucks).

4. Delivery truck real world temperature distribution

- Data: 1 truck, 300 days, 24h per day
- User profile: Start 90% vehicle load, motorway. Generally re-load at mid day. Empty in 2-3 stops (half day)



5. Test results temperatures pre PM-cat

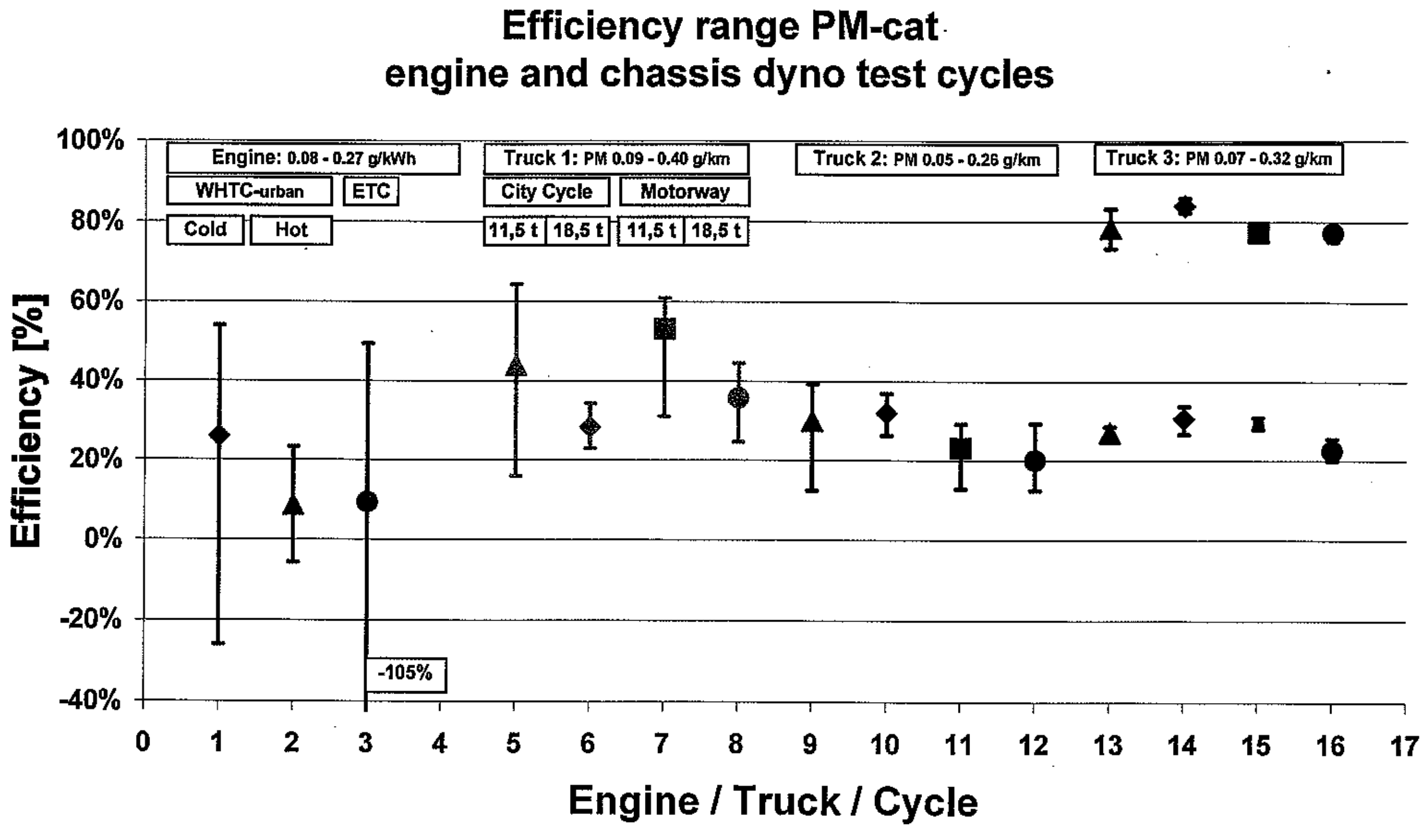


Temperature range pre PM-cat
engine and chassis dyno test cycles + real world

- Real world and laboratory PM-cat temperatures are similar
- Temperature pre PM-cat is adjusted to a real world level by adjustment of absorbed load

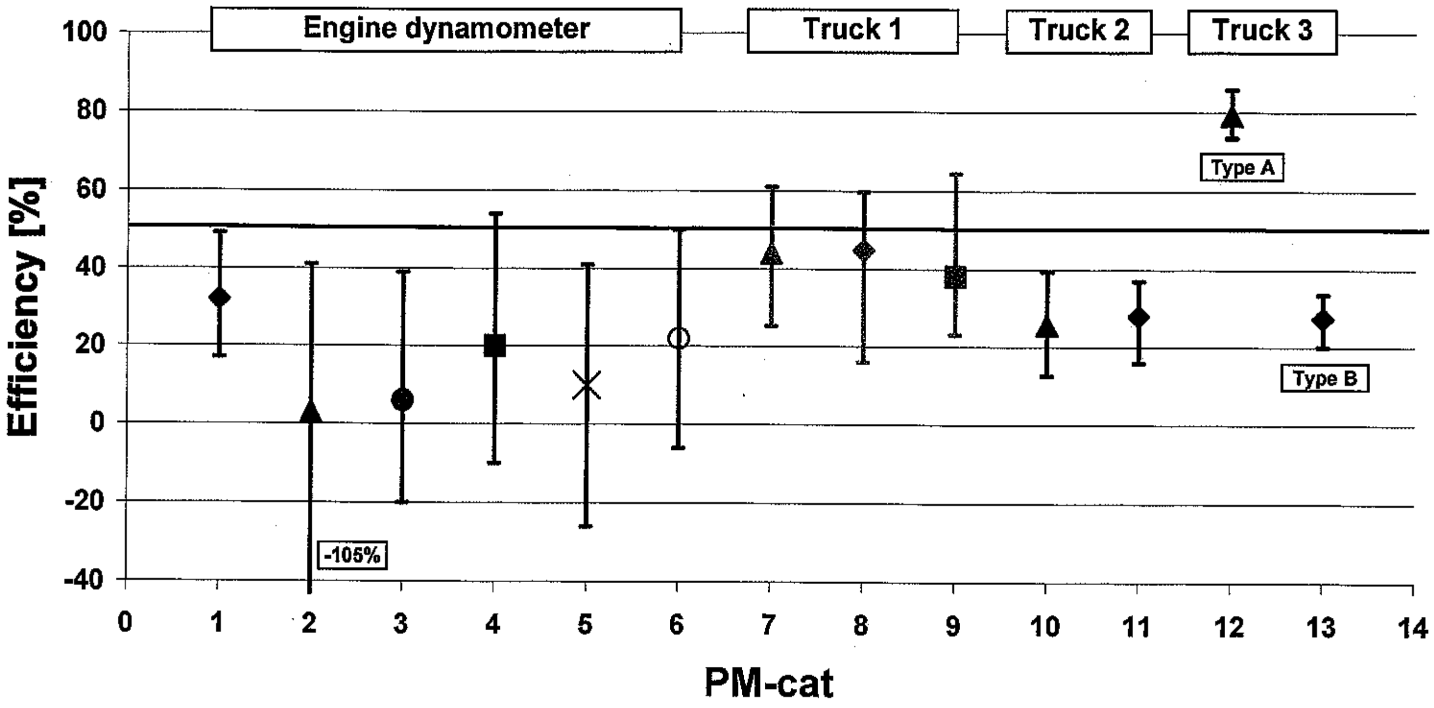
5. Test results PM-cat efficiencies per cycle

(minimum, average, maximum)



Some PM-cats have large variation in efficiency

5. Individual PM-cat efficiencies



Efficiency range PM-cats
engine and chassis dyno tests

- Real world average efficiency of 13 PM-cats is 29.3 %.
- 1 PM-cat has an average efficiency of more than 50%

6. Discussion and conclusions

- Strong variation in efficiency between different PM-cat truck combinations

- Real world PM-cat efficiency lower than type approval:
  - Total average = 29 %
  - City driving = 29 %
  - Motorway driving = 29 %

- PM-cat efficiency is very dependent on the historic load pattern
  - Start type approval with realistic loaded PM-cat (>1 week real world)
  - real world load pre-conditioning (250 – 275 °C) should be a part of the type approval

- Separate test cycles for city and motorway driving should be considered for type approval

Thank you very much for your attention !

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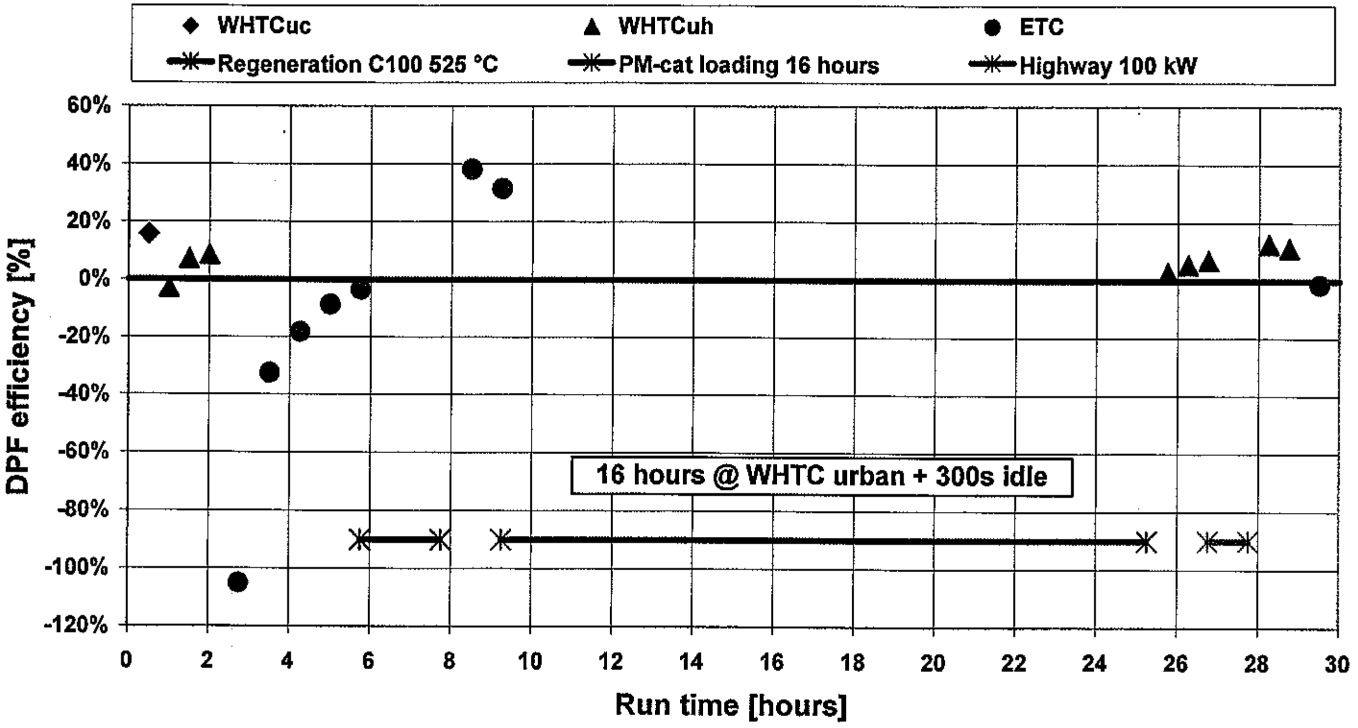
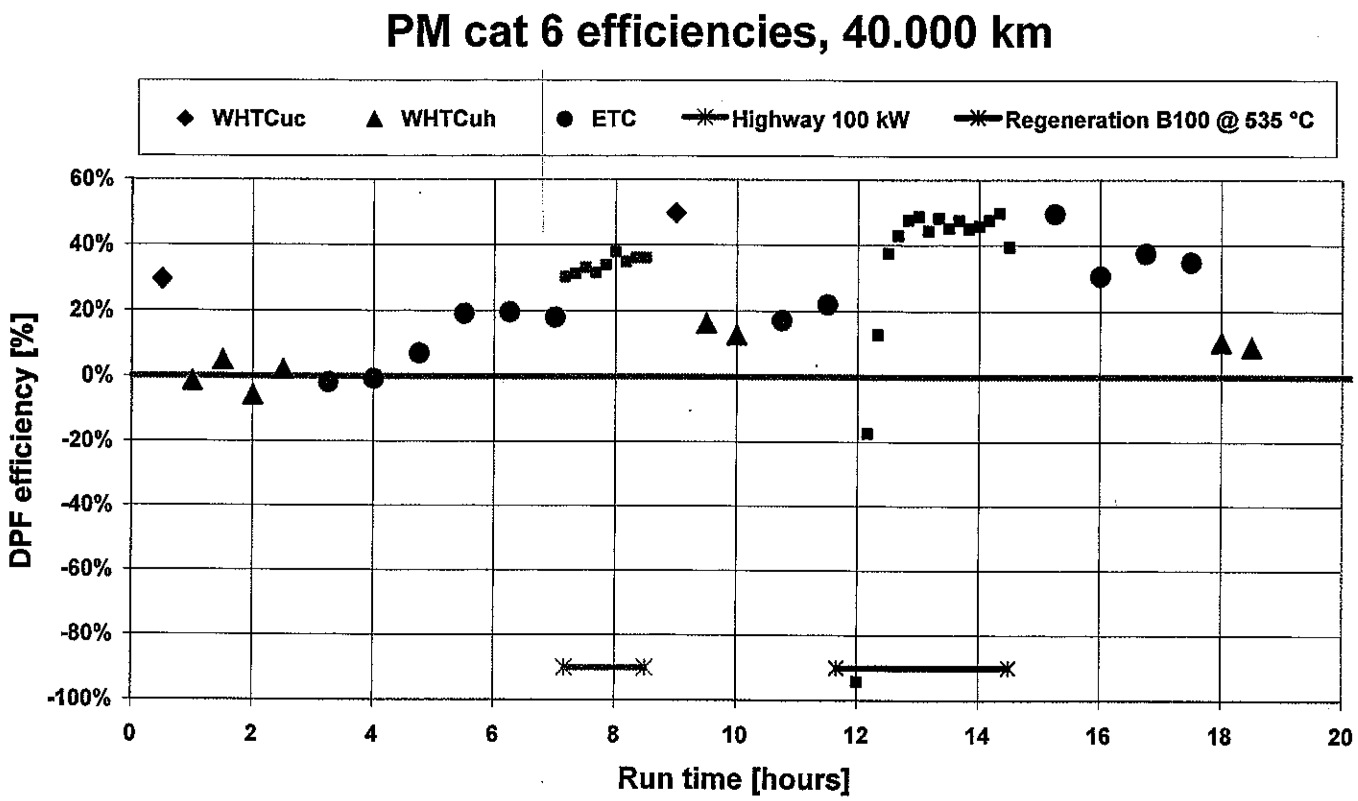
5. Results PM-cat 2 engine dyno (33.000 km/year)



PM cat 2 efficiencies, 30.000 km

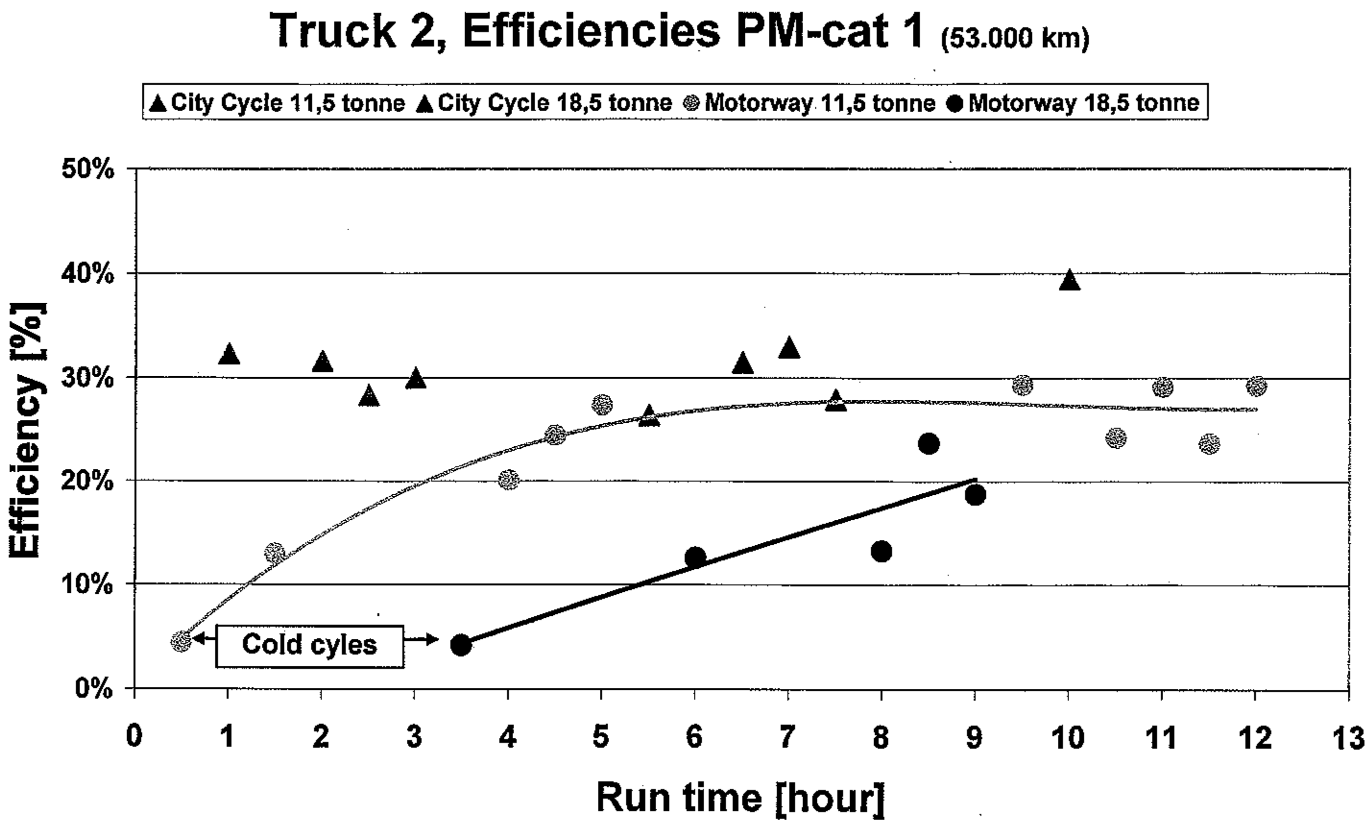
- PM-cat 2 has negative efficiencies and probably is loaded with PM (history)
- Stored PM releases during ETC-tests (PM-cat efficiency -107% - -3%)
- Extreme regeneration (2 hours @ 500 °C) removes stored PM. PM-cat efficiency is 40 and 32%
- 16 hours WHTC-urban + idle + 1 hour motorway results in an inactive PM-cat (eff. -1 - +13%)

5. Results PM-cat 6 engine dyno (29.000 km/year)



- First tests PM-cat efficiency is 0% and increases to 20% at higher loads (history)
- Steady state testing: PM-cat efficiency is 35 - 50%
- PM-cat efficiency in WHTC-urban cycle is - 6 – 5 – 16%
- After heavy regeneration PM-cat efficiency in ETC-test is 31 – 50%.

5. Results PM-cat 1 chassis dyno Truck 2, 45.000 km/yr



Truck 2, Efficiencies PM-cat 1 (53.000 km)

- PM-cat history determines efficiency
- After a period of city use, the PM-cat efficiency on the motorway is poor