diesel fuel emissions performance with oxidation catalyst equipped diesel passenger vehicles - part I

Prepared for the CONCAWE Automotive Emissions Management Group and based on work carried out by the Special Task Force on Diesel Fuel Emissions, (AE/STF-7).

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ABSTRACT

This study confirms the very effective control of diesel exhaust particulate, carbon monoxide and hydrocarbon emissions with oxidation catalyst technology. In addition, the investigation documents the ability of an exhaust oxidation catalyst to effectively reduce the variation in emission levels with fuels meeting the EN 590 specifications. However, a balanced design of catalyst, engine and vehicle seems to be important if optimum performance is to be achieved.

KEYWORDS

Carbon monoxide, catalyst, diesel engine, diesel fuel, emissions, hydrocarbons, measurement, nitrogen oxides, oxidation, particulates, sulphur.

SUMMARY

The harmonized European specification for diesel fuel (EN 590) has been established to improve diesel engine operation and to assist in the control of exhaust emissions. With the introduction of engine exhaust oxidation catalysts for diesel passenger vehicles, exhaust emissions (including particulates) can be effectively decreased. CONCAWE decided to study the emissions performance of vehicles fitted with this catalyst technology on a range of diesel fuels.

The investigation was conducted using the European ECE15+EUDC test procedure and steady-state driving with seven fuels having key properties in the range of 48 to 54 for cetane number, 0.834 to 0.850 kg/l for density and 337 to 367°C for the 95% Boiling Point. Total aromatics content ranged from 16 to 26% volume. Six of the seven fuels were adjusted to a constant sulphur level of 0.05% mass, one fuel was doped to a 0.20% mass sulphur level. Six modern diesel passenger vehicles equipped with exhaust oxidation catalysts were included in the programme.

The findings of this study will be published in two reports. This report covers vehicle emissions performance with and without the oxidation catalyst in place. The second report will provide detailed discussions on the influence of specific fuel properties on emissions performance as well as the analytical data of the composition of the particulates generated in this programme.

The study found a significantly reduced variation in levels of exhaust emissions (HC, CO, Pm) with the tested fuels when results with the catalyst in operation were compared with ordinary exhaust pipe emissions. For particulate emissions these reductions ranged from 30 to 74%. As expected, the absolute levels of particulate emissions were also significantly decreased for most vehicles.

Two of the six vehicles showed higher particulate emissions when tested on the higher sulphur fuel with the catalyst in place. This was thought to be linked to higher catalyst temperatures, but might also be related to catalyst technology.

With all vehicles, the level and range of carbon monoxide and - with most vehicles - the level and range of hydrocarbon emissions is significantly reduced when the catalyst is in place. As expected, nitrogen oxides were not affected by the catalyst. Indeed, some vehicles showed slightly higher NOx levels.

CONTENTS

1. INTRODUCTION

A harmonized European specification for diesel fuel (EN 590) was established in the early 1990s and then introduced into European national standards during 1993. In addition to harmonization, this specification is intended to improve diesel engine operation and to help control exhaust emissions. During this period, oxidation catalyst technology has been introduced for European diesel passenger cars to further reduce gaseous emissions and, in particular, particulate emissions.[1, 2, 3.]

The Special Task Force on Diesel Fuel Emissions (AE/STF-7) was requested by the CONCAWE Automotive Emissions Management Group to set up a programme to investigate the influence of such commercial fuels on the emissions performance of cars fitted with exhaust oxidation catalysts. The objective of this study was to determine the amount and nature of gaseous and particulate emissions (both engine-out and after-catalyst)* from a range of light duty diesel vehicles. Three aspects were of most importance:

- the range of exhaust emission measurements of the fuel set at engine-out and after-catalyst positions
- the influence of fuel properties on emissions performance under the above conditions
- the effect of fuel sulphur on particulate emissions with the catalyst in operation.

The work described was carried out in the laboratories of four CONCAWE member companies. Additional analytical studies were sub-contracted to Ricardo Consulting Engineers as an integral part of the programme. Every attempt was made to standardize test and analytical procedures throughout the programme, such that a consistent body of data be made available.

This report summarizes the CONCAWE findings on the performance of diesel engine emissions of the tested range of fuels with light duty vehicles equipped with exhaust oxidation catalysts. A separate report will provide detailed discussions on the influence of specific fuel properties on emissions and the analytical data on the composition of the particulates generated in this programme.

* ***Note:*** *The following terminology is used throughout the report:*

- *<u>'Engine-out'</u> - Exhaust emissions measured with the catalyst replaced with a conventional exhaust system.*
- *<u>'After-catalyst'</u> - Exhaust emissions measured with the catalyst fitted.*

2. CHOICE OF DIESEL VEHICLES FOR THE PROGRAMME

The number of diesel vehicles tested was limited by constraints on fuel availability. Subject to this limitation, the programme covered a range of European oxidation catalyst equipped diesel passenger vehicles including naturally aspirated (NA), turbocharged (TC), turbo-charged and inter-cooled (TC/IC), indirect injection (IDI) and direct injection (DI) types.

The characteristics of the diesel passenger vehicles employed in the programme are as follows:

Vehicle Number	Engine Displacement (litres)	Engine Configuration	Performance Standard
1	1.9	TC/IDI	91/441/EEC
2	2.5	TC/IC/DI	91/441/EEC
3	1.8	NA/IDI	91/441/EEC
4	2.5	TC/IC/IDI	91/441/EEC
5	2.5	NA/IDI	STVZO annex XXIII*
6	1.9	TC/IC/IDI	STVZO annex XXIII*

* very low emissions model complying with German traffic regulations

3. TEST DIESEL FUELS

The seven fuels were blended for the programme to reflect the harmonized European diesel fuel specification EN 590 which was implemented in national specifications in 1993. The main fuel properties range as follows:

- Cetane number between 48 and 54
- Density between 0.834 and 0.850 kg/l
- 95% distillation point between 337 and 367°C
- Total aromatics between 15.6 and 25.7% vol. (by HPLC).

Six of the seven fuels were adjusted to a constant sulphur level (0.05% mass) by doping with tertiary butyl disulphide. This ensured that the influence of sulphur content on particulate emissions remained constant. The effect of fuel sulphur was investigated by raising the sulphur content of one fuel to 0.2% mass. It has been documented [4] that particulate emissions from fuels containing similar levels of sulphur, originating from either natural or doped sources, were identical. Two fuels were treated with 2-ethylhexyl nitrate ignition improver additive to provide higher cetane levels.

The matrix is considered to be typical of fuels that will be commercially available in the future in Europe and to be sufficiently wide to enable the influence of fuel characteristics on the emissions performance of exhaust oxidation catalyst equipped passenger vehicles to be determined.

Analytical data on the seven fuels used in the programme are given in **Table 1**. These data are mean values calculated from individual results obtained in the laboratories of the CONCAWE member companies involved in the programme.

4. LUBRICATING OIL

In order to eliminate any influence of lubricating oil quality on the amount or nature of particulates generated in this programme, a commercial lubricating oil was chosen which satisfied the short-term test requirements of each engine employed in the programme. This oil, which was of SAE 15W/40 quality meeting API SF and DB 227.1 requirements, was used in all cars throughout the test programme.

Inspection data on the unused oil are:

Reference L92/10091

Grade SAE 15W/40, API SF, DB 227.1

Pour point	°C	-33
Sulphur content	% mass	0.475
kV 40°C	mm^2/sec	112.3
kV 100°C	mm^2/sec	14.6
Viscosity Index		133
Volatility (DIN 51581) 1 hour, 250°C	% mass	11.1
Phosphorus	% mass	0.11
Calcium	% mass	0.21
Magnesium	% mass	0.11
Zinc	% mass	0.12
IBP	°C	133
FBP	°C	534

5. VEHICLE TEST PROCEDURES

The procedures used in the basic programme were those adopted for EC legislation covering emissions from diesel vehicles. Thus, the ECE-15 test cycle was used, followed by the EUDC (extra urban driving cycle). In addition steady state emission testing at 120 km/h was carried out, mainly to determine particulate emissions performance. ECE-15 and EUDC cycle testing was first conducted with the exhaust oxidation catalyst fitted and, in a second test set, with the catalyst replaced by an ordinary exhaust system.

Vehicle tests were conducted in four CONCAWE member companies' laboratories. All tests were carried out in duplicate, using a random order of fuel testing in each laboratory.

Details of the vehicle test procedures used are as follows:

Pre-conditioning

1. Fit new catalyst to vehicle and accumulate 2000 km of mixed road driving and any suitable lubricant. Fuel to be CEC reference low sulphur fuel RF-73-T-90.

2. Change lubricating oil to the standard AE/STF-7 lubricant.

3. Carry out a lubricating oil and injector nozzle pre-conditioning programme using CEC reference fuel RF-73-T-90, with a total driving distance of 1000 km. This programme has a duration of two days (500 km/day), 33% running on a motorway at a maximum speed of 130 km/h (about 165 km/day) and 67% road driving at an average of 60 km/h (335 km/day).

4. Pre-condition the vehicle with the fuel under test using three EUDC cycles, followed by an 8 hour soak period.

ECE15+EUDC tests with catalyst in place

5. Cold start, followed by the ECE-15 and EUDC test procedures, measuring gaseous and particulate emissions, using Whatman glass fibre filter papers.

6. Use a separate gas sampling bag filter, for both the ECE-15 and EUDC sections of the test procedure. Repeat preconditioning Step 4 between all tests.

7. Carry out at least two complete ECE15+EUDC tests. Report ECE15, EUDC (g/test) and combined ECE15+EUDC gaseous and particulate emissions (g/km).

8. Repeat ECE15+EUDC test runs with one or more fuels.

Steady state testing with catalyst in place

9. Perform steady state tests at 120 km/h and sample particulate matter using one of the two options to maintain a maximum temperature of 52°C at the sampling probe.

   Option "A"

   Change CVS flow rates as required and continue with duplicate steady-state runs at 120 km/h, simulate road temperature upstream of catalyst box using additional under-vehicle cooling as required (and when possible).

   Option "B"

   Maintain CVS flow-rates used at ECE15+EUDC testing and split exhaust flow. Sample only diluted portion of the exhaust volume. Keep same split throughout testing of all fuels. Keep sampling time constant (Note: only relative results can be obtained by this technique).

ECE15+EUDC tests with the catalyst replaced by an ordinary exhaust pipe

10. Carry out ECE15+EUDC cycle tests having adjusted CVS flow rates back to values used in Section 7 above. Keep the back pressure at the level observed with the catalyst fitted. Random order of testing to be kept as in Section 7.

6. REGULATED EMISSIONS DATA

The gaseous and particulate emissions data from duplicate runs are shown in the form of mean values for each vehicle/fuel combination as total emissions (in g/km) over the combined ECE15+EUDC cycles in **Tables 2** to **5**.

These tables give gaseous and particulate emissions data (in g/km) for both engine-out and after-catalyst operation. For "engine-out operation" the catalyst was replaced by an ordinary exhaust pipe. For "after-catalyst operation" the catalyst was in place.

A wide range of emissions levels was obtained covering different engine and fuel injection types. The ranges for individual emissions when the vehicles were equipped with catalysts are set out in **Table A**, below.

Table A Approximate ranges of emissions values for exhaust oxidation catalyst equipped diesel passenger vehicles

Emission species	Combined ECE15 +EUDC cycles g/km
CO	0.2 - 1.4
HC	0.05 - 0.33
NOx	0.6 - 0.7
Pm	0.05 - 0.16 - 0.20*

* with higher sulphur fuel

Using the combined cycle data, the range of emissions across the fuel matrix with the most fuel tolerant vehicle versus the most fuel sensitive vehicle are as follows:

Table B Comparison of emissions performance between 'fuel tolerant' and 'fuel sensitive' vehicles

Emission Species	**Emissions (g/km) - Low and High Values***			
	Engine-out		With catalyst	
	fuel tolerant vehicle #1	fuel sensitive vehicle #4	fuel tolerant vehicle #1	fuel sensitive vehicle #4
CO	0.07	0.22	0.08	0.26
HC	0.02	0.12	0.03	0.12
NOx	0.03	0.04	0.03	0.04
Pm	0.02	0.06	0.01	0.03

* without DI engine and higher sulphur fuel

The data show a significant difference for the range of emissions across the low sulphur fuel matrix when run with the most fuel tolerant versus the most fuel sensitive vehicle. The factor is generally three but increases up to six for HC. For particulate emissions, the variation is smaller with the catalyst in place. Indeed, when the catalyst is fitted, the fuel 'sensitive' vehicle is almost as 'insensitive' as the most fuel tolerant vehicle at engine-out conditions.

If the direct injection engine model is included, the spread would increase somewhat for particulates (0.07 g/km without catalyst, 0.05 g/km with catalyst). It would be significantly higher for CO, i.e. at engine-out condition (0.54 g/km) and with the catalyst in place (0.31 g/km).

The performance benefits observed for the new catalyst technology extend beyond lowered emission levels. The influence of fuel characteristics on the variation in emissions performance is substantially narrowed, as shown for particulates in **Table C**:

Table C Influence of exhaust oxidation catalysts on the range of particulate emissions with low sulphur fuels, g/km (combined data)

Catalyst in Place	**Vehicle**					
	1	**2**	**3**	**4**	**5**	**6**
no	0.015	0.074	0.043	0.056	0.035	0.054
yes	0.008	0.052	0.026	0.032	0.014	0.014
reduction	-0.007	-0.022	-0.017	-0.024	-0.021	-0.04
% change	-47	-30	-40	-43	-60	-74

(" - " signs are Δ changes)

7. CONSTANT SPEED EMISSIONS DATA

The particulate emissions data obtained from duplicate steady state runs at 120 km/h with the catalyst in place are shown in the form of mean normalized values in **Table 6**.

The normalized data were generated by referencing individual particulate values obtained with the fuels for each vehicle to the respective mean value. Thus the data are comparable. Absolute particulate values can be misleading since the measurements were conducted on the individual vehicles employing the CONCAWE recommended constant speed test procedure option (see **Section 5**) applicable to that testing laboratory.

Temperatures upstream of the catalyst measured at road and test conditions on the chassis dynamometer are given in **Table 7**. A comparison of temperatures during road driving and dynamometer testing indicates that, for some vehicles, the test conditions are more severe (i.e. generate higher temperatures) than road load. As a consequence, higher conversion rates of SO_2 to SO_3 can take place over the catalyst on the chassis dynamometer. With some vehicles the catalyst temperatures exceeded 350°C, which is understood to be a critical limit above which the SO_2 conversion rate can increase exponentially. [3, 5] Under these circumstances, the higher sulphur fuel showed higher particulate levels because more sulphate had been generated. All other fuels with a sulphur level at 0.05% mass - being the marketed sulphur level from 1996 onwards - showed satisfactory particulate levels, even at these elevated temperatures.

8. EVALUATION OF THE INFLUENCE OF FUEL PROPERTIES ON THE EMISSIONS PERFORMANCE OF OXIDATION CATALYST EQUIPPED CARS

In order to assess the fuel emissions performance of oxidation catalyst technology it is advisable to compare emissions values obtained with and without the catalyst. In the latter case the catalyst should be replaced with an ordinary exhaust system. Particulate and gaseous emissions results obtained with the regulated test procedures (ECE15+EUDC) and under steady-state conditions are discussed below.

8.1 PARTICULATE EMISSIONS

ECE15+EUDC Procedure

With the low sulphur fuels (fuels 1 to 6), particulate emissions are significantly lowered with the catalyst in operation. Only vehicle 5 exhibits unchanged mean particulate values between ‘engine-out’ and ‘with catalyst’ performance (**Figure 1**). In addition, **Figure 1** clearly demonstrates that the range of particulate emissions is substantially curtailed when the catalyst is in place. **Figure 2,** which shows a reduction of the spread by the catalyst of 30 to 74%, is under-pinned by the data presented in **Table 8**.

With only two out of the six vehicles (with the catalyst in place) did the higher sulphur fuel (No. 7) result in particulate emissions which exceeded the range obtained with the low sulphur fuels (**Figure 3**). As shown in **Table D**, overleaf, catalyst temperatures under dynamometer test conditions exceed those measured on the road and result in higher conversion rates from SO_2 to SO_3. This was previously discussed in **Section 7**. It is understood that, with some current oxidation catalyst technology, catalyst temperatures around 350°C will stimulate SO_2 to SO_3 conversion exponentially. As a result, much higher sulphate and bound water fractions are collected on the particulate filter, adding significantly to the mass reported. Vehicles 3 and 5, which exceeded the emissions spread with the 0.2% mass fuel, gave peak catalyst temperatures of 508 and 480°C respectively.

Table D Exhaust temperatures upstream of catalyst, °C

	Test condition / Speed, km/h	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Road	idle	-	**106**	**95**	**97**	**93**	**90**
	60	-	**198**	**188**	**220**	**177**	**164**
	90	-	**242**	**252**	**250**	**250**	**208**
	120	255	**324**	**340**	**285**	**305**	**259**
Dynamometer	ECE-15						
	avg.	-	**165**	**155**	**120**	**187**	**127**
	peak	-	**216**	**253**	**152**	**270**	**161**
	EUDC						
	avg.	-	**268**	**282**	**204**	**308**	**211**
	peak	-	**356**	**508**	**320**	**480**	**304**
Dynamometer	Steady State (120)	318	**400**	**425**	**310**	**370**	**329**

Note: Temperatures for vehicle 1 are not available over the ECE-15 & EUDC cycles

Steady-state 120 km/h operation

At steady-state operation at 120 km/h all low sulphur fuels show little variability in particulate emissions. Only with vehicle 4 was a larger range measured (**Figure 4**). With the higher sulphur fuel, particulate emissions are significantly above the levels observed for vehicles 2, 3 and 5. The far higher temperatures upstream of the catalyst during dynamometer operation again explain the differences. A comparison of these temperatures is given in **Figure 4**.

8.2 GASEOUS EMISSIONS

Carbon monoxide emissions are significantly reduced with all vehicles when the catalyst is in place (**Figure 5**). Individual CO emissions ranged from 0.46 to 0.90 g/km without the catalyst and from 0.16 to 0.78 g/km with the catalyst installed. With the direct injection engine the highest CO levels were 1.68 g/km (without catalyst) and 1.43 g/km (with catalyst).

Hydrocarbon (HC) emissions are reduced for all the vehicles powered by indirect injection engines (**Figure 6**). The direct injection engine powered vehicle 2 did not exhibit this behaviour. Individual HC emissions ranged from 0.06 to 0.26 g/km without the catalyst and from 0.05 to 0.23 g/km with the catalyst in place. For the direct injection engine, the highest HC levels were 0.35 g/km (without catalyst) and 0.33 g/km (with catalyst).

In general the range of carbon monoxide and hydrocarbon emissions is significantly narrowed with the test fuels with the catalyst in operation. Such a reduction was observed for hydrocarbon emissions with five vehicles of up to 76% (one showed a 40% increase) and for carbon monoxide emissions with four vehicles of up to 43% (two showed an increase of 17 and 19% respectively) (**Tables 9 to 10**).

As expected, nitrogen oxides were not influenced by an oxidation catalyst. However, with three vehicles higher nitrogen oxide emissions were measured (**Figure 7, Table 11**). Nitrogen oxides emissions ranged from 0.57 to 0.69 g/km without the catalyst and from 0.60 to 0.71 g/km with the catalyst installed. Results from the direct injection engine are within the mentioned ranges.

9. OXIDATION CATALYST PERFORMANCE

The oxidation catalyst technology provided with the vehicles used in this programme demonstrated two important advantages:

- Substantial reductions in diesel particulate, hydrocarbon and carbon monoxide emissions
- Lower sensitivity to the influence of fuel characteristics on vehicle emissions performance

As discussed in the previous section, fuel sulphur at a level of 0.20% mass can lead to higher particulate matter resulting from the higher production of sulphate and bound water at elevated temperatures. The conversion rate of SO_2 to SO_3 increases with the temperature at which the catalyst operates. This may be exacerbated on the chassis dynamometer where the lack of under-body cooling might lead to higher temperatures than those experienced 'on the road'. Only two vehicles showed this characteristic, so it could be concluded that the catalyst, plus an optimal design of catalyst, engine and vehicle, represent important parameters to control sulphate formation. With the low sulphur containing fuels (0.05% mass) satisfactory low particulate emission levels were obtained with all the vehicles tested.

For a comprehensive overview, the mean percent reductions obtained with the catalyst in place versus non-catalyst operation are given in **Table E**:

Table E Mean percent change with the catalyst in place (combined ECE15+EUDC cycle; low sulphur fuels only)

Emission species	**Vehicle**					
	1	**2**	**3**	**4**	**5**	**6**
Pm	-21	-26	-2	-22	+1	-52
CO	-30	-7	-29	-25	-70	-15
HC	-35	+6	-2	-20	-52	-31
NOx	+3	0	0	+7	-2	+14

(" - " signs are reductions)

The per cent reductions indicate that different emissions species are specifically controlled with individual catalyst/engine/vehicle combinations.

Average absolute reductions of individual emissions obtained in the ECE15+EUDC cycle tests with the catalyst installed are illustrated in **Figures 8 to 11**.

Five of the six vehicles exhibited decreased particulates during ECE15+EUDC cycle testing with the catalyst in place (**Figure 8**). Carbon monoxide emissions are significantly lowered for all vehicles (**Figure 9**). Hydrocarbons were significantly cut with four vehicles, the other two vehicles showing little significant response (**Figure 10**). Combined hydrocarbon and nitrogen oxides emissions were only reduced with three vehicles (**Figure 11**), whilst the others exhibited very small increases due to nitrogen oxides increases (**Figures 11 and 12**).

10. CONCLUSIONS

- A series of emissions tests have been conducted on diesel passenger vehicles factory-fitted with oxidation catalysts integrated in their exhaust systems. In a second phase of experiments the catalysts were replaced with conventional exhaust systems.

- Tests were carried out over the European ECE15+EUDC cycle with typical European commercial fuels (EN 590).

- It was found that, with the catalyst in operation, the range of exhaust emissions was significantly reduced. This is especially true for particulate emissions. In addition, the results of this study confirm the known potential of exhaust oxidation catalyst technology to lower the overall level of particulate, carbon monoxide and hydrocarbon emissions.

- With the catalyst installed the range of particulate emissions with the 0.05%m sulphur containing fuels was reduced by between 30 and 74% versus ‘engine-out’ emissions over the ECE15+EUDC test cycles. All fuels at 0.05% m sulphur (the marketed level from 1996 onwards) showed satisfactory particulate levels.

- When the sulphur level was increased to 0.20%, particulate emissions were deemed excessive for just two of the catalyst-equipped vehicles These particulate increases resulted from higher conversion rates of SO_2 to SO_3 (generating sulphate and bound water). This was due to the higher catalyst temperatures observed under dynamometer test conditions. In these cases, temperatures were above 350°C, which is still considered to be a critical temperature level for the onset of higher SO_2 conversion rates.

- At 120 km/h steady-state driving conditions on the dynamometer particulate emissions were significantly higher with 0.20% mass versus 0.05% mass sulphur fuels with three vehicles. Again, catalyst temperatures on the dynamometer were well above 350°C and higher than those measured under road conditions.

- The programme demonstrated that the range of carbon monoxide emissions and - with most vehicles - the range of hydrocarbon emissions is significantly lowered by the application of diesel exhaust oxidation catalysts. The decreases observed for hydrocarbon emissions were up to 76% and, for carbon monoxide emissions, approaching 43%.

- With the oxidation catalyst installed, the level of particulates, carbon monoxide and hydrocarbon emissions was significantly reduced in most cases. This applied not only to the range but also to the absolute emission levels, demonstrating the effectiveness of this emissions control technology. As expected, nitrogen oxides were not reduced with the catalyst in place, some vehicles showing somewhat higher NOx levels.

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13. TABLES

Table 1 Analytical data on test fuels used in the programme (mean values)

Fuel No		OC1 - OC3	OC4	OC5	OC6	OC7
Property	Unit					
Sulphur content	%m	0.052	0.053	0.046	0.048	0.199
Density @ 15°C	kg/l	0.8408	0.8341	0.8505	0.8367	0.8427
kV @ 20°C	mm^2/sec	3.98	3.47	4.91	5.02	4.02
kV @ 40°C (3)	mm^2/sec	2.62	2.34	3.18	3.11	2.75
Flash point	ºC	69	67	67	72	69
Cloud point	ºC	-1	-10	+6	+2	-2
CFPP	ºC	-20	-24	-5	-7	-18
Water content	ppm	64	50	68	63	70
Copper corrosion		1a	1a	1a	1a	1a
Carbon residue	%m	0.05	0.03	0.02	0.02	0.03
AROMATICS AND IGNITION QUALITY						
FIA (4)	%v	30.0	28.6	29.8	23.2	31.7
HPLC [a] (2)	%m	27.1	26.0	26.7	17.0	27.3
HPLC [b] :						
mono aromatics (3)	%v	19.7	22.0	16.5	11.6	20.0
di aromatics (3)	%v	4.0	3.3	5.1	3.5	4.1
tri aromatics (3)	%v	0.5	0.4	0.6	0.5	1.1
total aromatics (3)	%v	24.2	25.7	22.2	15.6	25.2
HPLC [b]:						
mono aromatics (2)	%m	20.9	22.5	18.1	13.4	19.7
di aromatics (2)	%m	5.3	4.2	6.6	4.4	4.8
tri aromatics (2)	%m	0.8	0.7	0.6	0.7	1.4
total aromatics (2)	%m	27.0	27.4	25.3	18.5	25.9
Cetane number		48.5, 51.7, 54.3	49.5	48.3	52.8	48.2
Calculated Cetane Index		49.0	49.7	47.6	54.1	48.4
DISTILLATION DATA						
IBP	ºC	176	175	175	180	176
10%	ºC	207	201	215	223	207
20%	ºC	220	213	231	239	220
30%	ºC	234	226	245	251	235
40%	ºC	248	240	258	263	249
50%	ºC	262	255	270	274	263
60%	ºC	276	269	283	285	276
70%	ºC	290	283	299	300	290
80%	ºC	307	299	318	318	307
90%	ºC	332	319	346	341	330
95%	ºC	354	337	367	358	351
FBP	ºC	369	356	387	372	368
Recovery (5)		98.4	98.6	98.5	98.3	98.4
Loss (5)		0.2	0.1	0.2	0.2	0.2
Residue (5)		1.4	1.3	1.3	1.5	1.4

(All values are the mean of six analyses, except where indicated)
[a] IP368/90 [b] IP391/90
* Contain ignition improver additive

Table 2 Mean particulate data (g/km) combined ECE 15 + EUDC cycle (Engine-out and after-catalyst data)

Fuel	**Vehicle**					
	1	2	3	4	5	6
Engine-out						
1	0.100	0.173	0.146	0.110	0.125	0.114
2	0.092	0.158	0.103	0.111	0.120	0.094
3	0.088	0.154	0.107	0.098	0.121	0.090
4	0.099	0.154	0.117	0.118	0.131	0.088
5	0.099	0.228	0.146	0.154	0.149	0.142
6	0.086	0.175	0.107	0.118	0.114	0.092
7	0.092	0.175	0.129	0.141	0.126	0.098
After-catalyst						
1	0.075	0.125	0.120	0.082	0.127	0.046
2	0.078	0.119	0.109	0.081	0.134	0.048
3	0.070	0.127	0.115	0.079	0.120	0.046
4	0.076	0.107	0.113	0.092	0.129	0.047
5	0.073	0.159	0.134	0.111	0.130	0.060
6	0.073	0.129	0.110	0.104	0.121	0.047
7	0.074	0.125	0.146	0.106	0.200	0.059

Table 3 Mean carbon monoxide data (g/km) combined ECE 15 + EUDC cycle (Engine-out and after-catalyst data)

Fuel	**Vehicle**					
	1	2	3	4	5	6
Engine-out						
1	0.483	1.522	0.584	0.689	0.624	0.851
2	0.478	1.240	0.475	0.605	0.579	0.764
3	0.461	1.137	0.478	0.591	0.582	0.665
4	0.480	1.422	0.550	0.657	0.603	0.743
5	0.530	1.675	0.620	0.811	0.671	0.898
6	0.461	1.237	0.496	0.665	0.598	0.678
7	0.511	1.453	0.546	0.713	0.602	0.784
After-catalyst						
1	0.352	1.393	0.378	0.510	0.194	0.658
2	0.351	1.205	0.338	0.454	0.172	0.626
3	0.304	1.180	0.351	0.406	0.157	0.568
4	0.328	1.272	0.378	0.499	0.166	0.668
5	0.386	1.425	0.424	0.668	0.221	0.779
6	0.306	1.120	0.386	0.495	0.177	0.589
7	0.377	1.356	0.412	0.664	0.201	0.750

Table 4 Mean hydrocarbon data (g/km) combined ECE 15 + EUDC cycle (Engine-out and after-catalyst data)

Fuel	Vehicle					
	1	2	3	4	5	6
Engine-out						
1	0.103	0.313	0.109	0.191	0.118	0.238
2	0.100	0.243	0.063	0.135	0.099	0.198
3	0.095	0.231	0.064	0.146	0.108	0.156
4	0.107	0.289	0.094	0.177	0.118	0.183
5	0.107	0.353	0.092	0.256	0.149	0.250
6	0.087	0.247	0.085	0.188	0.100	0.167
7	0.099	0.420	0.108	0.240	0.107	0.194
After-Catalyst						
1	0.063	0.330	0.083	0.143	0.054	0.141
2	0.065	0.283	0.072	0.115	0.050	0.131
3	0.051	0.277	0.081	0.110	0.055	0.117
4	0.059	0.309	0.081	0.128	0.055	0.140
5	0.079	0.326	0.084	0.229	0.067	0.172
6	0.069	0.231	0.081	0.156	0.050	0.116
7	0.074	0.315	0.082	0.207	0.056	0.174

Table 5 Mean nitrogen oxides data (g/km) combined ECE 15 + EUDC cycle (Engine-out and after-catalyst data)

Fuel	Vehicle					
	1	2	3	4	5	6
Engine-out						
1	0.684	0.655	0.604	0.620	0.597	0.573
2	0.675	0.653	0.613	0.592	0.686	0.576
3	0.685	0.643	0.623	0.598	0.702	0.593
4	0.689	0.647	0.616	0.603	0.627	0.572
5	0.679	0.613	0.615	0.591	0.595	0.582
6	0.659	0.613	0.593	0.582	0.653	0.590
7	0.643	0.644	0.610	0.621	0.613	0.595
After-catalyst						
1	0.682	0.641	0.614	0.651	0.617	0.661
2	0.711	0.646	0.606	0.648	0.659	0.666
3	0.709	0.658	0.609	0.655	0.648	0.665
4	0.682	0.650	0.609	0.636	0.604	0.649
5	0.713	0.616	0.598	0.615	0.630	0.687
6	0.681	0.609	0.609	0.625	0.598	0.640
7	0.665	0.648	0.608	0.632	0.624	0.674

Table 6 Mean normalized particulate data at 120 km/h constant speed (After-catalyst data)

Fuel	Vehicle					
	1	2	3	4	5	6
1	0.989	0.971	1.080	0.963	1.039	1.015
2	1.139	1.013	0.940	1.331	1.002	1.032
3	1.038	0.980	0.896	0.997	1.007	1.031
4	1.114	1.029	1.068	0.779	0.924	0.979
5	0.887	1.024	1.119	1.028	1.056	1.029
6	0.834	0.984	0.896	0.902	0.972	0.914
7	1.027	1.448	1.324	0.978	2.017	1.136

Table 7 Temperatures (°C) measured upstream of the catalyst at 120 km/h Road and dynamometer (test) conditions

Condition	Vehicle					
	1	2	3	4	5	6
Road	255	324	340	223	305	259
Dynamometer	318	400	425	310	370	329

Table 8 Spread of particulates emissions with low sulphur fuel range, g/km (combined data)
Data without and with catalyst in place

Catalyst in place	Vehicle					
	1	2	3	4	5	6
No Yes	0.015 0.008	0.074 0.052	0.043 0.026	0.056 0.032	0.035 0.014	0.054 0.014
Delta	0.007	0.022	0.017	0.024	0.021	0.04
% Change	-47	-30	-40	-43	-60	-74

(" - " signs are reductions with catalyst in place)

Table 9 Spread of hydrocarbon emissions with low sulphur fuel range, g/km (combined data)
Data without and with catalyst in place

Catalyst in place	Vehicle					
	1	2	3	4	5	6
No Yes	0.020 0.028	0.122 0.099	0.046 0.011	0.121 0.119	0.050 0.017	0.094 0.056
Delta	-0.008	0.023	0.035	0.002	0.033	0.038
% Change	+40	-19	-76	-2	-66	-40

(" - " signs are reductions with catalyst in place)

Table 10 Spread of carbon monoxide emissions with low sulphur fuel range, g/km (combined data)
Data without and with catalyst in place

Catalyst in place	Vehicle					
	1	2	3	4	5	6
No Yes	0.070 0.082	0.538 0.305	0.145 0.086	0.220 0.262	0.092 0.064	0.233 0.212
Delta % Change	-0.012 +17	0.233 -43	0.059 -41	-0.042 +19	0.028 -30	0.021 -9

(" - " signs are reductions with catalyst in place)

Table 11 Spread of nitrogen oxides emissions with low sulphur fuel range, g/km (combined data)
Data without and with catalyst in place

Catalyst in place	Vehicle					
	1	2	3	4	5	6
No Yes	0.030 0.032	0.042 0.049	0.030 0.017	0.038 0.040	0.107 0.061	0.021 0.047
Delta % Change	-0.002 +7	-0.007 +17	0.013 -43	-0.002 +5	0.046 -43	-0.026 +124

(" - " signs are reductions with catalyst in place)

14. FIGURES

**Figure 1 Particulate emissions (engine out vs. after catalyst)
Levels and spread with low sulphur fuels**

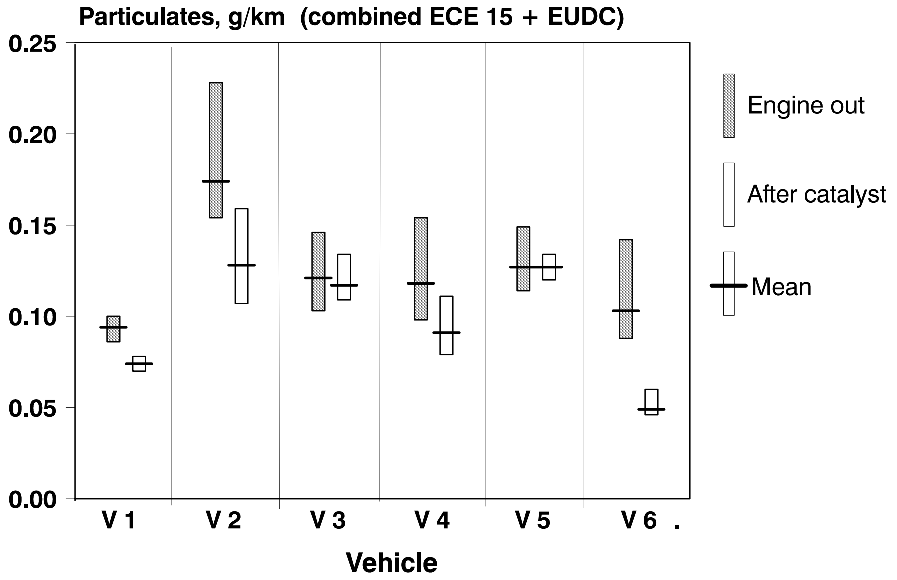


**Figure 2 Particulate emissions spread (engine out vs. after catalyst)
Low sulphur fuels**

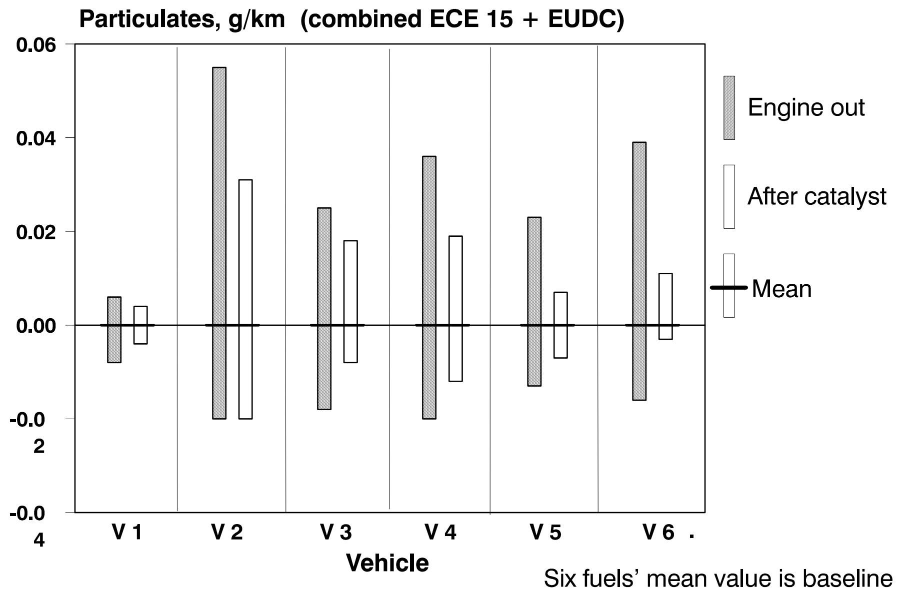


Figure 3 Effect of fuel sulphur on particulate emissions with oxidation catalyst

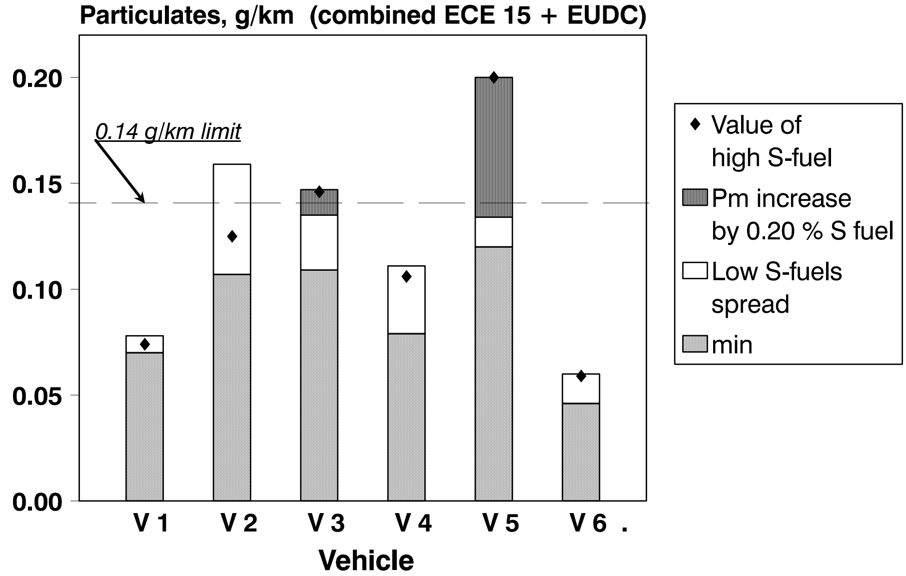
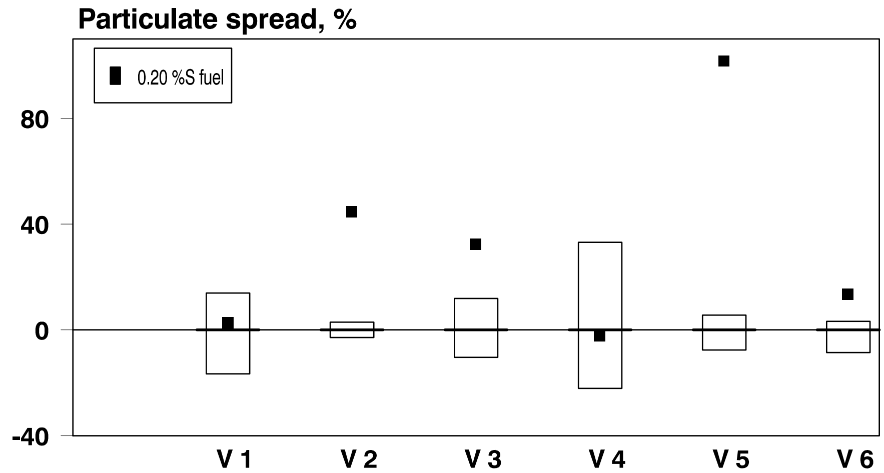


Figure 4 Particulate emissions spread at 120 km/h const. speed, with oxidation catalyst



Temperatures (°C) at catalyst at bay and road condition :

	V 1	V 2	V 3	V 4	V 5	V 6
Bay	370	310	329	318	425	400
Road	*305*	*223*	*259*	*255*	*340*	*324*

Figure 5 Carbon monoxide emissions (engine out vs. after catalyst)
Levels and spread with low sulphur fuels

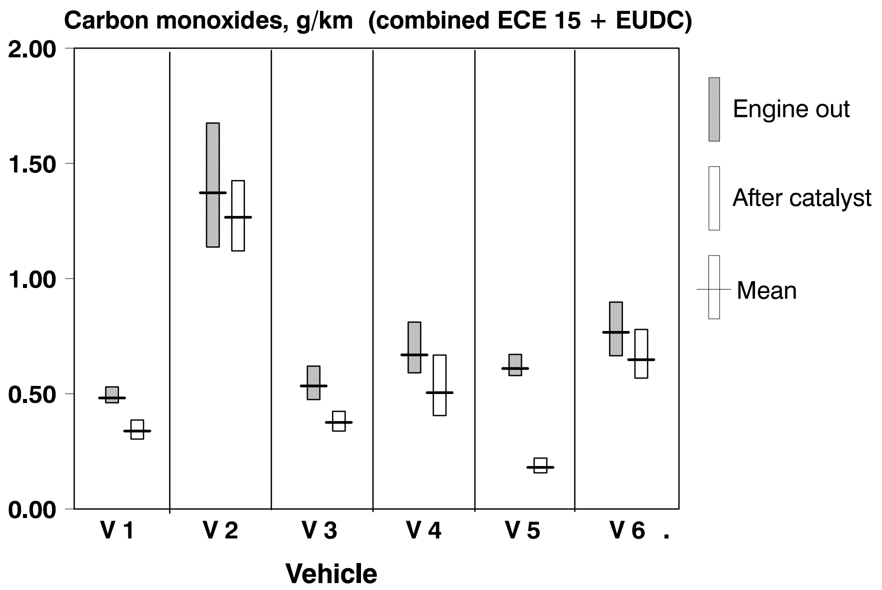


Figure 6 Hydrocarbon emissions (engine out vs. after catalyst)
Levels and spread with low sulphur fuels

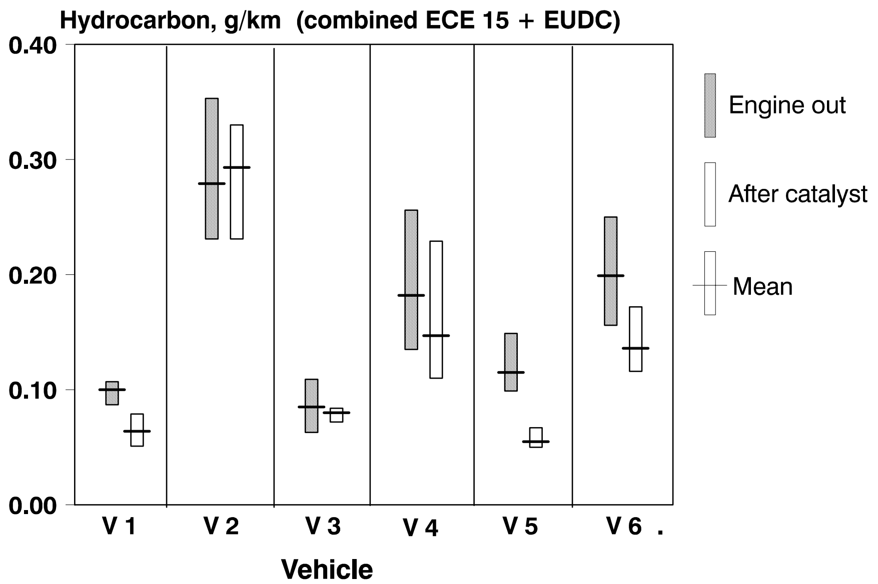


Figure 7 Nitrogen oxides emissions (engine out vs. after catalyst)
Levels and spread with low sulphur fuels

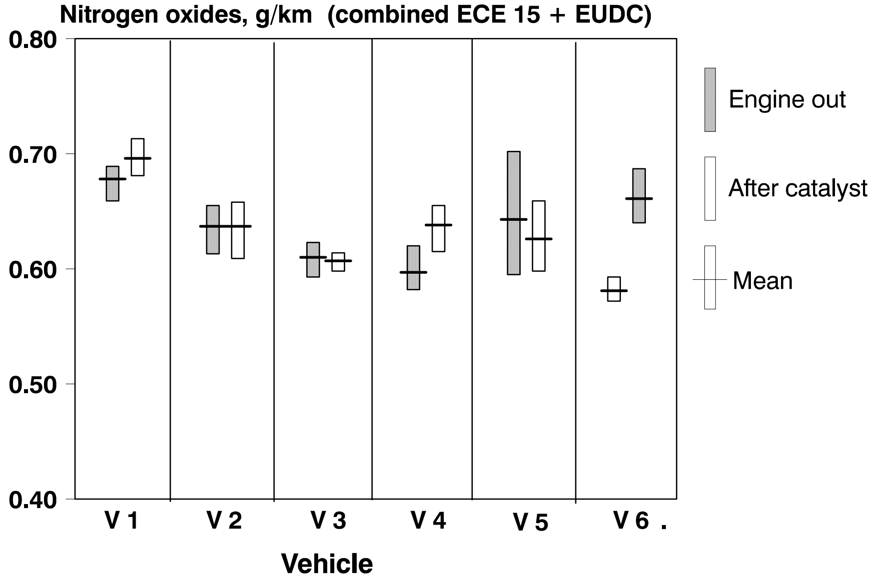


Figure 8 Average reduction of particulate emissions
with oxidation catalyst in operation (low sulphur fuels)

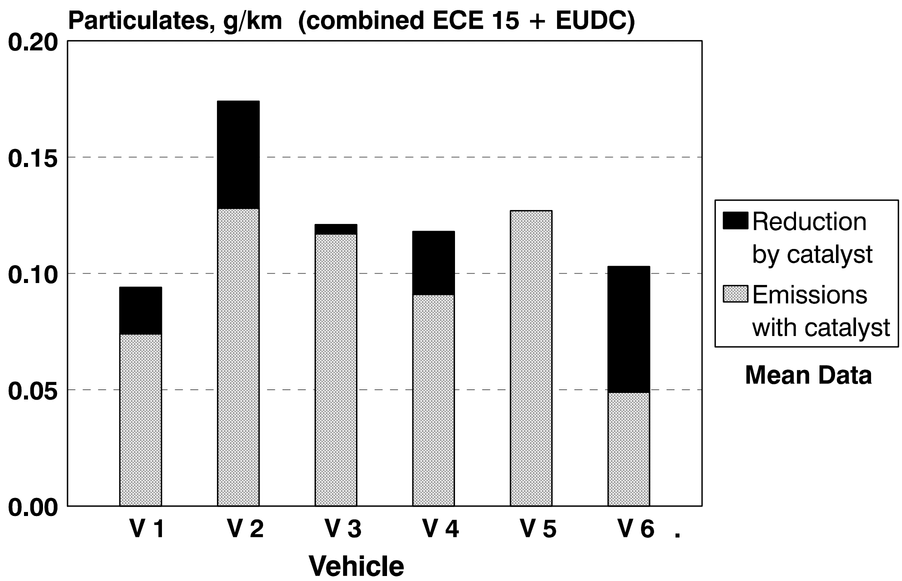


Figure 9 Average reduction of carbon monoxide emissions with oxidation catalyst in operation

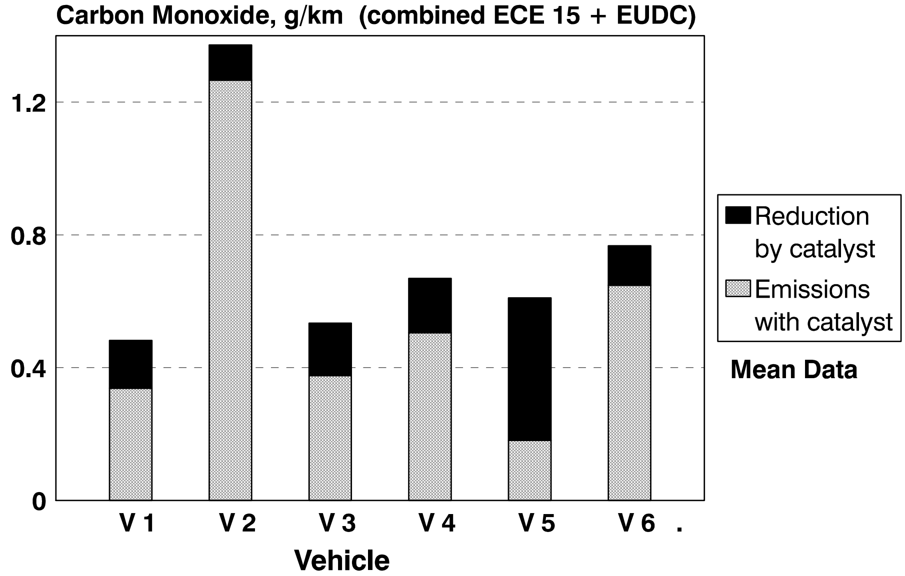


Figure 10 Average reduction of hydrocarbon emissions with oxidation catalyst in operation

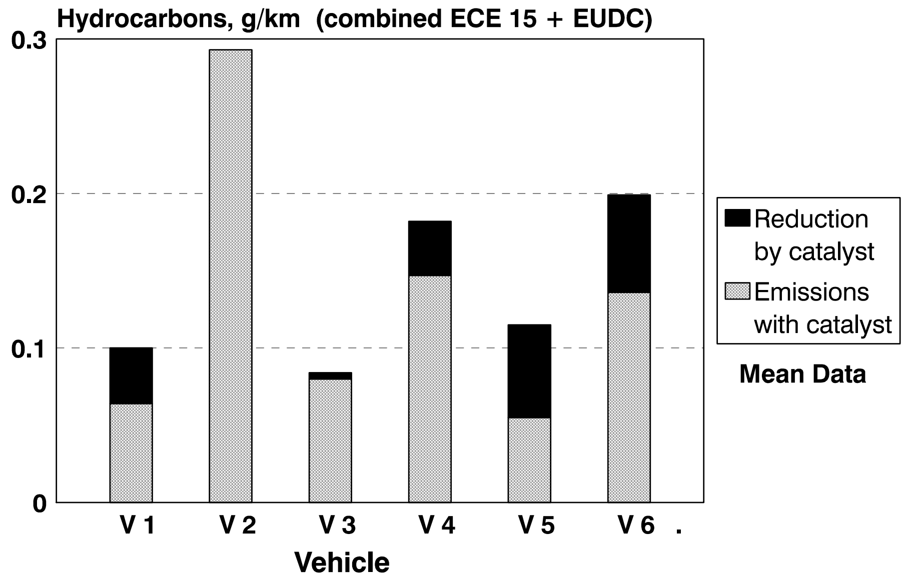


Figure 11 Average reduction/increase of HC + NOx emissions with oxidation catalyst in operation

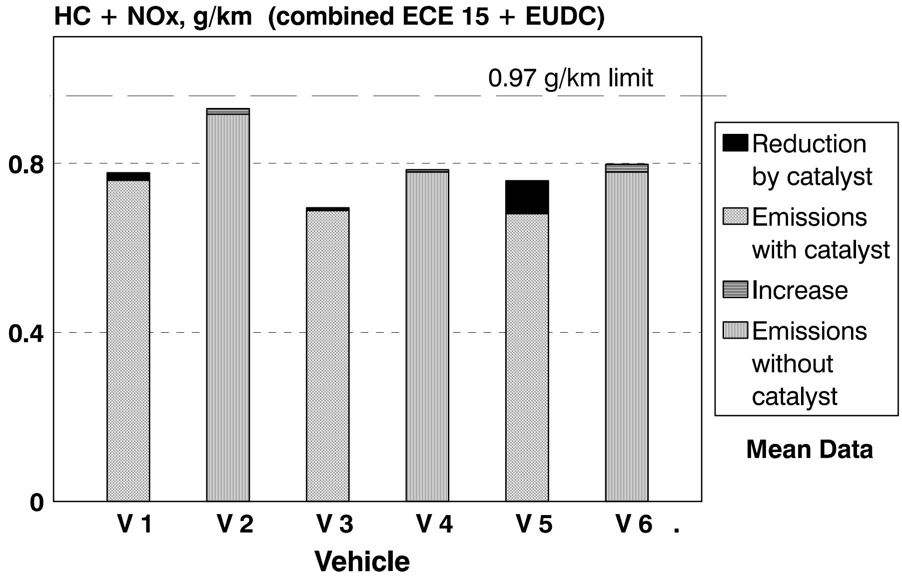


Figure 12 Average reduction of nitrogen oxides emissions with oxidation catalyst in operation