Testing of particulate emissions from positive ignition vehicles with direct fuel injection system

Technical Report

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1. List of Abbreviations

A4 / A5 / A6	4-speed / 5-speed / 6-speed automatic gearbox
CO	Carbon monoxide
CO_2	Carbon dioxide
CVS	Constant Volume Sampler; exhaust emission sampling system
EC	European Community
EUDC	Extra Urban Driving Cycle; Part 2 of the New European Driving Cycle
Euro 5, Euro 6	Type approval test in accordance with Directive 715/2007/EC
FC	Fuel consumption
HC	Hydro carbons; see THC
M1	Vehicles for passenger transportation with a capacity of max. 8 seats excluding the driver and a maximum total vehicle mass of 3,500kg
M5 / M6	5-speed / 6-speed manual gearbox
NEDC	New European Driving Cycle according to Directive 715/2007/EC
NO_X	Nitrogen oxides
OBD	On-Board Diagnosis
PEMS	Portable Emission Measurement System
PM	Particle Mass
PN	Particle Number
RPA	Relative Positive Acceleration
SHED	Sealed Housing for Evaporative Emissions Determination
SFTP – US06	Supplemental Federal Test Procedure
THC	Total Mass of hydro carbons emitted by a vehicle, given in C_1 equivalent
TSN	Type code number
T&E	Transport and Environment
UDC	Urban Driving Cycle; Part 1 of the New European Driving Cycle
UNECE	United Nations Economic Commission for Europe
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

2 Summary

Within this testing programme the possibility of using a particle filter on vehicles with positive ignition engine and direct fuel injection system to bring down the high particle emissions was analysed.

Three vehicles with positive ignition engine and direct fuel injection system were measured on the chassis dynamometer in serial condition and with a particle filter mounted in the exhaust system.

All vehicles were approved according to Commission Regulation (EC) 715/2007 (Euro 5). During the programme the New European Driving Cycle (NEDC) given by Regulation 715/2007 was used to prove that no emission related problem could influence the values. All cars complied with the approved values and the limits given by regulation.

In addition the upcoming Worldwide Harmonized Light Vehicles Test Cycle (WLTC) was driven to demonstrate that the particle number emissions occur in the new cycle as well as in the NEDC.

The Supplemental Federal Test Procedure (SFTP) US 06 Cycle was used to demonstrate the possibility of reducing the particle emissions by using a particulate filter in cars with positive ignition engines. Therefore the cycle was driven in serial condition and in addition equipped with a filter.

The values measured during the programme show that the use of a particulate filter also in a car with positive ignition engine and direct injection system provides an opportunity of a significant reduction of particle emission.

The decrease of the measured particulate mass was about 2/3, the particulate number could be reduced by 10 to the power of 3. All cars equipped with a particle filter fulfilled the Euro 6c limit which will be 6.0x10 to the power of 11.

3 Project Implementation

3.1. Investigation Programme

Within the framework of this programme a total of 3 vehicles with positive ignition engine and direct fuel injection system were tested in serial condition and with a particulate filter mounted in the exhaust system.

The measurements were carried out in the respective type approval cycle, i.e. the "New European Driving Cycle“ (NEDC) in accordance with Commission Regulation (EC) 715/2007. In addition to this the upcoming WLTC (Worldwide harmonized Light Vehicles Test Cycle) and the SFTP-US06 (Supplemental Federal Test Procedure) Cylce were tested. The different driving cycles are shown in **section 3.3**. NEDC-, WLTC- and SFTP-US06-Cycle were driven with vehicle in serial condition, SFTP - US 06-cycle was repeated after a particulate filter had been mounted in the exhaust system.

During the measurements on the dynamometer, the emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X) and carbon dioxide (CO_2) were collected in bags in accordance with the regulations and the integral values were determined. For all vehicles particle mass and number was determined according to Commission Regulation (EC) 715/2007. In addition the gaseous and particle number emissions were measured second by second. The results of the modal measurements serve as the basis for the evaluation of the exhaust emissions that appear during the cycle.

In addition to exhaust emissions, fuel consumption was determined in accordance with Commission Regulation (EC) 715/2007. The fuel consumption was calculated from the emissions of the carbon-containing exhaust components (CO_2, CO and HC).

3.2. Vehicle Selection

The vehicles were selected by the customer Transport and Environment (T&E).
All three vehicle types were approved according to Commission Regulation (EC) 715/2007 and fulfilled the Euro 5 limit
Table 3.1 shows the exhaust emission-limit valid for the type approval test of passenger cars and light duty vehicles. The "New European Driving Cycle" is described in section 3.3.

Engine	Limit	Vehicle Class *)	Reference Mass (RM) [kg]	CO [mg/km]	HC [mg/km]	NMHC [mg/km]	NO_x [mg/km]	PM [mg/km]	PN [#/km]
Gasoline	Euro 5	M1 ≤ 2500kg	All	1000	100	68	60	4,5	$6{,}0*10^{11*}$

*) $6{,}0*10^{11}$ valid for positive ignition engine vehicles Euro 6c

Table 3.1: Emission limits for passenger cars and light-duty vehicles, valid for the Type I test (NEDC)

The vehicle selection was done in cooperation with local dealers to guarantee a good maintenance condition of the vehicles. Further criteria such as kilometre reading and date of first registration were taken into consideration. When the vehicles were taken over for the programme, additional data regarding repairs carried out on the vehicles as well as deviations from the series production condition was noted. The components which are relevant for exhaust emissions were checked for directly recognisable damage. OBD information was read to ensure that no emission relevant fault code was stored.

The following criteria were used as a basis when selecting individual vehicles:

- regular servicing according to manufacturer's advice
- vehicle is unmodified series production model
- no mechanical damage to components

The vehicles which were investigated are shown in **Table 3.2** along with the relevant technical data.

Type No.	Manufacturer	Trade name	Transmission	Engine type	Engine capacity [cm^3]	Power [kW]	Emission approval	Mileage [km]	Registration year
1	Ford	Forcus Tunier	Manual 6 gear	1.0l EcoBoost	998	92	Euro 5	10,681	2013
2	Hyundai	i 40 Kombi	Manual 6 gear	1.6l GDI	1591	99	Euro 5	11,000	2013
3	Renault	Megane	Manual 6 gear	1.2l Energy TCe 115	1198	85	Euro 5	14,500	2013

Table 3.2: Vehicles

3.3. Implementation of Tests

After the vehicles had been received at the laboratory, a check was made as to whether the specified maintenance intervals had been observed and that the vehicles were in a proper condition. Proof was provided by means of the service record manual. Before commencement of the measurements on the chassis dynamometer, the vehicles were checked with respect to the tightness of the exhaust system.

For dynamometer setting the same inertia weight and coast down values were chosen as for the type approval test.

The vehicles were tested in a measuring programme which includes three different Driving Cycles: NEDC, WLTC and US 06.

An OBD check was done at the beginning and the end of test procedure to make sure that failures could not affect the results of the tests. **Table 3.3** displays the procedure of the different tests during the programme.

Step	Item	Number	Condition
1	Coast down	1	--
2	Precon NEDC	1	--
3	NEDC	2	Cold (min. 6 hours soak time)
4	Precon WLTC	1	--
5	WLTC	2	Cold (min. 6 hours soak time)
6	Precon US 06	1	--
7	US 06	2	Warm (after 10 minutes 80km/h)
8	Filter installation		--
9	US 06	2	Warm (after 10 minutes 80km/h)

Table 3.3 Test programme

The different driving cycles are illustrated in the following section.

New European Driving Cycle (NEDC)

After conditioning the vehicle for at least 6 hours at an ambient temperature of 20 °C up to 30 °C the New European Driving Cycle (NEDC) begins with a cold start. The Urban Driving Cycle (UDC) has a duration of 780 seconds, a driving distance of 4.1 km, an average speed of 19 km/h and a maximum velocity of 50 km/h. It is followed by an Extra Urban Driving Cycle (EUDC) with a duration of 400 seconds, a driving distance of 6.9 km, an average speed of 62.6 km/h and a maximum velocity of 120 km/h. Exhaust emissions of both UDC and EUDC are combined to get a total test result.

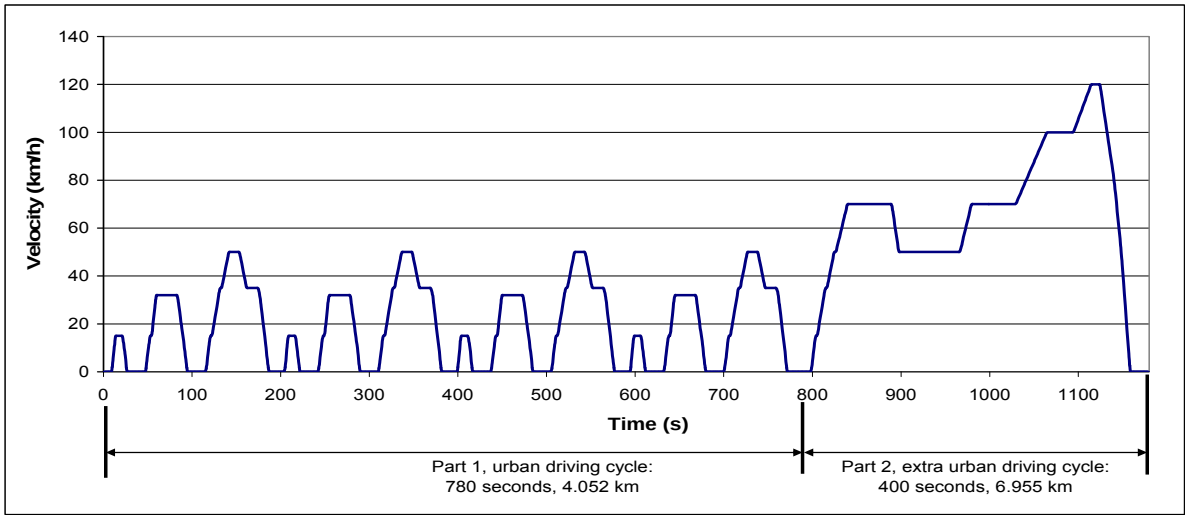

Figure 3.2: New European Driving Cycle

Worldwide Harmonized Light Vehicles Test Cycle (WLTC)

For the upcoming WLTP Cylce there are different parts existing. The first part is a low speed part, the second driven with medium speed followed by a high speed part and a extra high speed part. As a function of the mass and the power of the test vehicle the Cycle is generated by changing the different parts.
For this programme the WLTC class 3b (>120km/h) had to be selected.**Figure 3.3** shows this cycle:

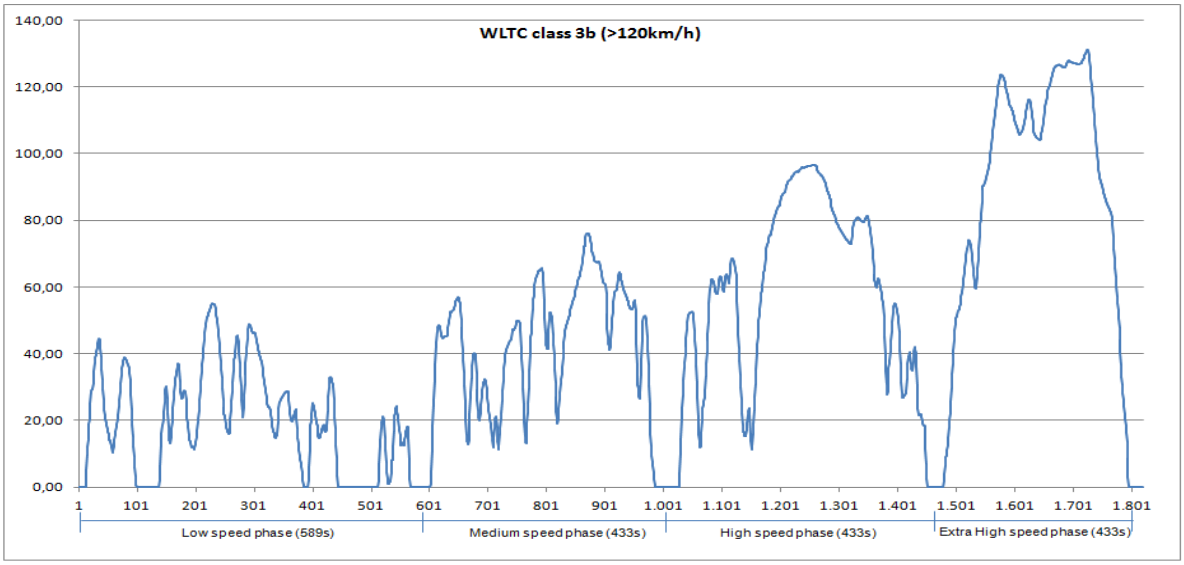

Figure 3.3: WLTC class 3b (>120km/h)

Supplemental Federal Test Procedure Cycle (US 06)
Figure 3.4 shows the SFTP US 06 cycle. This cycle contains a number of strong acceleration and is driven in warm conditions.

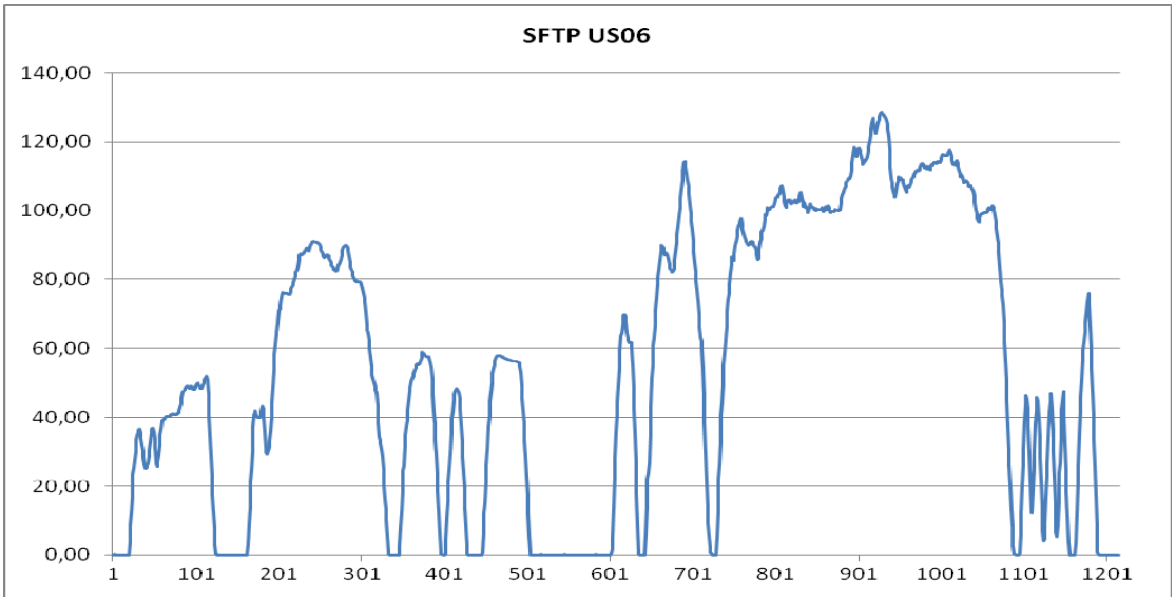

Figure 3.4: **SFTP US06**

3.4. Particulate Measurement

For particle number detection Commission Regulation (EC) 715/2007 specifies the Condensation Particle Counter (CPC). The CPC determines the number concentration of particles contained in the exhaust emissions. The particles are enlarged by condensation and counted by the method of light scattering. For particle number (PN) detection, a complex sampling system is used. The particles are preclassified by a cyclone. The pre-classifier 50 per cent cut point particle diameter shall be between 2.5 µm and 10 µm. For counting particles, the sample has to be diluted within two steps. To eliminate condensed volatile hydrocarbons the probe is heated to a temperature between 150°C up to 300°C and cooled down again for measuring. **Figure 3.5** illustrates the sampling system for particle number determination.

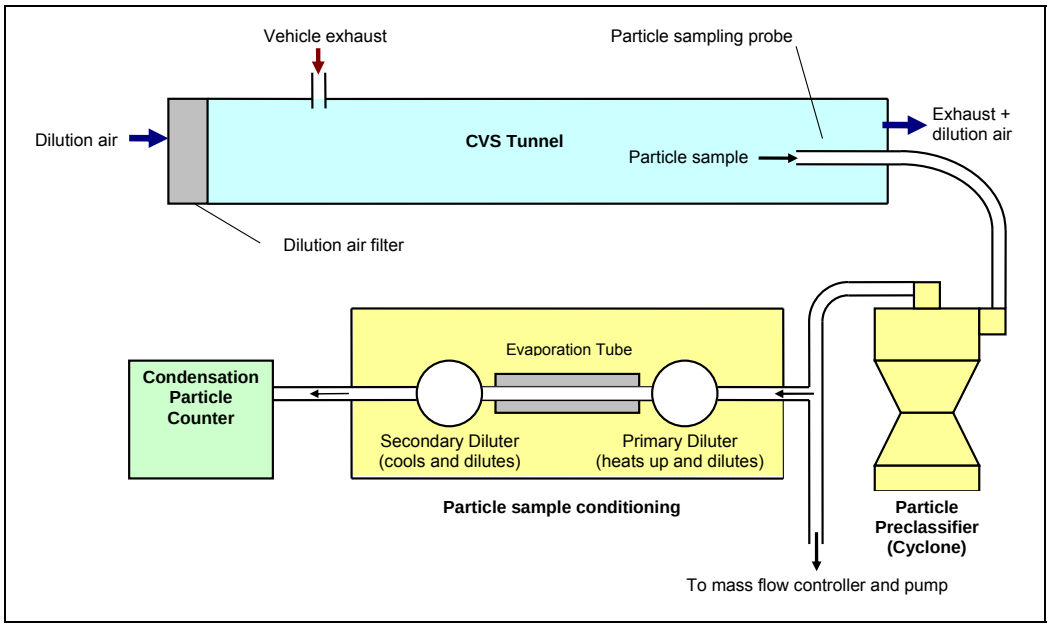

Figure 3.5: Sampling system for particle number detection

The update of European exhaust emission legislation proposes particle limits both for vehicles with compression ignition engine and vehicles with positive ignition engine and direct injection. The limits for particle emissions are given in **Table 3.4.**

Category	Reference Mass (RM) [kg]	Euro 5a	Euro 5b	Euro 6b	Euro 6c
		Gasoline Direct Injection			
		PM [mg/km]	PM [mg/km]	PN [#/km]	PN [#/km]
M1	All	5.0	4.5	6.0E+12	6.0E+11

Table 3.4: Commission Regulation (EC) 715/2007

4. Presentation of Results

In the following sections the values for the measured exhaust emissions and CO2 Emissions of the various vehicles in the different cycles are examined. **Figure 4.1** shows the Average Exhaust emissions measured during the three different cycles driven without particulate filer.

Vehicle	Cycle	Average Exhaust Emissions						
		HC	NMHC	NOX	CO	CO2	PM	PN
		[mg/km]	[mg/km]	[mg/km]	[mg/km]	[g/km]	[mg/km]	[1/km]
FORD	NEDC 1	74,665	67,322	54,981	423,852	124,857	2,365	2,363E+12
	NEDC 2	70,360	62,963	58,519	373,563	124,152	2,071	2,275E+12
	Average	72,512	65,143	56,750	398,708	124,504	2,218	2,319E+12
	LIMIT (Euro 6c)	**100**	**68**	**60**	**1000**	**--**	**4,5**	**6,0E+11**
	WLTC 1	42,809	37,749	69,705	274,312	126,667	1,947	2,371E+12
	WLTC 2	45,857	40,979	71,090	267,506	127,839	2,250	2,463E+12
	Average	**44,333**	**39,364**	**70,398**	**270,909**	**127,253**	**2,099**	**2,417E+12**
	US06 1	18,446	14,597	97,480	486,095	154,803	1,812	2,189E+12
	US06 2	16,655	13,133	89,897	520,930	154,633	1,283	1,833E+12
	Average	**17,551**	**13,865**	**93,688**	**503,513**	**154,718**	**1,548**	**2,011E+12**
Hyundai	NEDC 1	23,203	21,229	4,888	314,617	170,272	1,487	2,710E+12
	NEDC 2	23,596	21,448	5,174	353,090	171,185	1,305	2,491E+12
	Average	**23,400**	**21,339**	**5,031**	**333,853**	**170,729**	**1,396**	**2,600E+12**
	LIMIT (Euro 6c)	**100**	**68**	**60**	**1000**	**--**	**4,5**	**6,0E+11**
	WLTC 1	15,794	14,537	7,194	353,085	167,399	1,496	2,454E+12
	WLTC 2	15,106	13,849	7,620	345,454	167,366	1,392	2,227E+12
	Average	**15,450**	**14,193**	**7,407**	**349,269**	**167,382**	**1,444**	**2,341E+12**
	US06 1	6,327	5,328	10,652	3663,752	179,237	1,879	2,676E+12
	US06 2	4,950	4,132	16,110	3262,322	179,007	1,740	2,819E+12
	Average	**5,639**	**4,730**	**13,381**	**3463,037**	**179,122**	**1,810**	**2,747E+12**
Renault	NEDC 1	24,038	21,672	9,735	143,772	155,542	3,058	3,735E+12
	NEDC 2	29,106	26,322	13,682	154,373	149,222	3,819	4,214E+12
	Average	**26,572**	**23,997**	**11,709**	**149,073**	**152,382**	**3,439**	**3,974E+12**
	LIMIT (Euro 6c)	**100**	**68**	**60**	**1000**	**--**	**4,5**	**6,0E+11**
	WLTC 1	15,703	13,672	29,045	103,011	150,843	3,944	5,282E+12
	WLTC 2	12,267	10,389	13,191	99,561	150,752	3,680	4,713E+12
	Average	**13,985**	**12,031**	**21,118**	**101,286**	**150,798**	**3,812**	**4,997E+12**
	US06 1	12,550	8,889	49,998	524,570	167,169	4,534	4,568E+12
	US06 2	11,475	8,415	24,599	662,595	166,197	4,025	5,621E+12
	Average	**12,013**	**8,652**	**37,298**	**593,582**	**166,683**	**4,279**	**5,095E+12**

Table 4.1: Average Exhaust emission without filter

All vehicles tested complied with the limits given in Commission Regulation (EC) 715/2007 during the NEDC. In comparison the WLTC shows slightly lower results. The results of the US06 cycle show that dynamic driving causes the highest emission- and CO2-values. With focus on the particulate emission all measured values were higher than the limit given for vehicles with compression ignition engine (6,0E+11). With the new legislation Euro 6c vehicles with positive ignition engine have to fulfil this limit.

In **Table 4.2** the average of the measured exhaust emissions for the different vehicles after a particulate filter was placed in the exhaust system:

Vehicle	Cycle	Average Exhaust Emissions						
		HC	NMHC	NOX	CO	CO2	Particle	Particle number
		[mg/km]	[mg/km]	[mg/km]	[mg/km]	[g/km]	[mg/km]	[1/km]
FORD	US06 1	13,982	10,517	86,001	357,879	150,080	0,779	3,332E+09
	US06 2	12,891	9,229	94,283	637,941	148,899	0,286	3,867E+10
	Average	**13,437**	**9,873**	**90,142**	**497,910**	**149,489**	**0,532**	**2,100E+10**
	LIMIT NEDC (Euro 6c)	**100**	**68**	**60**	**1000**	**--**	**4,5**	**6,0E+11**
Hyundai	US06 1	7,701	6,783	8,656	2594,347	170,813	0,639	5,825E+10
	US06 2	7,064	6,222	9,891	3535,702	173,156	0,698	8,863E+10
	Average	**7,383**	**6,503**	**9,273**	**3065,025**	**171,985**	**0,668**	**7,344E+10**
	LIMIT NEDC (Euro 6c)	**100**	**68**	**60**	**1000**	**--**	**4,5**	**6,0E+11**
Renault	US06 1	11,880	8,088	21,997	475,978	163,110	1,284	2,336E+09
	US06 2	13,734	10,301	26,086	320,240	162,062	0,666	2,617E+09
	Average	**12,807**	**9,195**	**24,042**	**398,109**	**162,586**	**0,975**	**2,477E+09**
	LIMIT NEDC (Euro 6c)	**100**	**68**	**60**	**1000**	**--**	**4,5**	**6,0E+11**

Table 4.2: Average Exhaust emission with filter

Table 4.2 shows the direct influence on the particulate mass and number during the dynamic US 06 cycle. In the direct comparison of the average values the decrease of particulate mass comes up to factor of 3 for the Ford and the Hyundai and a factor of 4 for the Renault.

Fitting a particulate filter in the exhaust system reduce the particulate mass about a factor of 3.5 compared with a serial car. With focus on the particulate number, this effect is repeated. All cars complied with the upcoming limit for vehicles with positive ignition engine after a particulate filter was placed in the exhaust system.

Figure 4.1 indicates the mentioned effect with the average particulate mass in mind:

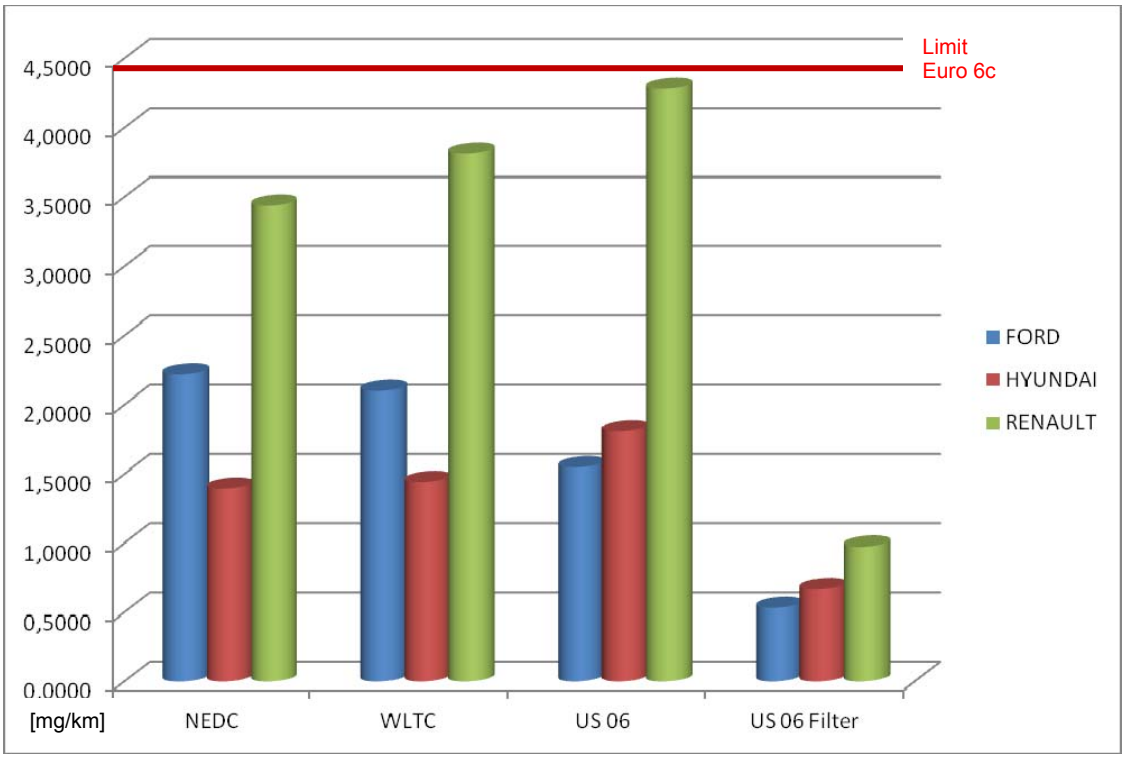

Figure 4.1: **Average particulate mass emission**

Looking at the particulate number emissions (**Figure 4.2**) the serious reduction of the emissions by mounting a filter in the exhaust system is illustrated.

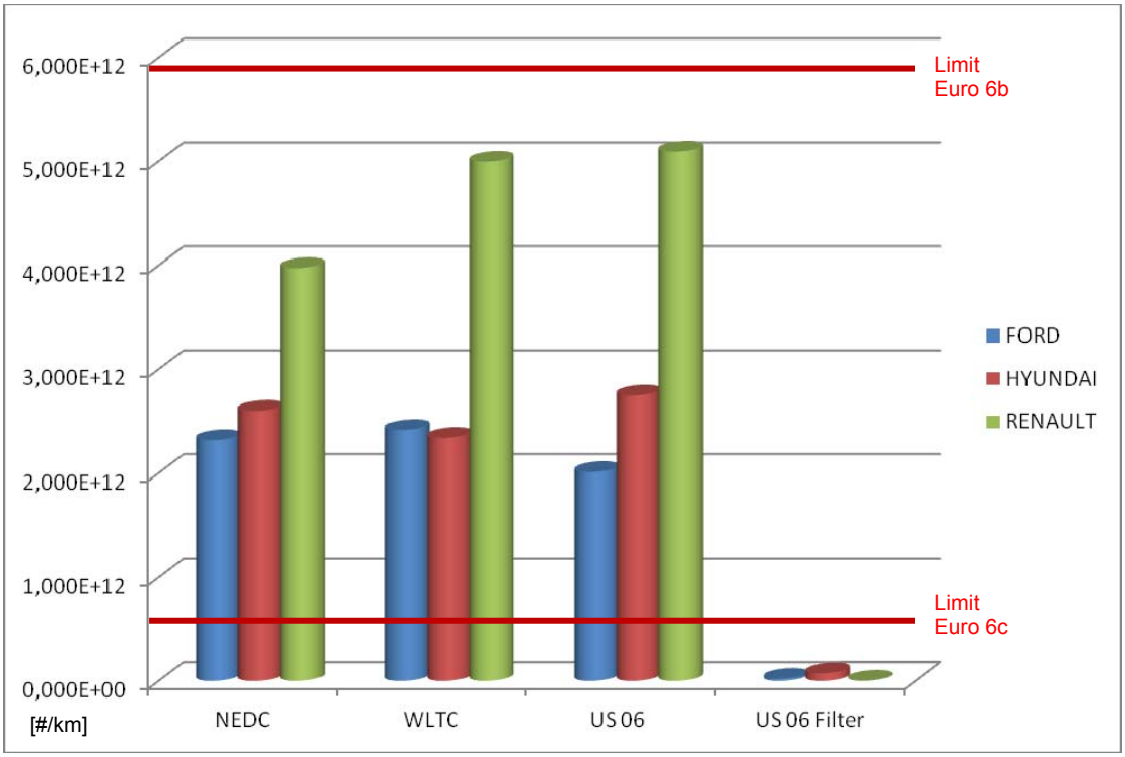

Figure 4.2: **Average particulate number emission**

In **Figure 4.3** the particle number values emitted during the US 06 cycle with and without particulate filter are illustrated second by second.

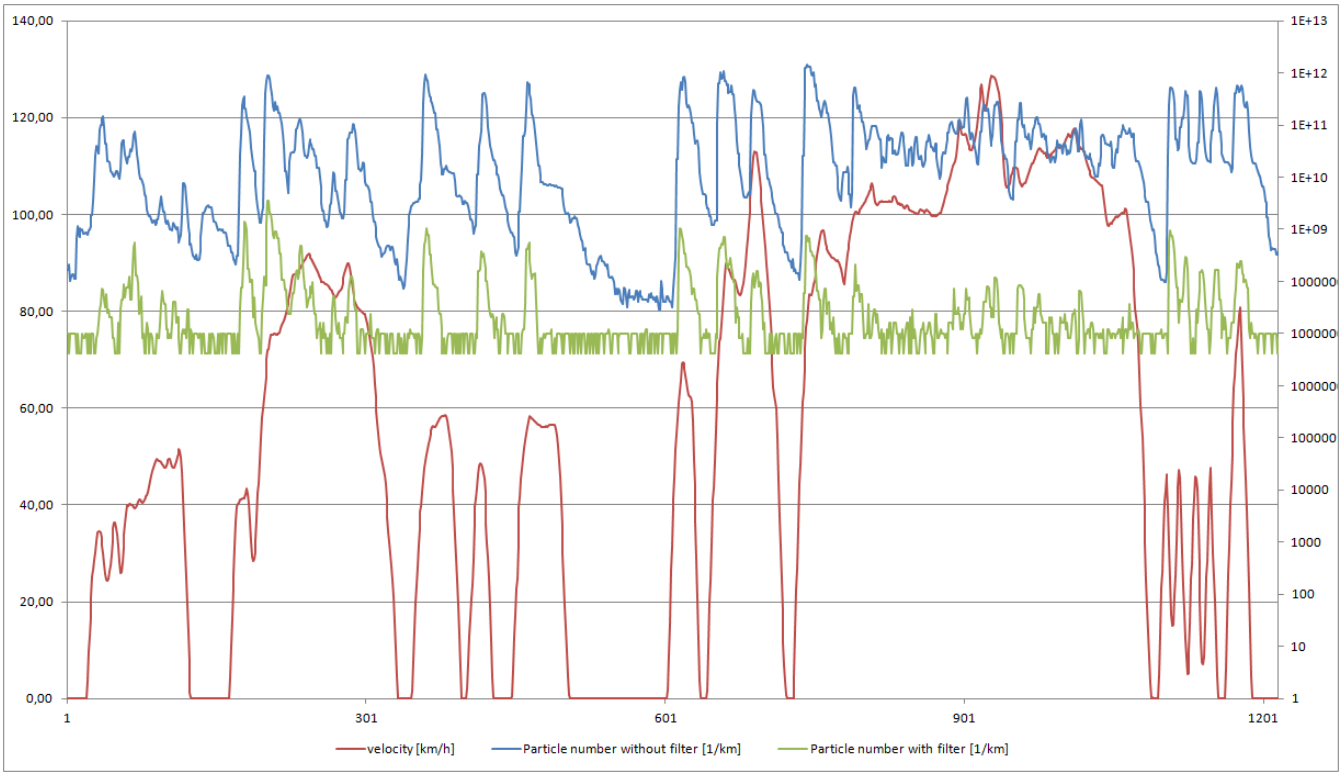

Figure 4.3: **Particle number emission during US06**

Figure 4.3 shows the effect of mounting a particulate filter in the exhaust system. The filter brings down the emission to a level that is typical for normal ambient air. The effect on in this test (Renault Megane) expressed in numbers is a factor of reducing the emissions about 2000.

5. Conclusions

The measurements conducted on vehicles with ignition engine during the programme show a clear result:

The use of a particulate filter could solve the problem of high emitting direct fuel injection positive ignition vehicles.

This is summarised and shown in Table 5.1 with the eye on the Particle emissions.

Vehicle	Cycle	Average Exhaust Emissions	
		Particle	Particle number
		[mg/km]	[1/km]
FORD	NEDC	2,218	2,319E+12
	WLTC	2,099	2,417E+12
	US06	1,548	2,011E+12
	US06 Filter	**0,532**	**2,100E+10**
	Limit Euro6c	**4,500**	**6,000E+11**
Hyundai	NEDC	1,396	2,600E+12
	WLTC	1,444	2,341E+12
	US06	1,810	2,747E+12
	US06 Filter	**0,668**	**7,344E+10**
	Limit Euro6c	**4,500**	**6,000E+11**
Renault	NEDC	3,439	3,974E+12
	WLTC	3,812	4,997E+12
	US06	4,279	5,095E+12
	US06 Filter	**0,975**	**2,477E+09**
	Limit Euro6c	**4,500**	**6,000E+11**

Table 5.1: Average Particle emission overview

The limit was set to be 6.0E+12 with legislation Euro 6b, it will come down to the compression ignition limit which is 6.0E+11 with Euro legislation 6c. During the programme none of the tested vehicles fulfilled the lower limit in serial condition. To solve the problem in short time, particulate filter system is an effective way.

6. References

- REGULATION (EC) No 715/2007 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
  on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair information, amending Directives; Working Party on Environment (Euro-5); European Commission

- COMMISSION REGULATION (EC) No 692/2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair information, amending Directives; Working Party on Environment (Euro-5); European Commission

- Regulation (ECE) No 83
  UNIFORM PROVISIONS CONCERNING THE APPROVAL OF VEHICLES WITH REGARD TO THE EMISSION OF POLLUTANTS ACCORDING TO ENGINE FUEL REQUIREMENTS