fuel effects on emissions from advanced diesel engines and vehicles

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ABSTRACT

To update understanding on emissions from road transport, CONCAWE is continuing to assess fuel effects on emissions from new engine / vehicle technologies as they approach the market. In this work, two advanced light-duty diesel vehicles and three heavy-duty diesel engines covering Euro-3 to Euro-5 technologies were tested on a wide range of fuels.

This report describes the results for the regulated emissions, HC, CO, NOx and PM, as well as CO_2 and fuel consumption. The detailed particulates characterisation (size and number measurements) is covered in the companion CONCAWE report 1/05 [1].

KEYWORDS

exhaust emissions, diesel, diesel fuel, diesel engine, engine technology, vehicle technology, fuel quality, euro-3, euro-4, euro-5

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SUMMARY

The introduction of sulphur-free fuels (10 mg/kg max. sulphur content) will enable advanced engine and exhaust after-treatment technologies to meet increasingly stringent exhaust emissions regulations. As these cleaner fuels and vehicles are introduced, the potential for further improvements in air quality through changes to fuel properties can be expected to diminish. Nevertheless, CONCAWE has continued to update knowledge by evaluating fuel effects on emissions from new engine/vehicle technologies as they approach the market.

In this work, carried out as part of CONCAWE's contribution to the EU "PARTICULATES" consortium [2], two advanced light-duty diesel vehicles and three heavy-duty diesel engines covering Euro-3 to Euro-5 technologies were tested. The fuels tested covered a range of sulphur content and compared conventional fuels with extreme fuel compositions such as Swedish Class 1 and Fischer-Tropsch diesel fuels. A 5% RME[1] blend was also tested.

The emissions benefits from the advanced engine/vehicle technologies operating on sulphur-free fuels are impressive and likely to bring substantial improvements in European air quality as the vehicle fleet is replaced. Particulate filters have the potential to reduce diesel particulate mass (PM) emissions by more than an order of magnitude. Capability for substantial improvements in control of NOx emissions is also evident.

Fuel effects on PM and NOx emissions were also observed. However, when advanced emission control technologies such as diesel particulate filters (DPFs) were used, PM emissions were so low that the impact of changing fuel properties other than sulphur became negligible. Extreme fuel changes continued to affect NOx emissions even with the advanced engine technologies, although these fuels also reduced maximum power. Optimisation of the exhaust after-treatment was also important, with increasing urea rate reducing NOx emissions. Further progress on NOx emissions can be expected as control of engine-out emissions improves and NOx after-treatment technology matures, with the availability of sulphur-free fuels.

Regarding fuel efficiency and CO_2 emissions, application of SCR/urea to control NOx in a Euro-5 prototype engine, with the engine tuned for better efficiency, improved fuel efficiency by about 5% compared to a Euro-3 base case engine. Conversely, the use of EGR plus CRT to achieve Euro-4 heavy-duty emissions limits resulted in a loss in engine efficiency versus the Euro-3 engine. Despite the wide range of fuels tested, the engine/vehicle energy efficiency was insensitive to fuel changes, and no statistically significant differences between fuels were seen.

[1] A full glossary of acronyms used in this report is given in **Section 8**.

1. INTRODUCTION

Exhaust emissions from road transport continue to decrease in response to increasingly stringent legislation. Euro-3 limits for Diesel passenger cars and heavy-duty engines were introduced in year 2000 and Euro-4 limits take effect from 2005 [3,4]. For heavy-duty engines, Euro-5 limits are also already enacted, with effect from 2008. Discussions are already underway on the next steps in emissions control, Euro-5 for light-duty and Euro-6 for heavy-duty, with a continuing focus on diesel particulate and NOx emissions.

To achieve the increasingly stringent exhaust emissions limits, advanced engines and exhaust after-treatment systems are being introduced. Sulphur-free fuels are being introduced [5] to enable the widest range of advanced vehicle technologies to be employed.

The EPEFE programme [6] provided a comprehensive basis for understanding the interactions between diesel fuel quality, engine technologies and exhaust emissions for both light-duty and heavy-duty diesel fleets. However, EPEFE only included engine technologies up to Euro-2. To update understanding on the interactions between fuels, vehicle technologies and emissions, CONCAWE has continued to evaluate fuel effects on emissions from new engine / vehicle technologies as they approach the market. CONCAWE report 4/02 [7] described a study of diesel fuel effects on emissions from Euro-3 engines and vehicles and CONCAWE reports 5/03 [8] and 2/04 [9] described similar work on gasoline vehicles.

This programme was carried out as part of CONCAWE's contribution to the DG TREN "Particulates" consortium [2]. Two advanced light-duty diesel vehicles (Euro-3) and three heavy-duty diesel engines covering Euro-3 to Euro-5 technologies were assessed. Fuels tested covered a range of sulphur content and compared conventional fuels with two extreme fuel compositions, Swedish Class 1 and Fischer-Tropsch diesel fuels. Although such fuels cannot be expected to be available in substantial volumes, even by the year 2020, they provide a means to assess the maximum possible fuel effects. A rigorous test programme was carried out, based on EPEFE principles, but with an enhanced test design providing more long-term repeats.

The main objectives of this programme were:

- To assess the exhaust emissions benefits achieved by advanced diesel engine and exhaust after-treatment technologies in conjunction with low sulphur fuels,
- To assess the remaining potential for improvements in vehicle emissions through fuel quality.

Only the regulated emissions, CO_2 and fuel consumption data are described in this report. The detailed particulates characterisation (size and number measurements) is covered in the separate CONCAWE report 1/05 [1].

2. ENGINES/VEHICLES SELECTION

2.1. HEAVY-DUTY ENGINES

The heavy-duty test engines were selected to cover the range of technologies likely to be used to meet Euro-3, Euro-4 and Euro-5 exhaust emissions standards. The Euro-3 engine was an existing market technology without after-treatment. As Euro-4 and Euro-5 engines were not yet available in the market, prototype systems developed at AVL were used. The prototype Euro-4 engine used a combined system of EGR plus a Continuously Regenerating Trap (CRT). The prototype Euro-5 engine used SCR/urea, together with engine modifications to optimise engine out NOx/PM (without a particulate filter). These two approaches represented those considered at the time to be most likely to be used to meet the advanced EU emissions standards. Further technical details on the engines are given in **Table 1***:*

Table 1 Heavy-Duty engine specification data

	Euro-3	Euro-4	Euro-5
Certification level	Production Euro-3	AVL prototype Euro-4	AVL prototype Euro-5
Cylinders	6	6	6
Displacement (dm^3)	12	11	12
Max Torque [Nm] @ rpm [min-1]	2019 @ 1200	1865 @ 1200	1894 @ 1300
Max Power [kW] @ rpm [min-1]	300 @ 1800	300 @ 1900	300 @ 1800
Valves per cylinder	4	4	4
Fuel injection equipment	Unit injectors	Unit injectors	Unit injectors
Aspiration	TC	TC	TC
EGR	No	Cooled EGR	No
Exhaust after- treatment	None	CRT	SCR / urea

2.2. LIGHT-DUTY VEHICLES

Two diesel passenger cars were selected for testing representing advanced technologies available in the European market in 2002. These included a medium sized DI diesel car with an oxidation catalyst and a large DI diesel car with a particulate filter system which regenerated with the aid of a fuel-borne catalyst. More details on the main technical characteristics of the engines are reported in **Table 2**.

Table 2 Light-duty diesel vehicle specification data

Vehicle Type	**Car A**	**Car B**
Displacement (cm^3)	1896	2179
Max. Power (kW @ rpm)	74 @ 4000	98 @ 4000
No. of Cylinders	4	4
Max. Torque (Nm @ rpm)	240 @ 1800	314 @ 2000
Compression Ratio	19	17.6
Aspiration	TC	TC
Intercooler Y (yes) N (no)	Y	Y
Combustion Type	DI	DI
Injection System	Unit injectors	Common Rail
EGR Y (yes) N (no)	Y	Y
Exhaust after-treatment	Oxidation catalyst	Additised DPF
Model Year	2002	2001
Certification level	Euro-3	Euro-3

3. TEST FUELS

Sulphur content has been recognised as the key fuel parameter for emissions due to its enabling effect for advanced engines and exhaust after-treatment systems, as well as its direct effect on sulphate production. The recent update to the EU Fuels Directive [5] specifies a maximum sulphur content of 50 mg/kg in gasolines and diesel fuels from 2005, with “appropriately balanced geographic availability” of sulphur-free fuels (10 mg/kg max sulphur content) from the same date, progressing to 100% coverage of sulphur free fuels by 2009 (this date being subject to a further review for diesel).

The test fuels for this programme were selected in view of the objectives of the DG TREN “Particulates” consortium to develop representative emissions factors for the current and future vehicle fleets, as well as to enhance understanding of the benefits of sulphur reduction versus the effects of other diesel fuel properties.

Test fuels D2 to D4 were designed to study the sulphur effect, using a base fuel with sulphur content as low as possible and with other properties held as close as possible to typical year 2000/05 levels. Sulphur levels were adjusted by doping with di-tertiarybutyl-di-sulphide, to cover a range from current sulphur levels to the projected sulphur-free case.

Additional fuels were included to assess the largest possible range of fuel properties. These included two additional sulphur-free fuels with extremely low density and aromatics content: Swedish Class 1 diesel fuel (D5) and Fischer-Tropsch diesel fuel (D8). A second diesel fuel (D6) at the current (year 2000) sulphur level but with higher density and aromatics content was also tested to provide the other extreme of fuel composition. Finally, fuel D7, a blend of fuel D4 with 5% RME, was tested.

Table 3 shows the analytical data for the test fuels.

Table 3 Diesel Fuel Analyses

Fuel Code			D2 to D4	D5	D6	D7	D8
Fuel Description	Units	Test method	**Sulphur Matrix**	**Swedish Class 1**	**EN590: pre-2000**	**5% RME in D4**	**Fischer-Tropsch**
Cetane Number		D 613	**54.0**	**55.1**	**46.5**	**54.5**	**>75**
Cetane Index		IP 380	**51.1**	**51.7**	**46.7**	**50.6**	*****
Density	kg/m^3	EN ISO 3675	**845**	**810**	**856**	**846**	**785**
T50	°C	EN ISO 3405	**282**	**226**	**279**	**284**	**298**
T95	°C	EN ISO 3405	**358**	**282**	**366**	**358**	**349**
FBP	°C	EN ISO 3405	**368**	**294**	**373**	**367**	**355**
CFPP	°C	EN 116	**-33**	**-39**	**-14**	**-33**	**0**
KV @ 40°C	mm^2/s	EN ISO 3104	**3.04**	**1.79**	**3.15**	**3.08**	**3.61**
Poly-aromatics	% m/m	IP 391	**4.3**	**<0.1**	**7.3**	**5.0**	**0.0**
Mono-aromatics	% m/m	IP 391	**14.1**	**1.7**	**31.0**	**12.9**	**0.1**
Carbon	% m/m		**86.8**	**85.7**	**87.1**	**86.3**	**85.0**
Hydrogen	% m/m		**13.2**	**14.3**	**12.9**	**13.1**	**15.0**
H:C ratio	atomic ratio		**1.82 : 1**	**2.00 : 1**	**1.78 : 1**	**1.82 : 1**	**2.12: 1**
LHV	MJ/kg		**42.87**	**43.63**	**42.69**	**42.70**	**44.17**
Lubricity	µm	HFRR	**375**	**386**	**389**	**237**	**279**
FAME	% v/v		**Nil**	**Nil**	**Nil**	**5**	**Nil**
Sulphur	mg/kg	D 3120/2622		**<5****	**307**	**7**	**<5****
D2	**EN 590 : 2000**		**280**				
D3	**EN 590 : 50 ppm S**		**38**				
D4	**EN 590 : 10 ppm S**		**8**				

* Cetane index equation is not applicable to FT diesel fuel.
** Below detection limit

A common batch of lubricant, suitable for use in both light and heavy-duty diesel engines, was used for the programme in order to minimise any possible effects from the lubricant. The lubricant selected was representative of current typical European engine oil quality, i.e. a good quality, high volume, conventional mineral oil formulation, meeting: SAE 15W-40, ACEA Class A3 / B3 for light duty, ACEA Class E3 for heavy duty, with a sulphur content of 0.6% m/m.

4. TEST METHODOLOGY

The details on the driving cycles used for the tests were those prescribed by Deliverable 5 from the “Particulates” Consortium’s Work Package 400 [10]. In all cases the standard legislative emissions test cycles for light-duty vehicles and heavy-duty engines were used [3,4]. These were supplemented by some “real world drive cycles” (**See Appendix 1**) which were developed under the ARTEMIS programme [11] and several steady-state conditions. Light-duty vehicle tests were conducted by Shell Global Solutions and heavy-duty engine tests by AVL.

For heavy-duty engines, the relevant legislative heavy duty engine emissions test cycles, ESC and ETC, were used, together with a series of extended steady state modes covering both on-cycle and off-cycle measurement points. A common test sequence was required in order to obtain comparable results from different fuel/engine combinations. This general daily test sequence was:

Heavy-Duty Engine Test Sequence

- Warm-up (Road load, followed by 0.5 h at full load, rated speed)
- Dummy ESC
- ESC (full load points at full rack, part load points at constant torque for each fuel)
- ETC (full load points at full rack, part load points at constant torque for each fuel)
- Extended Steady-States - Range of on- and off-cycle conditions as below:
  - SS1 - ECE R-49 Mode 2
  - SS2 - ESC Mode 5 (50% load, speed A)
  - SS3 - ESC Mode 12 (75% load, speed C)
  - SS4 - Road load, speed 50/50 A/C
  - SS5 - 25% load, speed A-10%
  - SS6 - 50% load, 50% speed

For light-duty vehicles, the following basic daily test sequence was used:

Light-Duty Vehicle Test Sequence

- Fuel change
- Conditioning : 3* EUDCs
- Cold soak
- NEDC test
- Hot start NEDC test
- ARTEMIS urban test
- ARTEMIS road test
- ARTEMIS motorway test (130 km/h max speed)
- Steady-state tests : 50 and 120 km/h
- End of test

The test programme was constructed using the principles of statistical experimental design. Fuels were tested three times in each vehicle/engine, based on a randomised block design. Each fuel was tested once in each block of tests, minimising the risk of fuel comparisons being contaminated by any drift in vehicle performance or other time-related effects. Repeat tests on a fuel were not conducted back-to-back to ensure that the results were truly independent.

All fuels were tested in the light-duty vehicles. In the heavy-duty engines, the 300 ppm sulphur fuels were not considered relevant to test in the Euro-4 or Euro-5 engines, likewise the Fischer-Tropsch diesel was not tested in the Euro-3 engine. The actual engine/vehicle/fuel combinations tested are given in **Table 4**.

Table 4 Engine/vehicle/fuel combinations tested

	Fuel Code						
	D2	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**
Light-Duty Vehicles							
Car A	√	√	√	√	√	√	√
Car B	√	√	√	√	√	√	√
Heavy-Duty Engines							
Euro-3	√	√	√	√	√	√	
Euro-4		√	√	√		√	√
Euro-5		√	√	√		√	√

5. STATISTICAL ANALYSIS METHODOLOGY

The test programme was constructed using the principles of statistical experimental design as described in **Section 4**.

The results were statistically analysed by emission (CO, NOx, HC, PM, CO_2) on a vehicle-by-vehicle and cycle-by-cycle basis. Fuel consumption was also analysed, based on direct gravimetric measurements for heavy-duty and by calculation from emissions for light-duty. Only the overall ESC and ETC (heavy-duty engines) and NEDC and Artemis motorway cycle data (light-duty vehicles) were examined in detail.

In the EPEFE gasoline project [6] and other previous emission studies, e.g. [7-9, 12-14], the variability in emissions measurements has typically been found to follow the lognormal distribution with the degree of scatter increasing as the emission level increases. This assumption was difficult to verify in the present study, e.g. using standard deviation vs. mean plots, as the levels of emissions differed little from fuel to fuel in any particular vehicle/engine (see **Appendix 4**). Nevertheless lognormality was assumed as mechanistically this is the most plausible model for emissions data.

Before carrying out the analysis, the data were validated by evaluation for outliers and trends as described below. Outliers were identified by inspecting studentized residuals (residuals divided by their standard errors).

In the heavy-duty data-set, a small number of data points were missing due to test equipment failures, mostly in the ETC. For practical reasons, some ETC tests in the Euro-5 engine were delayed until the end of the test programme.

Some emissions were below the limits of detection and were treated as zeros in the data analysis. These included all the HC measurements from the Euro-5 engine and all the CO measurements from car A on the ARTEMIS motorway cycle.

One test on fuel D8 in car A gave abnormally low NOx and HC emissions in the ARTEMIS motorway cycle. An emissions leak was suspected and this test was rejected in its entirety. No heavy-duty results were rejected.

There were some strong time trends in emissions from car B, with NOx showing a consistent increase over time in the NEDC (significant at $P < 0.1\%$) and CO_2 emissions showing a consistent decrease (significant at $P < 1\%$) in the Artemis motorway cycle.

Strong emission trends were also seen in the Euro-3 heavy-duty engine with CO_2 and FC showing a consistent decrease (significant at $P < 1\%$) in the ESC.

The mean emissions for each fuel in each of these data sets were adjusted using analysis of covariance techniques to eliminate any bias that might be caused by such trends. The adjustments had relatively little effect on mean emissions owing to robustness of the experimental design (see **Appendices 2 and 3**).

A large upward trend in CO emissions was seen in the Euro-4 engine in the ETC (significant at $P < 1\%$). This trend was nonlinear and was catered for by making an appropriate correction on the log emissions scale. This correction had a marked effect on the average CO emissions from fuel D8 as it needed to compensate for the missing result in the first block (see **Appendix 2**).

Statistical adjustments were only made for data sets where there was an unambiguous trend over the full range of tests which was significant at $P < 1\%$.

In the tables (**Appendices 2 and 3**) and graphs (**Section 6**) presented in this report, simple arithmetic means are used to summarise the emissions for each vehicle × fuel combination. Values below the limits of detection were treated as zeros when calculating means.

The error bars in the figures in **Section 6** show the

$$\text{mean value} \pm 1.4 \times \text{Standard error of mean.}$$

These are constructed, as in EPEFE [6], so that when two fuels are significantly different from one another at $P < 5\%$[2], their error bars will not overlap. We can be 84% confident that the true mean lies within the limits shown.

[2] $P < 5\%$ = the probability that such an event could be observed by chance when no real effect exists is less than 5%. In other words, we are 95% confident that the effect is real. Likewise $P < 1\%$ = 99% confidence and $P < 0.1\%$ = 99.9% confidence

6. RESULTS

The results are discussed first for heavy-duty engines and then for light-duty vehicles. The diagrams in the following sections show the average emissions measurements for the regulated cycles: ESC and ETC for heavy-duty engines and NEDC for light-duty vehicles. The results for other test conditions are only discussed where they proved helpful to understand or expand the trends, in particular the ARTEMIS Motorway cycle for light-duty vehicles, which provided a high temperature operation, for comparison with the standard NEDC. The average emissions results for the different engines/cars are grouped for each fuel, from D2 to D8. The Euro-3, Euro-4 and Euro-5 (the latter only for heavy-duty) limits are indicated in the diagrams. The actual mean emissions values are given in **Appendices 2 and 3.**

6.1. HEAVY-DUTY ENGINES

6.1.1. CO emissions

Figure 1 CO emissions - ESC

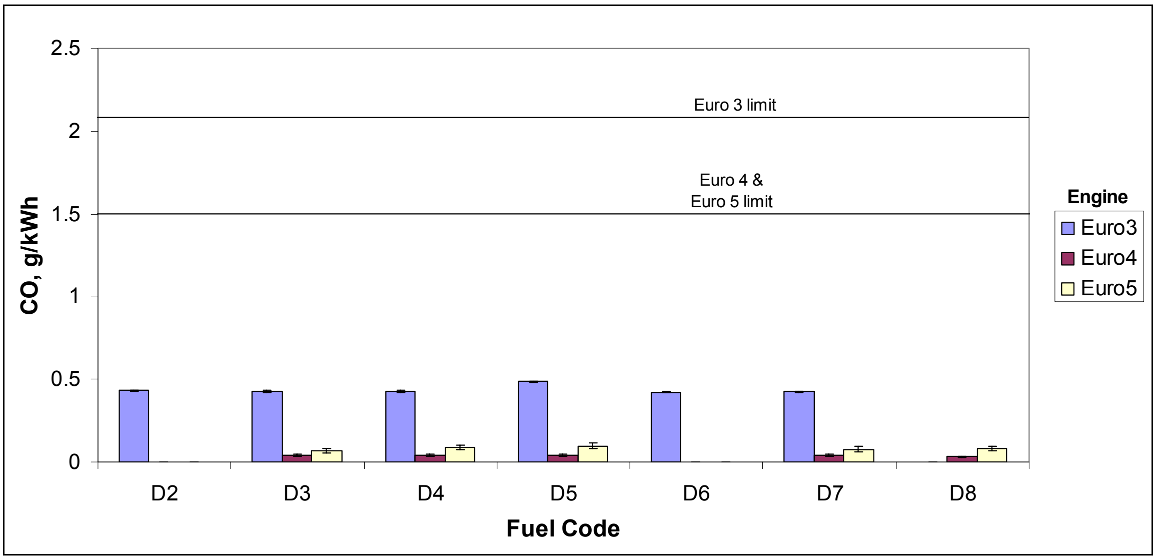
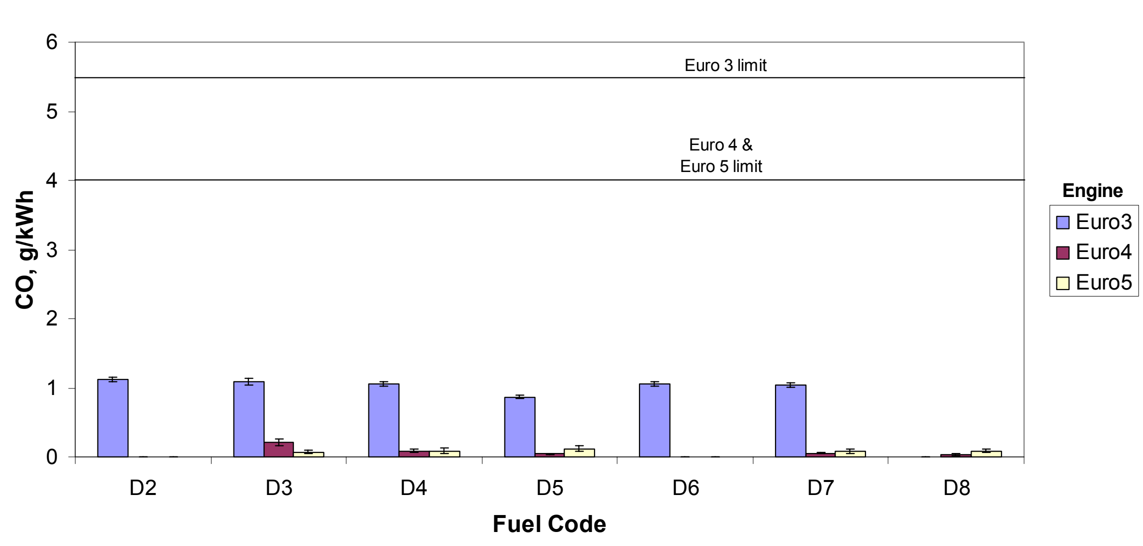


Figure 2 CO emissions - ETC



Figures 1 and 2 show that all of the CO emissions, even for the Euro-3 engine, were well below the Euro-5 limits and fuel effects were small relative to the regulatory limits. The CO emission values in the ETC were higher than in the ESC, but still far below the emission limits. The Euro-4 and Euro-5 engines, which include oxidation catalysts, both gave extremely low CO emissions.

In the Euro-3 engine, Swedish Class 1 fuel (D5) gave higher CO emissions than the other fuels on the ESC but lower CO emissions on the ETC. There appears to be an effect of sulphur in the Euro-4 engine with CRT, as indicated by the results on fuels D3 and D4 on the ETC, though this effect was not seen on the ESC. Other fuel effects were negligible.

6.1.2. HC emissions

Figure 3 HC emissions - ESC

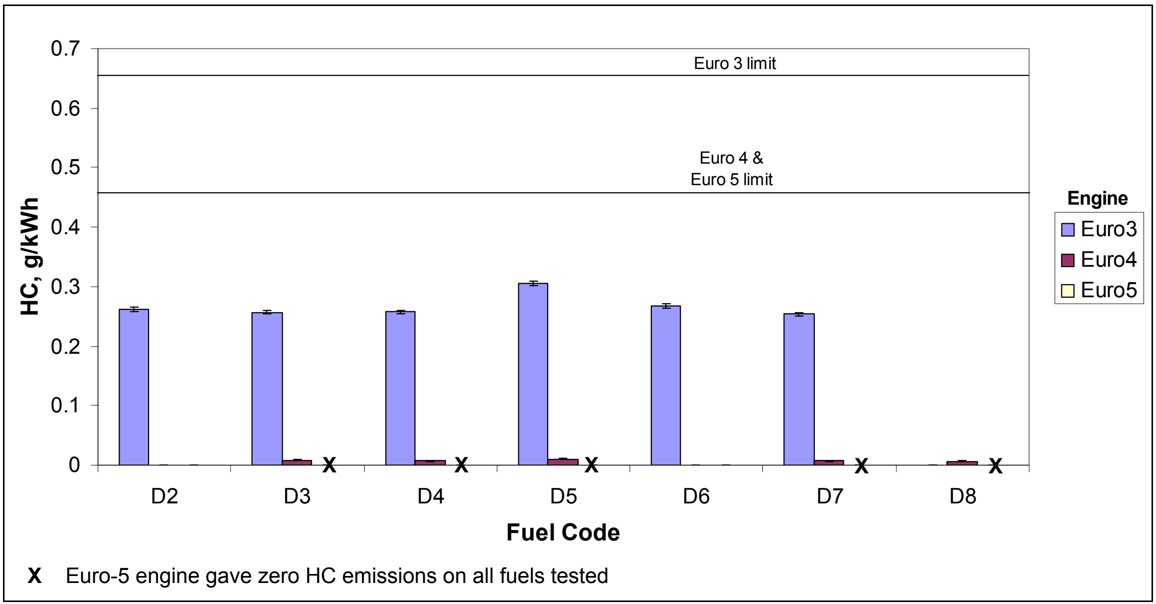
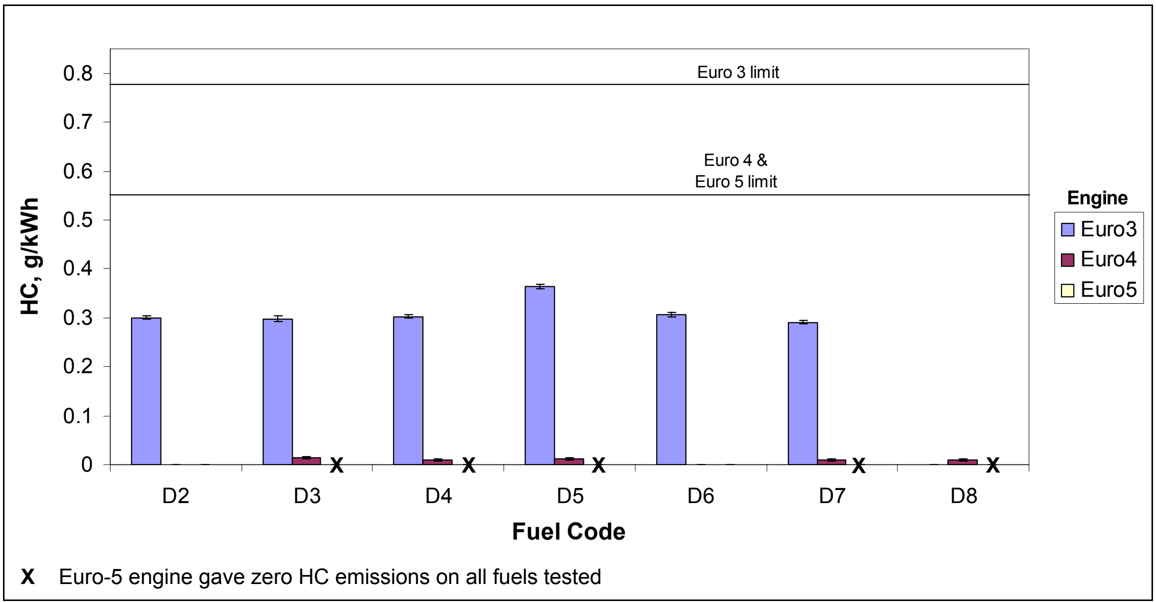


Figure 4 HC emissions - ETC



HC emissions results (**Figures 3 and 4**) showed the same pattern in the ESC and ETC tests. HC emissions from the Euro-3 engine were around half of the Euro-3 limits. HC emissions from the Euro-4 engine were very low and those from the Euro-5 engine were not detectable.

Swedish Class 1 fuel (D5) gave the highest HC emissions in the Euro-3 engine on both test cycles. There were no other substantial fuel effects.

6.1.3. NOx emissions

Figure 5 NOx emissions - ESC

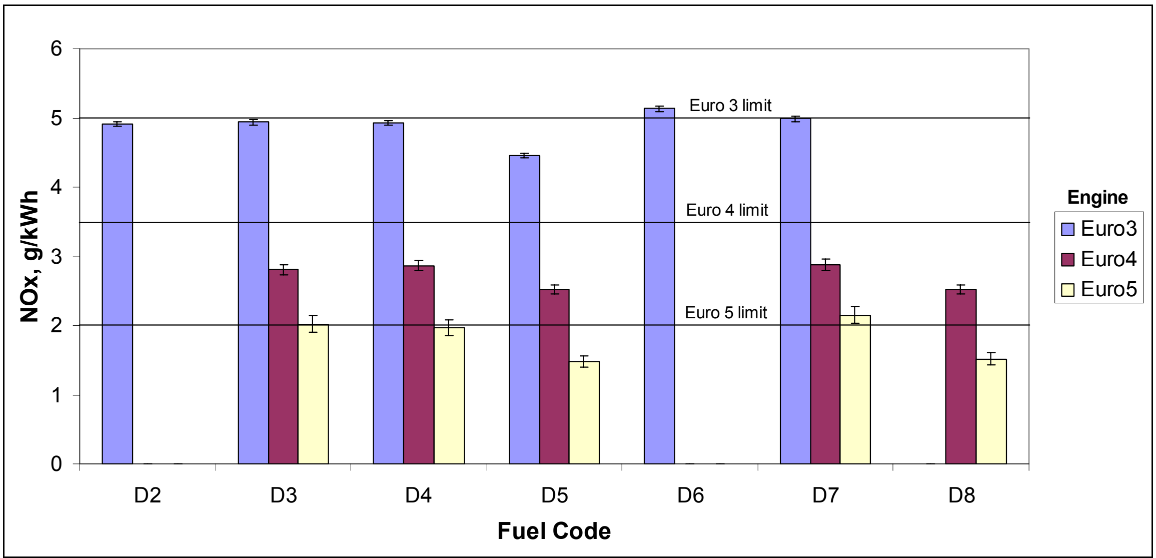
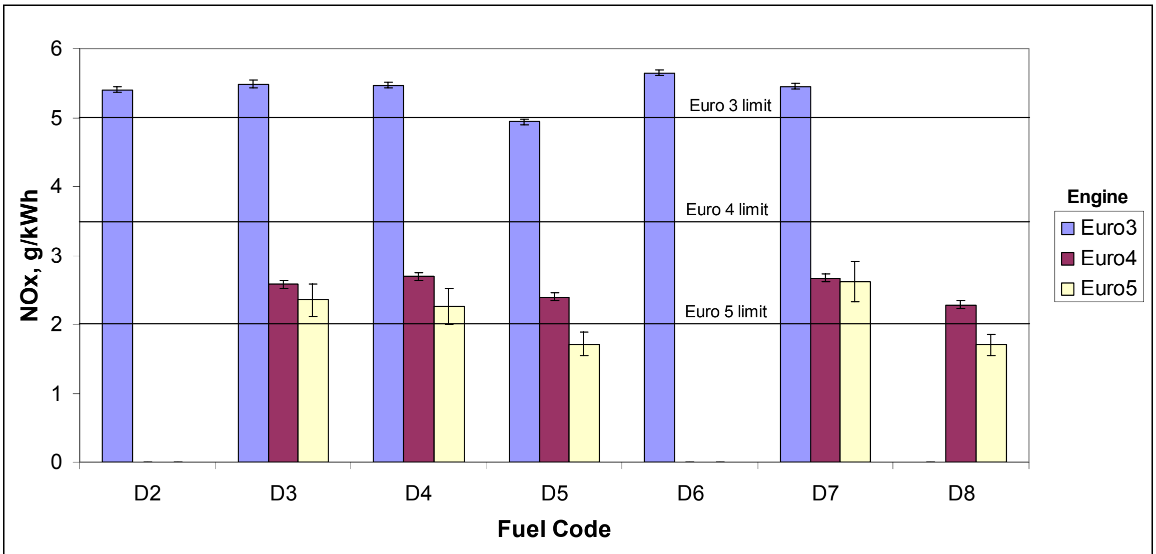


Figure 6 NOx emissions - ETC



As shown in **Figures 5 and 6**, NOx is a more critical emission. Trends in NOx emissions were similar in the ESC and ETC tests, although the emission limits were more often exceeded in the ETC test. The Euro-4 engine operated well within its NOx limits in both ESC and ETC tests on all fuels. NOx emissions from the Euro-3 and Euro-5 engines were very close to their respective ESC test limits. Considerable progress in control of NOx emissions from Euro-3 to Euro-5 engines is evident. However, even the Euro-5 NOx emissions levels are still relatively high compared to the US heavy-duty limits for 2007 and 2010 [15]. Further progress can therefore be expected as control of engine-out emissions improves and NOx after-treatment technology matures.

Fuel sulphur content, decreasing from D2 to D4, did not influence NOx emissions. Fuel D6 gave the highest NOx emissions in the Euro-3 engine, but the difference to fuels D2-D4 was small and in-line with previous studies [6,7]. Effects from addition of 5% RME were small (D7 vs. D4). Larger fuel effects on NOx emissions were observed with Swedish Class 1 (D5) and Fischer-Tropsch diesel fuel (D8), consistent with the extreme changes in fuel properties.

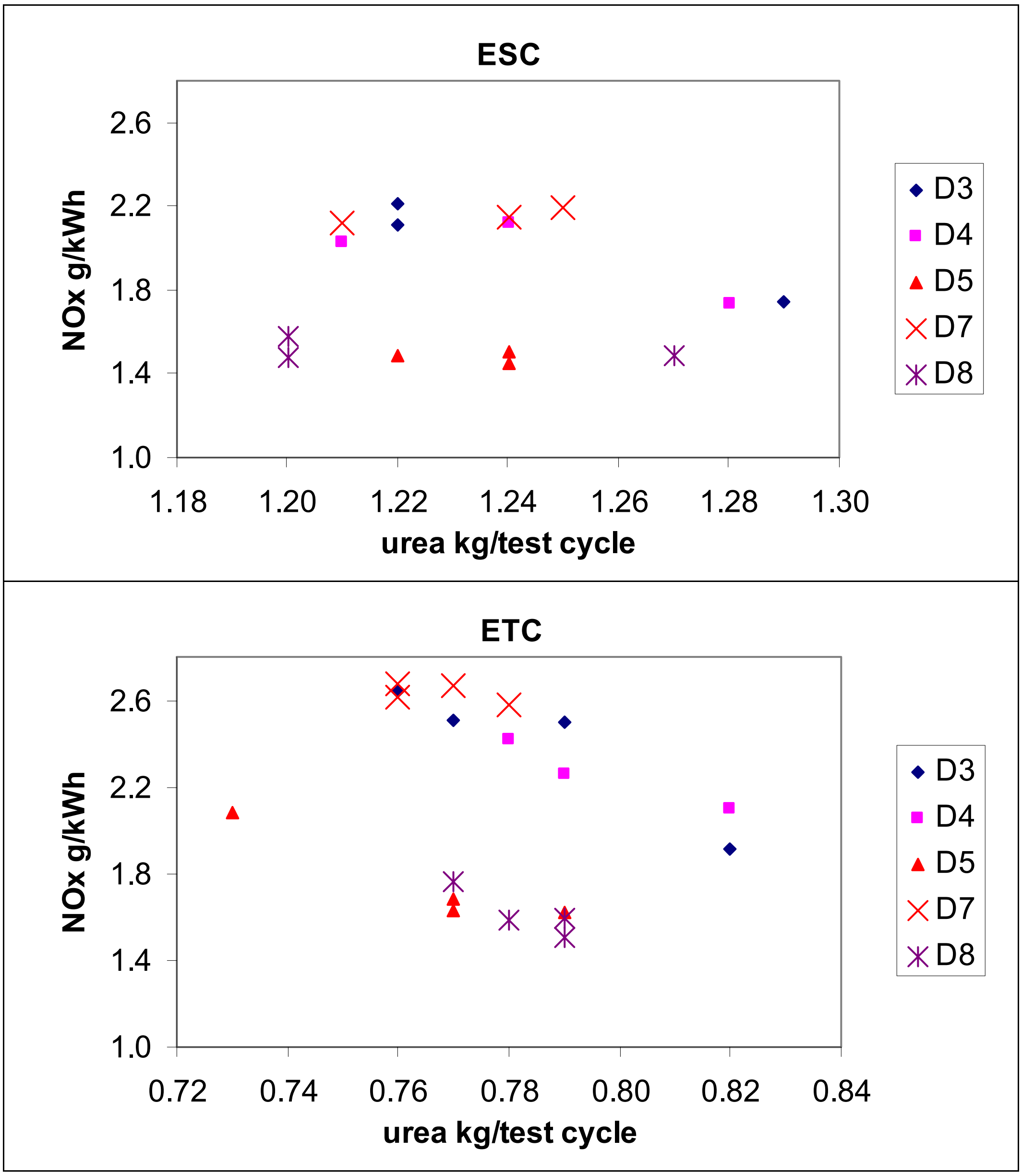
6.1.3.1. Impact of urea injection rate on NOx emissions of Euro-5 engine equipped with SCR

In the prototype Euro-5 engine, NOx after-treatment was by SCR/urea. Urea injection rate data were recorded by AVL for the complete ESC and ETC cycles. In this prototype engine system, there was some variability in the test-to-test urea injection rate that allowed the effect of different urea quantities to be examined.

In the ESC test, the effect of urea injection rate on NOx emissions was weak. The lower emissions from fuels D5 and D8 can be clearly seen in **Figure 7**. In the ETC test the effect of urea injection rate on NOx was much more marked. Lower emissions from D5 and D8 can again be clearly seen in **Figure 7**. However, the performance with the other fuels could also be improved by use of a higher urea injection rate.

Note: For the ESC test, the urea usage figures (kg / test cycle) relate to the whole cycle, not only the measurement stages.

Figure 7 NOx emissions versus urea usage - Euro-5 engine, ESC and ETC



6.1.4. PM emissions

Figure 8 PM emissions - ESC

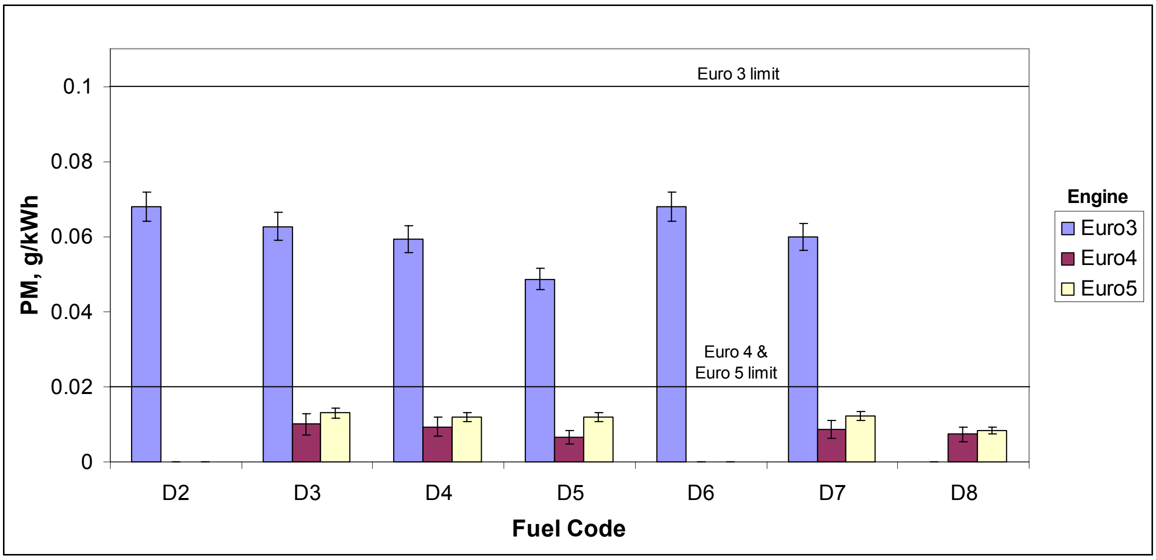
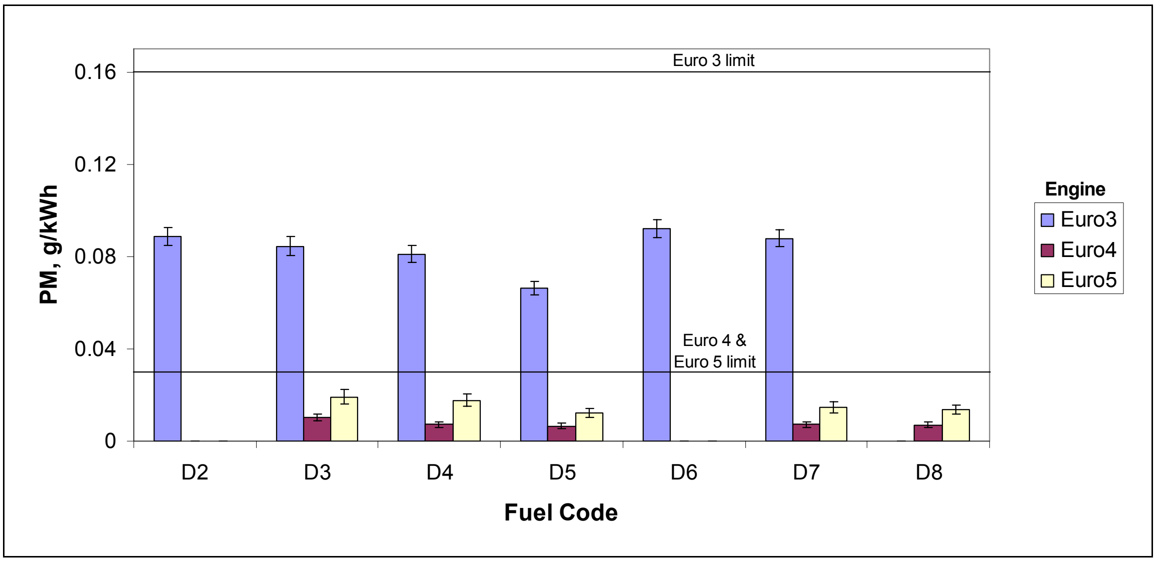


Figure 9 PM emissions - ETC



Particulate mass (PM) is the other critical Diesel pollutant. In the ESC and ETC tests, all 3 engines performed well within their respective PM emissions limits (see **Figures 8 and 9**). The Euro-4 engine with particulate trap gave the lowest PM emissions, although PM emissions from the Euro-5 engine were also very low.

In the Euro-3 engine, lower sulphur content reduced PM emissions (compare fuels D2 to D4). Fuels D2 and D6, with comparable sulphur contents, but differing in other properties, gave similar PM emissions. The addition of 5% RME to fuel D4 (fuel D7) did not change PM emissions.

Fuels D5 (Swedish Class 1) and D8 (Fischer-Tropsch) performed similarly and gave lower PM emissions than the other fuels. In the advanced Euro-4 and Euro-5 engines, the effects versus conventional 10ppm sulphur fuels were very small in absolute terms.

In the D2-D4 sulphur fuel series, the PM results are broadly consistent with the changes expected for a sulphate conversion factor in the range of 1-2%, which has been the recognised conversion factor for older (Euro-1 and Euro-2) engines. From these tests, there is no evidence of substantially higher sulphate conversions with these more advanced heavy-duty engine technologies.

6.1.5. Fuel efficiency and CO_2 emissions

In heavy-duty tests, fuel consumption was measured directly by gravimetric measurements. The fuel consumption results are described below for the ESC and ETC.

Figure 10 Mass Fuel Consumption, g/kWh - ESC

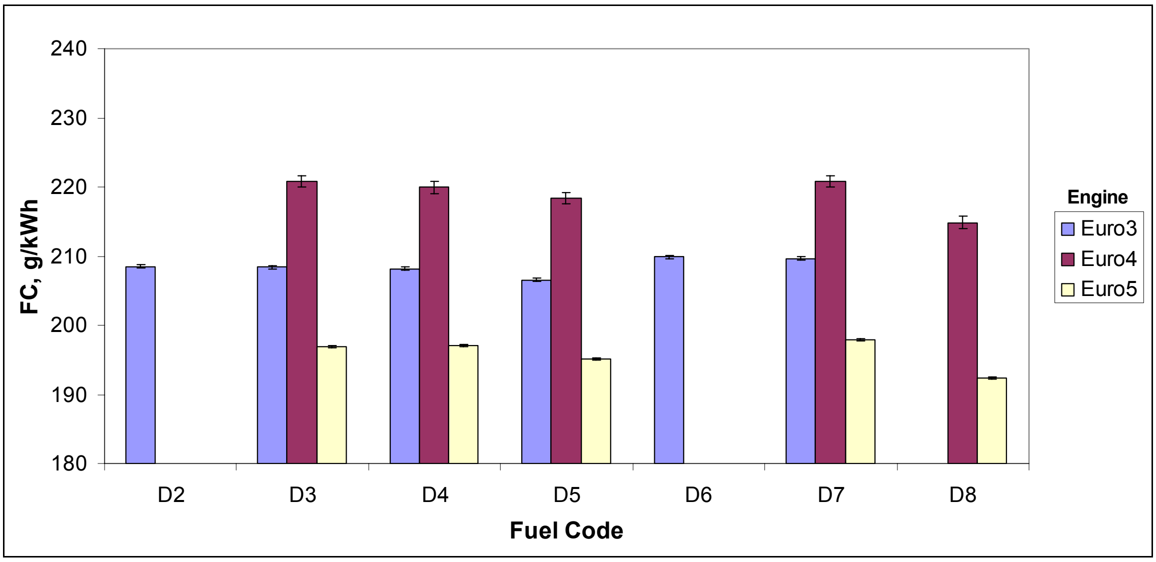
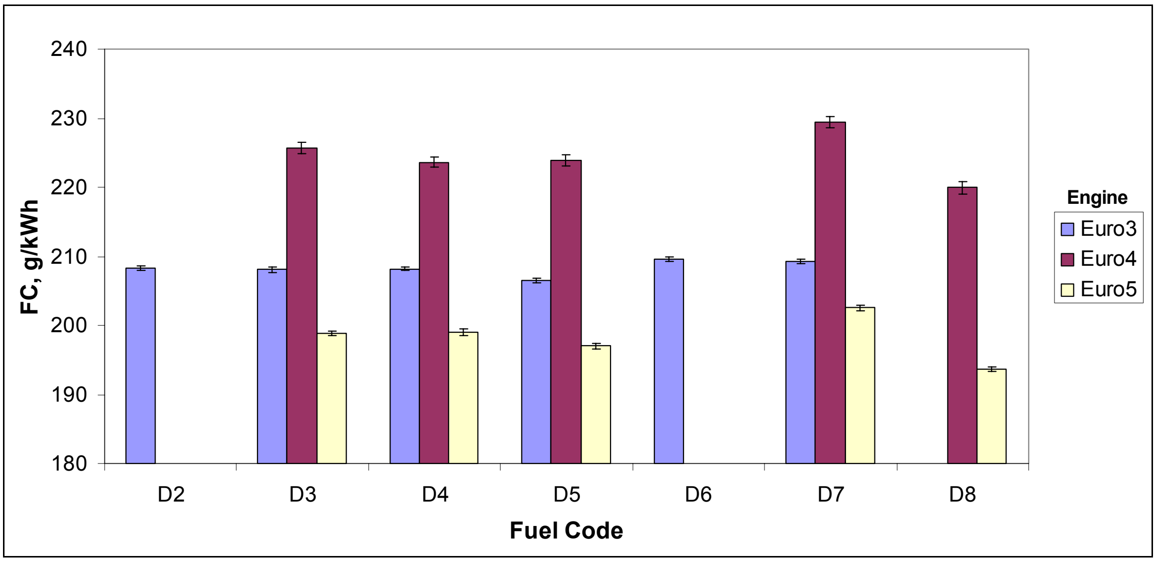


Figure 11 Mass Fuel Consumption, g/kWh - ETC



Figures 10 and 11 show similar trends in mass fuel consumption in the ESC and ETC tests. The use of SCR/urea to control NOx in the Euro-5 prototype engine, with the engine tuned for better efficiency, improved fuel consumption by about 5% versus the Euro-3 base case engine. Conversely, the use of EGR plus CRT to achieve Euro-4 heavy-duty emissions limits resulted in an increase in fuel consumption versus the Euro-3 engine (5-8% dependent on test cycle).

As regards fuel effects, small but significant reductions in mass fuel consumption were observed with Swedish Class 1 (D5) and Fischer-Tropsch diesel fuel (D8). In the Euro-3 engine, the highest density fuel (D6) showed the highest mass fuel consumption. These effects are mainly related to energy content (LHV) as explained further in the following sections.

Figure 12 Volumetric Fuel Consumption, litres/kWh - ESC

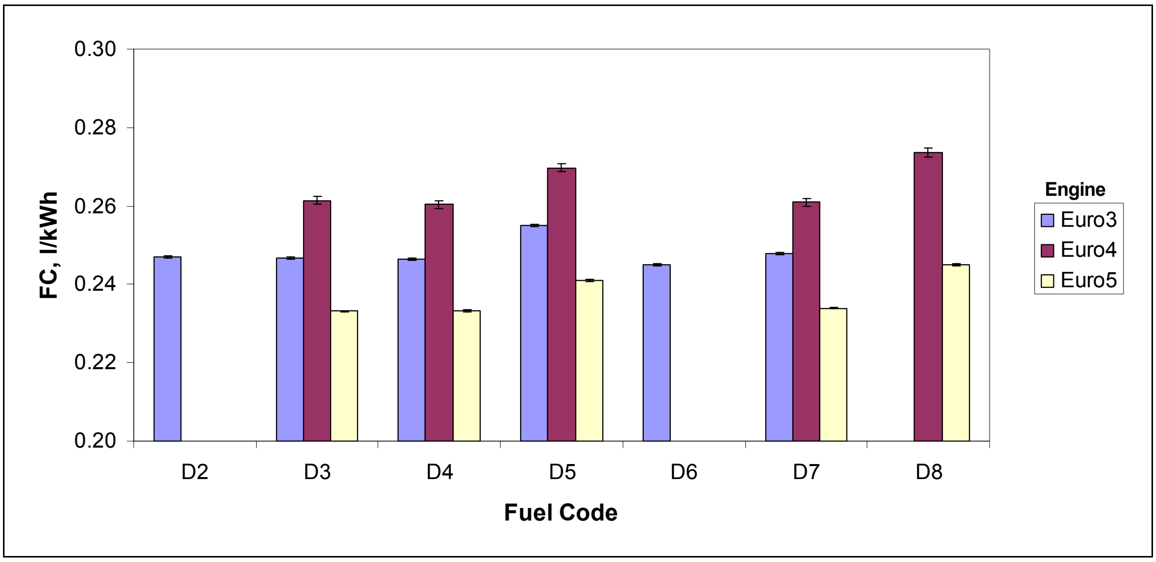
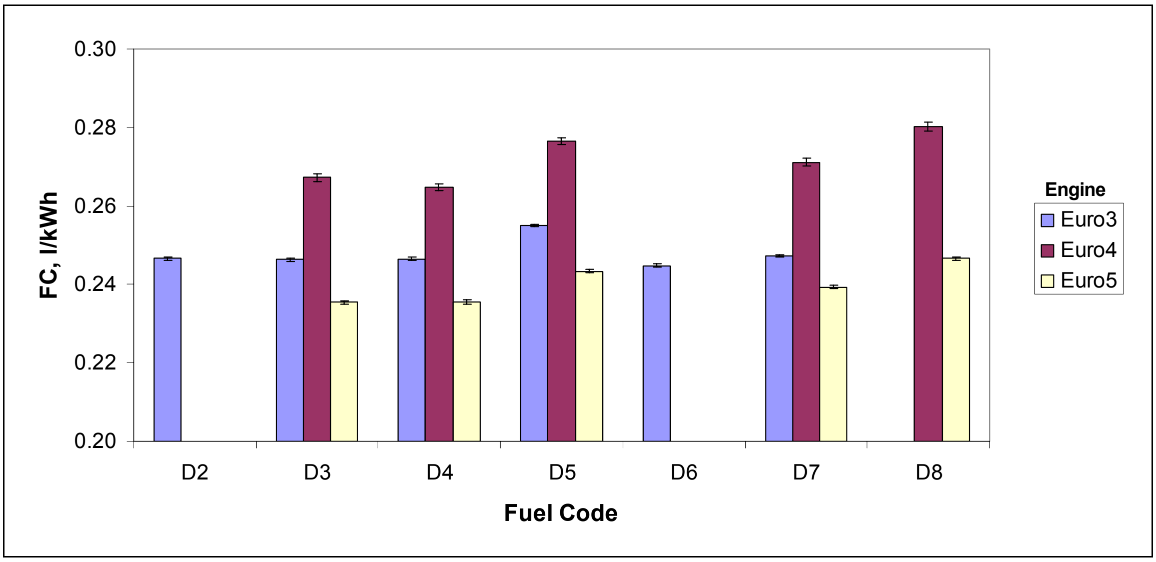


Figure 13 Volumetric Fuel Consumption, litres/kWh - ETC



Figures 12 and 13 show similar trends in volumetric fuel consumption in the ESC and ETC tests. Engine trends are the same as shown in the mass fuel consumption charts (**Figures 10 and 11**).

Fuel effects now appear rather differently. Significant increases in volumetric fuel consumption arise with Swedish Class 1 (D5) and Fischer-Tropsch diesel fuel (D8), principally due to their lower densities.

In order to clarify the observed fuel effects on mass and volumetric fuel consumption, engine efficiencies were calculated from the mass fuel consumption, engine power and fuel energy content (LHV values shown in **Table 3**). In the following energy efficiency graphs, the error bars include the variability in both the engine test results and the fuel LHV measurements.

Figure 14 Engine Efficiencies - ESC

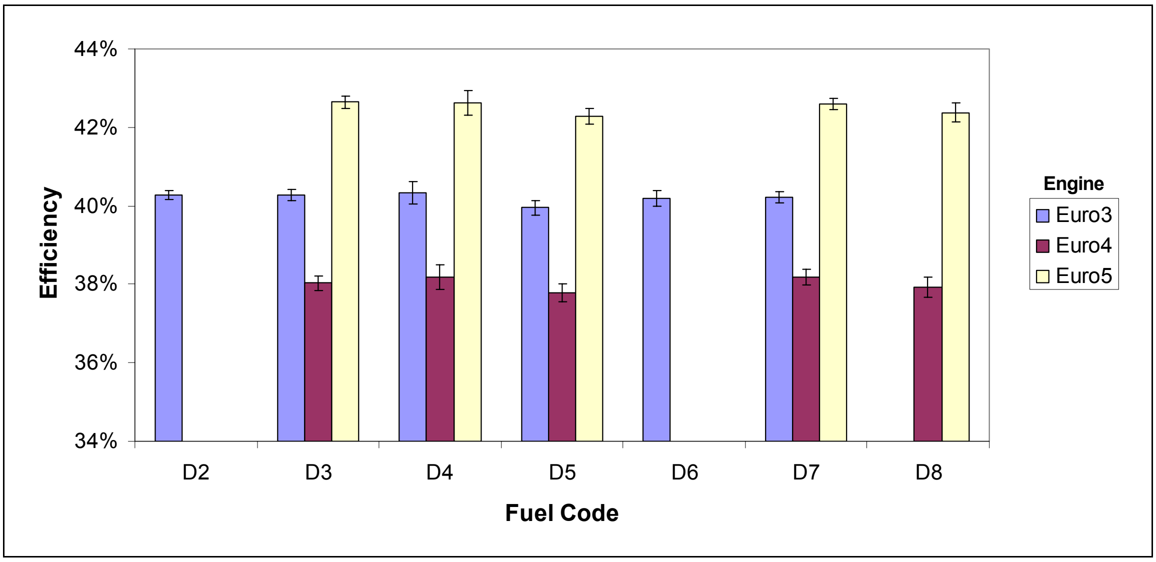
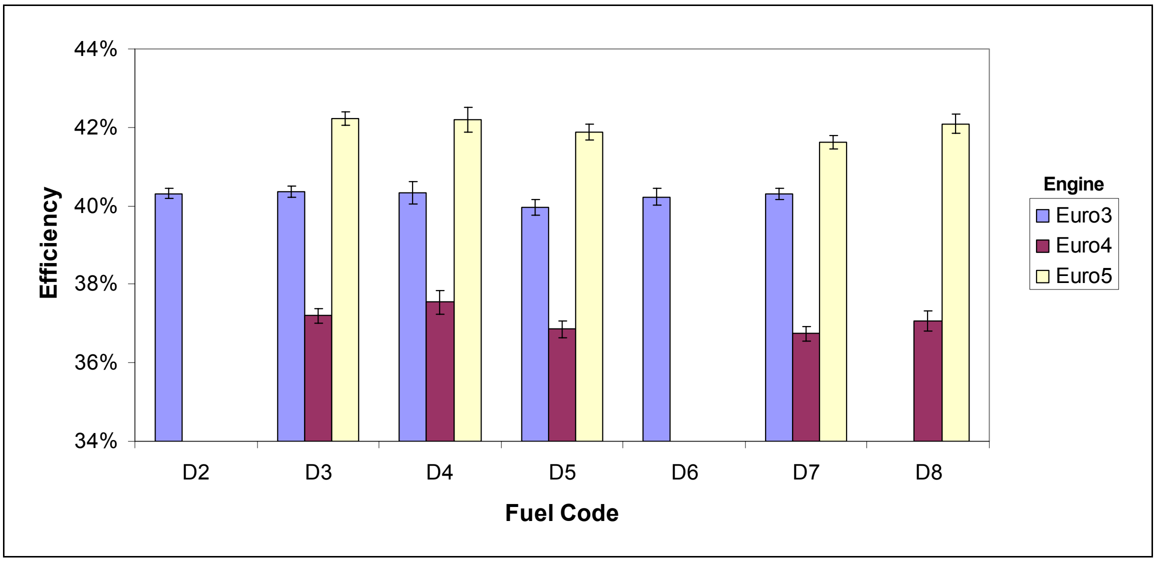


Figure 15 Engine Efficiencies - ETC

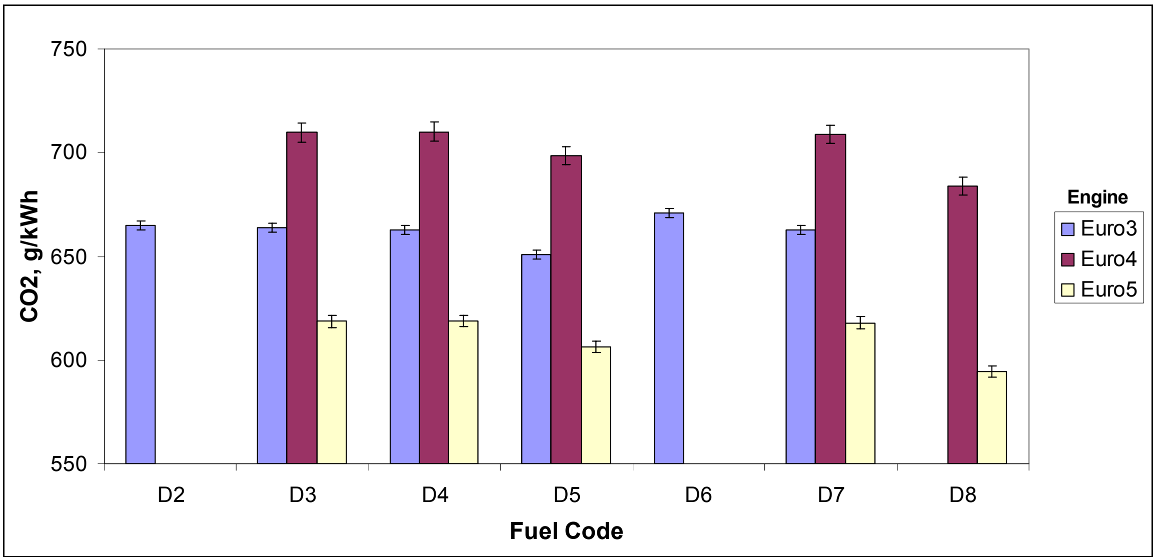


Figures 14 and 15 show similar trends in engine efficiencies in the ESC and ETC tests. Engine trends are the same as shown in the mass fuel consumption charts (**Figures 10 and 11**).

Fuel effects on engine efficiency were small. Swedish Class 1 (D5) and Fischer-Tropsch diesel fuel (D8) appear to show slightly lower efficiencies than the other fuels. However, these differences are at the level of about 1% and are not statistically significant. Quantifying such differences is further complicated by the fact that these fuels produced lower full load power than the conventional fuels. There was no significant effect of 5% RME (cf. D7 vs. D4) in the ESC test; in the ETC test, the RME blend showed a slightly lower efficiency, but again this is of borderline statistical significance.

Overall, we can conclude that fuel changes do not significantly affect the energy efficiency of the engine.

Figure 16 CO_2 emissions - ESC



Over the ESC (**Figure 16**) the differences between engines in CO_2 emissions follow the trends in fuel consumption and efficiencies presented earlier. The Euro-4 DPF-equipped engine gave higher CO_2 emissions than the Euro-3 engine, and the Euro-5 engine using SCR/urea technology gave lowest CO_2 emissions.

Fuel differences were small. Fuel D6 showed the highest CO_2 emissions and fuel D5 the lowest in the Euro-3 engine. Generally, fuels D5 and D8 gave lower CO_2 emissions than the other fuels, consistent with their lower carbon content. However, since the impact of CO_2 emissions is global and not local, engine emissions represent only part of the story. A full well-to-wheels analysis would be needed to draw meaningful conclusions on this aspect.

On the ETC, CO_2 emissions were not consistent with the trends in engine fuel efficiency. It was concluded that the ETC CO_2 data were not reliable and hence they are not presented here.

6.2. LIGHT-DUTY VEHICLES

The following charts are focussed on the standard NEDC test. Although both cars were certified to Euro-3 emissions limits, car A is approaching Euro-4 limits and car B with DPF performs far below the Euro-4 limit for PM. Both sets of emissions limits are shown on the charts. For PM and NOx emissions, charts are also given for the ARTEMIS Motorway cycle as this represents a higher temperature "real-world" drive cycle, where some significant differences can be seen versus the NEDC.

6.2.1. CO emissions

Figure 17 CO emissions - NEDC

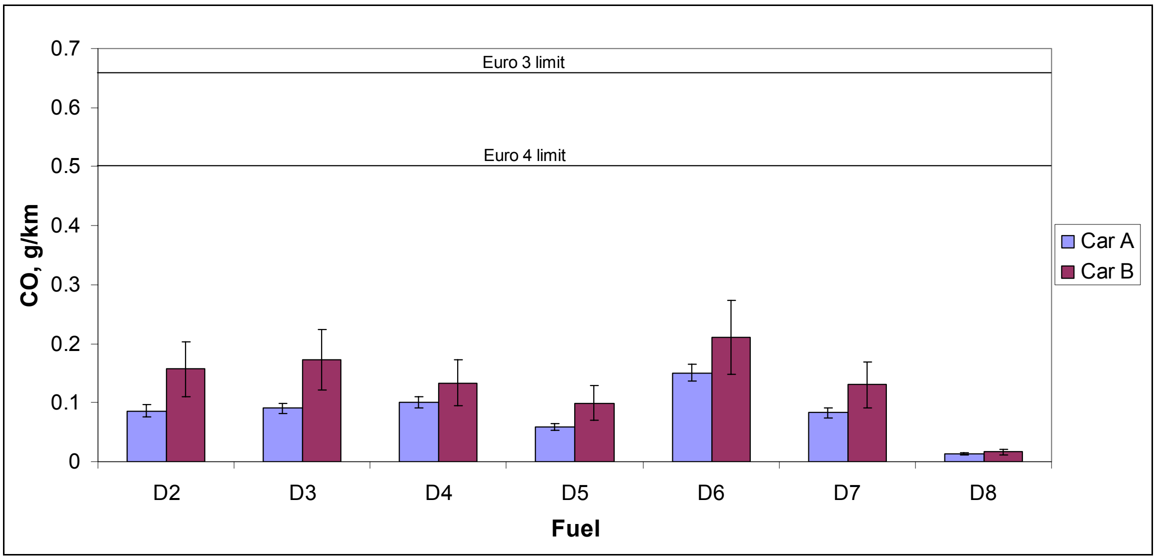
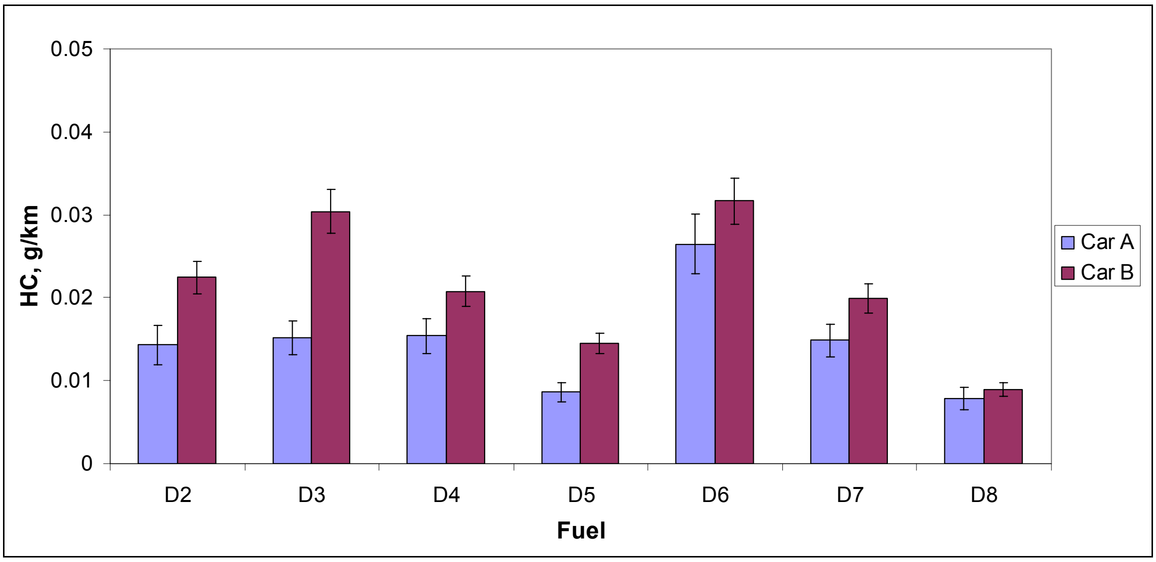


Figure 17 shows that both cars performed well within the Euro-4 CO emission limit, confirming that CO is not currently a critical emission for diesel cars. Car B gave higher CO emissions than car A.

Fuel sulphur content (compare D2-D4) did not rank the fuels in a consistent way. Fuel D6 emitted the highest CO emissions, though only significant in car A. Addition of 5% RME to fuel D4 did not significantly change CO emissions. Fischer-Tropsch diesel (D8) gave the lowest CO emissions, with Swedish Class 1 (D5) second best.

6.2.2. HC emissions

Figure 18 HC emissions - NEDC

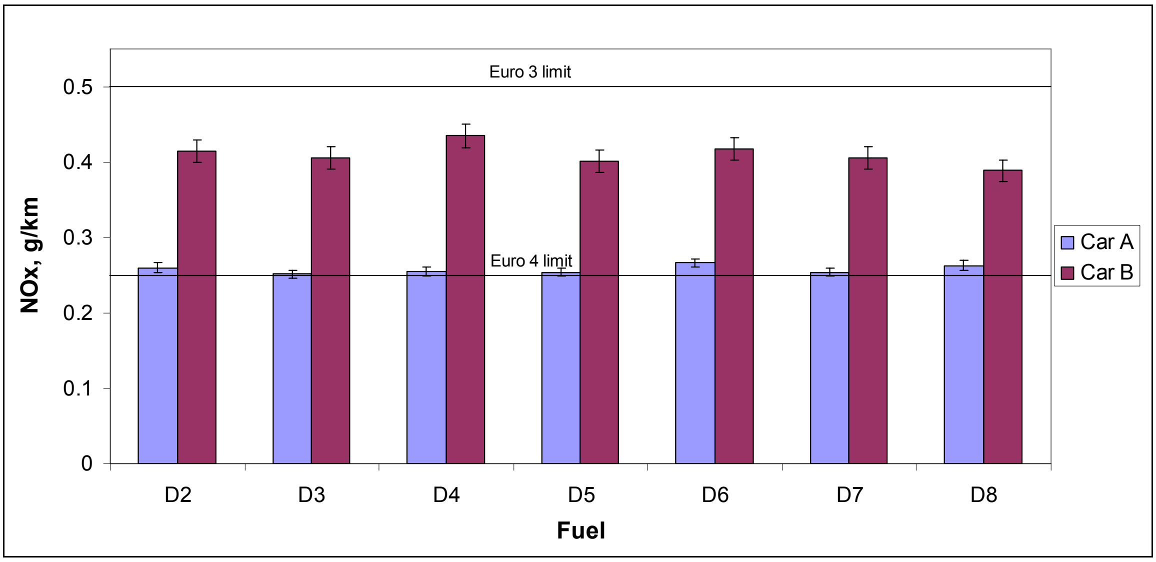


For light-duty vehicles, there are no separate Euro limits for HC emissions, HC emissions being limited through the sum of HC+NOx emissions. As with CO emissions, HC emissions from both cars were very low (**Figure 18**).

Car B gave higher HC emissions than car A. Trends in fuel effects were similar to those for CO emissions.

6.2.3. NOx emissions

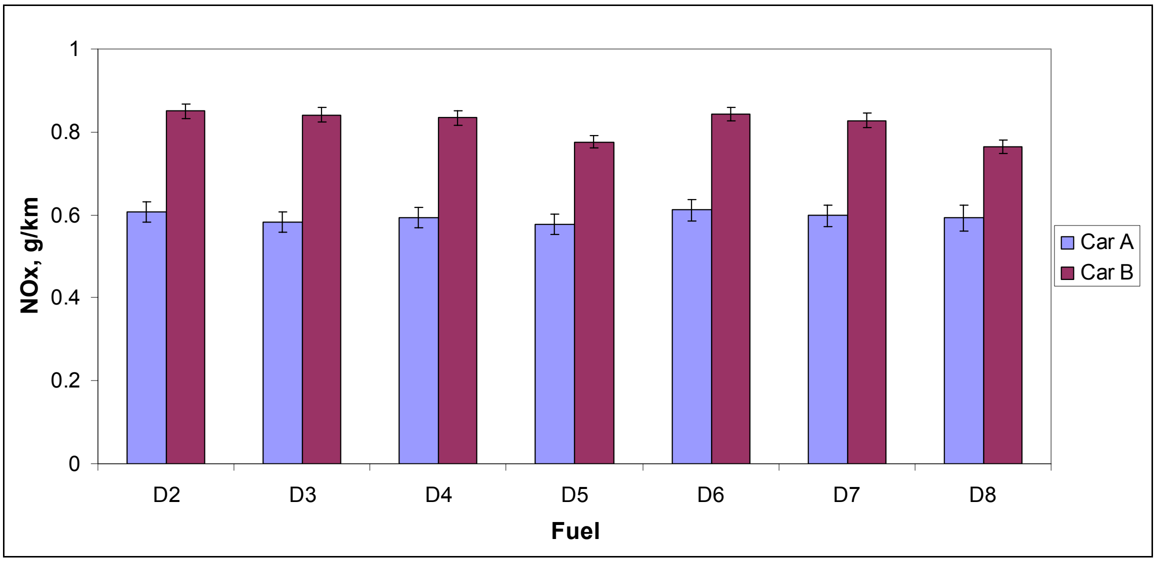
Figure 19 NOx emissions - NEDC



As with the heavy-duty Diesel engines, NOx remains a critical emission for the light-duty vehicles. Car A almost satisfied the Euro-4 limit, while car B gave NOx emissions within its Euro-3 certification limit (**Figure 19**).

In contrast to the heavy-duty engine test results, fuel effects on NOx emissions were generally not significant on the NEDC. Directionally fuels D5 and D8 gave lowest NOx emissions in car B.

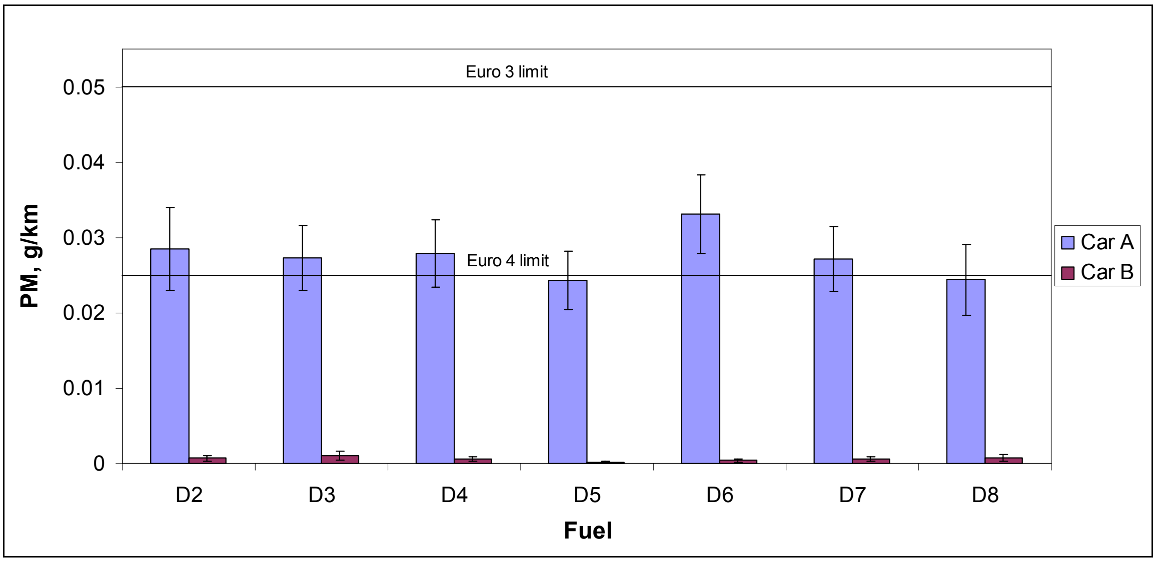
Figure 20 NOx emissions - ARTEMIS motorway cycle



Under the higher speed/load/temperature conditions of the ARTEMIS motorway cycle (**Figure 20**) NOx emissions roughly doubled for both cars. The lighter fuels, D5 and D8, now gave significant reductions in NOx emissions in car B, though still not in car A.

6.2.4. PM emissions

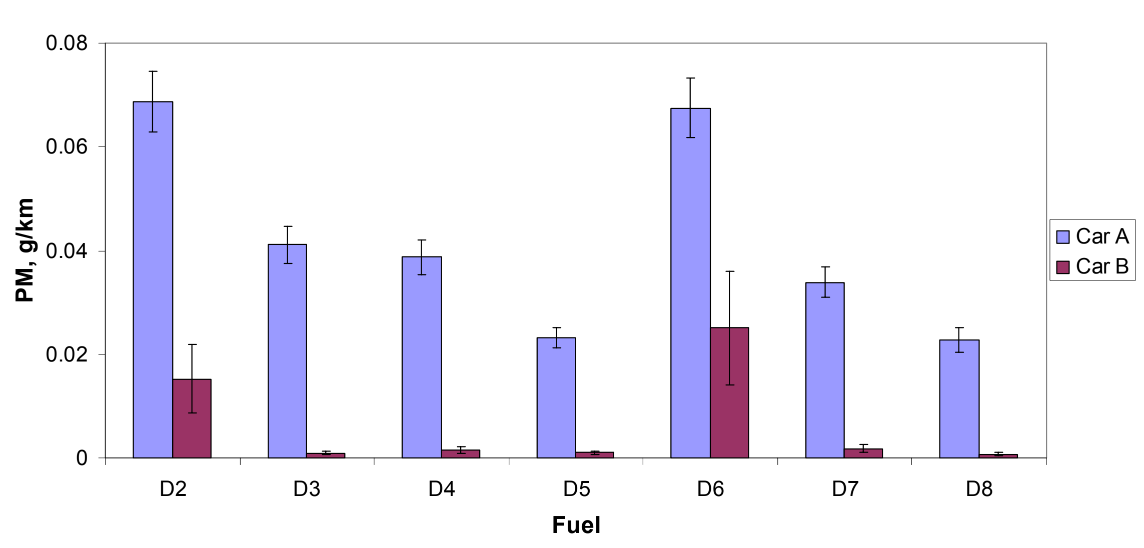
Figure 21 PM emissions - NEDC



Car A, although certified to Euro-3, produced PM emissions close to the Euro-4 limits. In this car, fuel D6 gave the highest PM emissions, Swedish Class 1 (D5) and FT diesel (D8) gave the lowest PM emissions. The addition of 5% RME to D4 did not significantly affect PM emissions.

The more striking effect was that of the diesel particulate filter (DPF). Car B produced extremely low PM emissions, below 10% of the Euro-4 limit on all fuels, due to the DPF. In this car, the differences between fuels on PM emissions over the NEDC were not significant (see **Figure 21**).

Figure 22 PM emissions - ARTEMIS motorway cycle

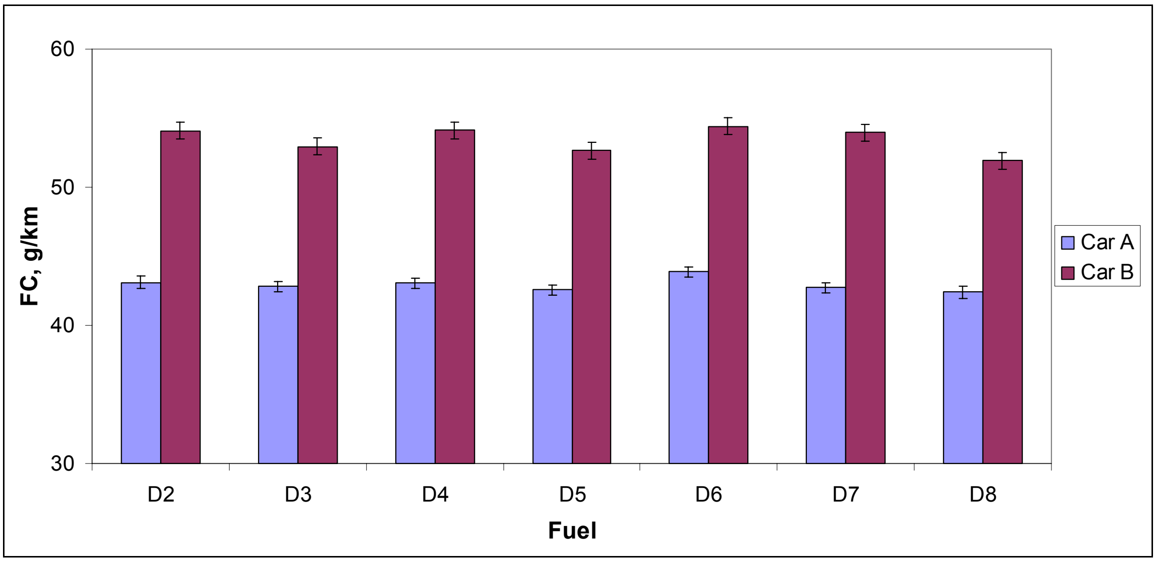


Under the higher speed/load/temperature conditions of the ARTEMIS motorway cycle, the effect of fuel sulphur content was evident (**Figure 22**). With both cars the 300ppm sulphur fuels, D2 and D6, showed significantly higher PM emissions than the other fuels. Fuels D5 and D8 showed further benefits over the other fuels in car A, but not in car B, as the PM emissions with this DPF-equipped car were already so low on all fuels with below nominal 50ppm sulphur content.

6.2.5. Fuel efficiency and CO_2 emissions

In the light-duty tests, mass fuel consumption was calculated from the CO_2, CO and HC emissions data. Volumetric consumption was calculated with a simple density conversion. Fuel consumption on an energy basis was calculated taking into account the energy content (LHV) of the test fuels. In the latter case, the variability in both the emissions test results and the fuel LHV measurements was taken into account in developing the error bars.

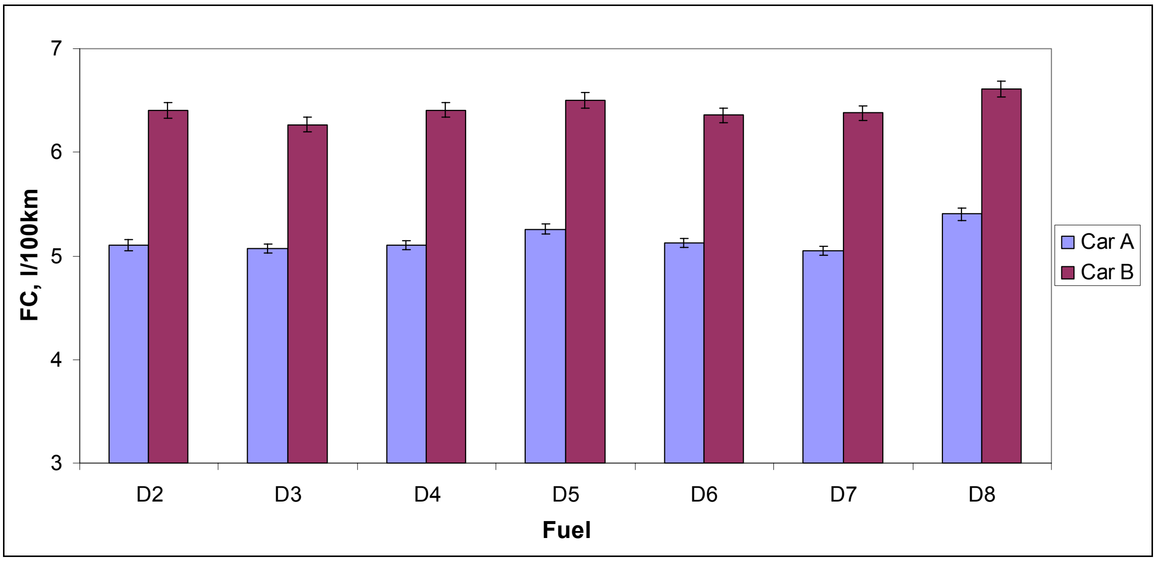
Figure 23 Mass Fuel Consumption, g/km - NEDC



Swedish Class 1 (D5) and FT diesel (D8) showed slightly better fuel consumption than the other fuels when measured on a mass basis (**Figure 23**). The highest density fuel (D6) showed the highest mass fuel consumption in car B. These effects relate largely to energy content (MJ/kg) and can be explained further in **Figures 25 and 26**.

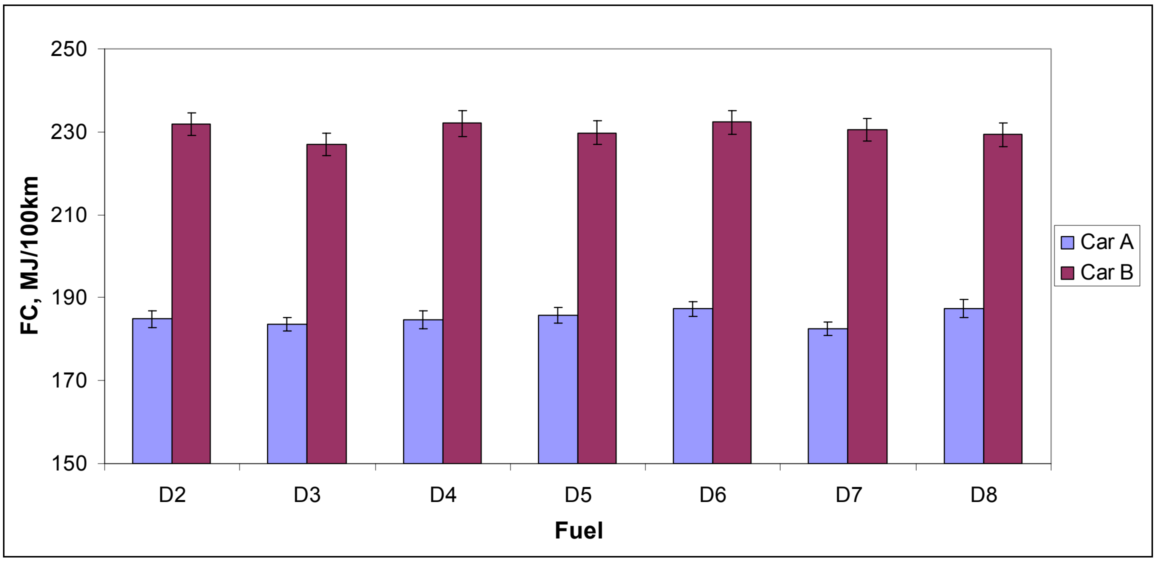
There were no significant differences in mass fuel consumption between the other fuels, including the effect of 5% RME (D7 vs. D4).

Figure 24 Volumetric Fuel Consumption, litres/100km - NEDC



When assessed on a volumetric basis (**Figure 24**), the low density fuels, D5 and particularly D8, show a higher fuel consumption than the other fuels (this was also confirmed in steady-state tests at 50 and 120 km/h). There were no significant differences between the other fuels.

Figure 25 Primary Energy Consumption, MJ/100km - NEDC



Finally, when the comparison is made on the basis of primary energy consumption (MJ/100 km) there are no significant differences between fuels. This is illustrated for the NEDC and the ARTEMIS motorway cycle (**Figures 25 and 26**).

Figure 26 Primary Energy Consumption, MJ/100km - ARTEMIS Motorway Cycle

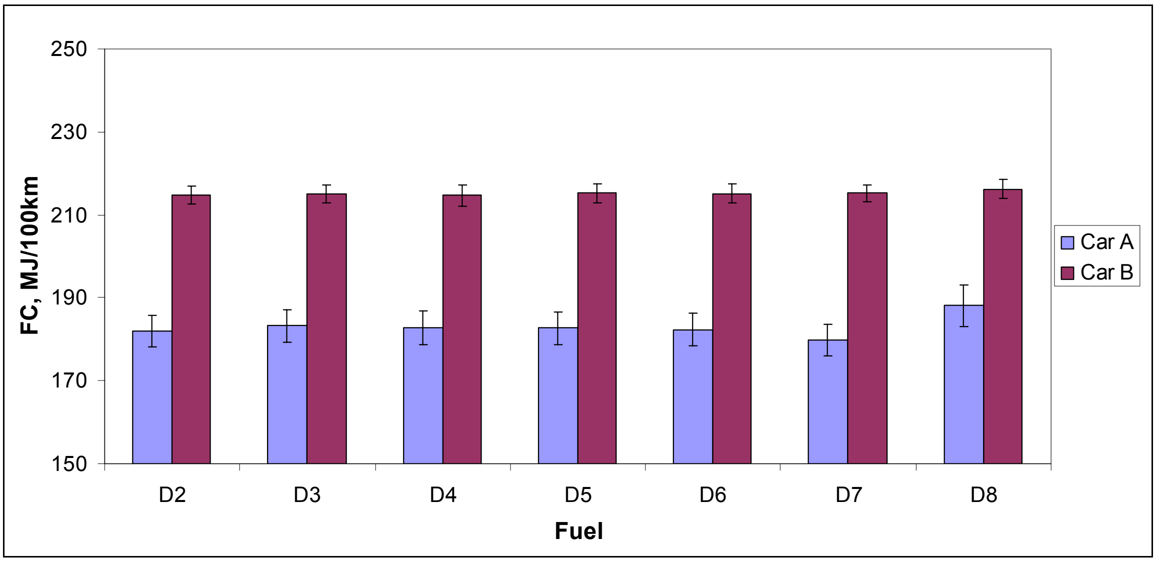
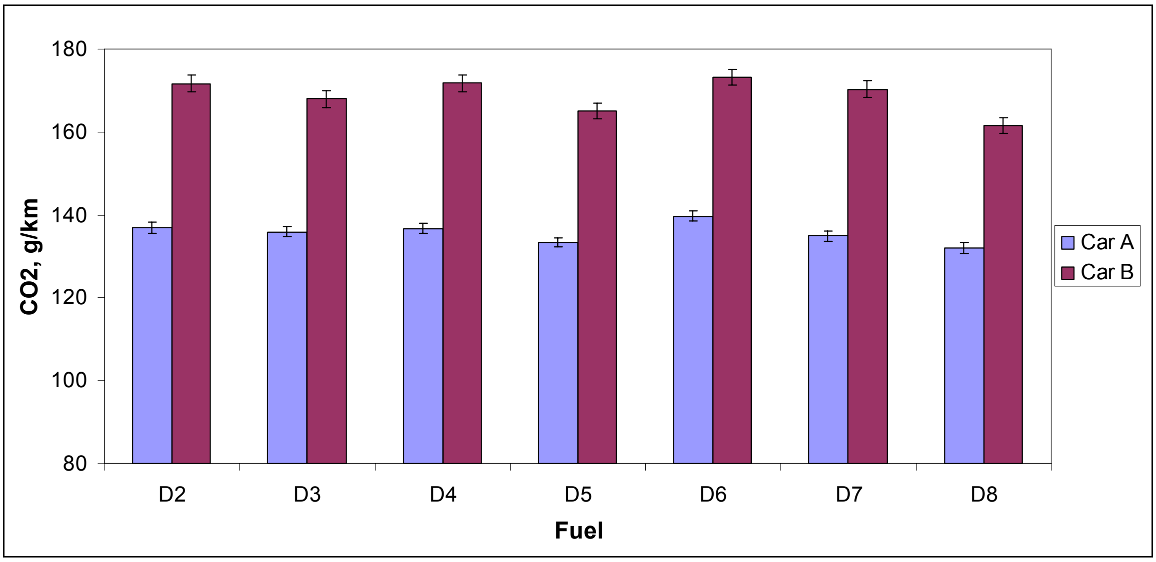


Figure 27 shows the challenge for the motor industry to achieve the fleet average CO_2 emissions targets for the new car population of 140g/km by 2008 and 120g/km in 2012. Car A, a medium sized, latest technology DI diesel car, achieves 140 g/km, giving about 20% lower CO_2 emissions than car B, consistent with its lower weight.

Figure 27 CO_2 emissions - NEDC



With regard to fuel effects, the highest CO_2 emissions were measured with fuel D6 and the lowest CO_2 emissions with fuels D5 and D8 (higher H/C ratio and higher LHV). However, as mentioned under the heavy-duty engine discussion, a full well-to-wheels analysis would be needed to draw meaningful conclusions on this aspect.

7. CONCLUSIONS

- Large improvements in exhaust emissions control were demonstrated with advanced engine / after-treatment technologies in combination with low sulphur fuels.
- HC and CO emissions from the advanced diesel engines and vehicles were very low, well below the prescribed emissions limits.
- For the heavy-duty engines, Euro-4 and Euro-5 emissions limits were achieved with the nominal 50ppm sulphur fuel.
- PM emissions were dramatically reduced in engines/vehicles equipped with diesel particulate filters.
  - In such cases, PM emissions were so low that the impact of fuel properties other than sulphur became negligible.
  - Fuel sulphur content influenced PM emissions under high speed/load (high temperature) conditions.
  - In the Euro-3 systems without DPFs, effects of both fuel sulphur and other properties on PM emissions were observed; the size of these effects varied with operating conditions.
- Clear progress in control of NOx emissions was demonstrated with the advanced diesel engine technologies.
  - Fuel sulphur content had no direct effect on NOx emissions in the engine/vehicle technologies tested here, though sulphur reduction should enable a wider range of NOx after-treatment systems to be employed.
  - Other extreme fuel property changes influenced NOx emissions in the heavy-duty engines, and in the light-duty vehicles in the ARTEMIS motorway cycle, but not in the NEDC. Fuel effects on NOx emissions were smaller in light-duty vehicles than in heavy-duty engines.
  - Optimisation of the exhaust after-treatment was also important, with increasing urea rate reducing NOx emissions.
  - Further progress on NOx emissions can be expected as control of engine-out emissions improves and NOx after-treatment technology matures, with the availability of sulphur-free fuels.
- Application of SCR/urea to control NOx in a Euro-5 prototype engine, with the engine tuned for better efficiency, improved fuel efficiency by about 5% versus a Euro-3 base case engine. Conversely, the use of EGR plus CRT to achieve Euro-4 heavy-duty emissions limits resulted in a loss in engine efficiency versus the Euro-3 engine.
- Diesel fuels with higher H:C ratios gave lower engine/vehicle CO_2 emissions, though this would need to be considered on a well-to-wheels basis. These fuels also gave higher volumetric fuel consumption and lower maximum power due to their lower density.
- Despite the wide range of fuels tested, the engine/vehicle energy efficiency was insensitive to fuel changes, and no statistically significant differences between fuels were seen.

8. GLOSSARY

ACEA	European Automobile Manufacturers Association
ARTEMIS	EU Project: Assessment and reliability of transport emission models and inventory systems
CADC	Common ARTEMIS Driving Cycles
CFPP	Cold Filter Plugging Point
COV	Coefficient of Variation (defined as standard deviation of sample over mean)
CR	Compression Ratio
CRT	Continuously Regenerative Trap
CVS	Constant Volume Sampling System
DG TREN	EU Commission's Directorate General for Transport and Energy
DI	Direct Injection
DPF	Diesel Particulate Filter
ECE	Urban driving part of the NEDC
EGR	Exhaust Gas Recirculation
EPEFE	European Programme on Emissions, Fuels and Engine Technologies
ESC	European Steady-State Cycle
ETC	European Transient Cycle
EU	European Union
EUDC	Extra Urban Drive Cycle
FAME	Fatty Acids Methyl Ester
FBP	Final Boiling Point
FIE	Fuel Injection Equipment
FC	Fuel Consumption
FT	Fischer-Tropsch (diesel)

HC	Total Hydrocarbons
HD	Heavy-duty
HFRR	High Frequency Reciprocating Rig (diesel fuel lubricity test)
KV40	Kinematic Viscosity at 40°C
LD	Light-duty
LHV	Lower Heating Value
NEDC	New European Driving Cycle
NOx	Nitrogen Oxides
PM	Particulate Mass
RME	Rape-seed Methyl Ester
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction (using urea)
SE	Standard Error
Significant	Statistically significant at >95% confidence
TC	Turbo Charged
T10	Temperature (°C) at which 10% v/v fuel is recovered
T50	Temperature (°C) at which 50% v/v fuel is recovered
T95	Temperature (°C) at which 95% v/v fuel is recovered

9. ACKNOWLEDGEMENTS

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- AVL List GmbH Graz, Austria for running the heavy-duty engine tests.
- Shell Global Solutions for running the light-duty vehicle tests.
- BP Global Fuels Technology, Shell Global Solutions and Total for provision of test fuels.
- Shell Global Solutions for statistical support.
- DG TREN "Particulates" consortium partners for their collaboration in this field.

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APPENDIX 1 ARTEMIS "REAL WORLD" DRIVE CYCLES

Figure A.1.1

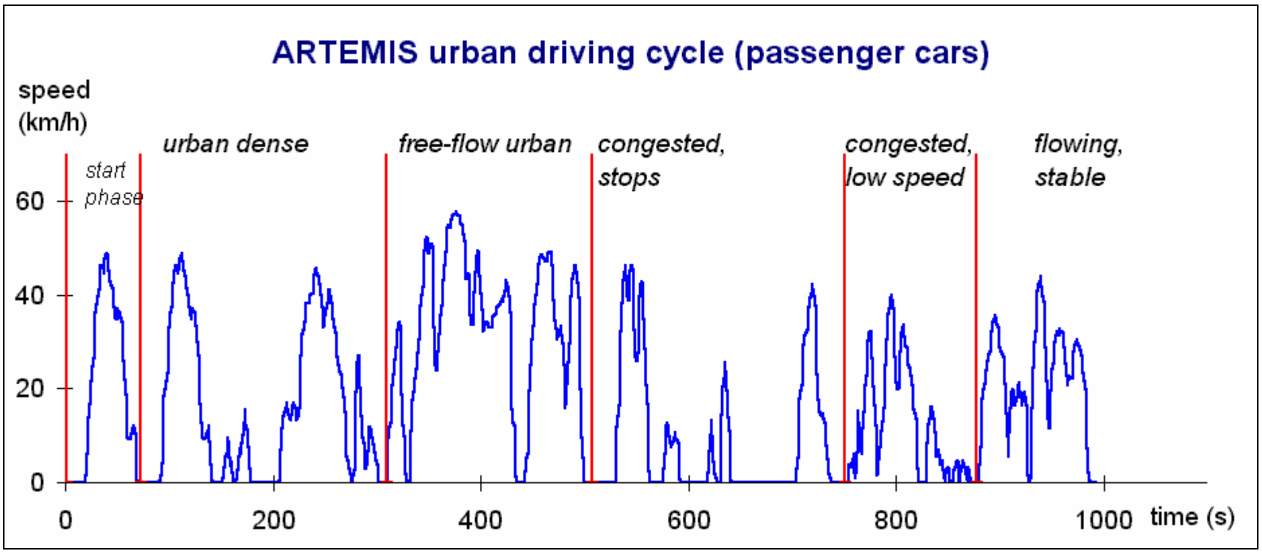


Figure A.1.2

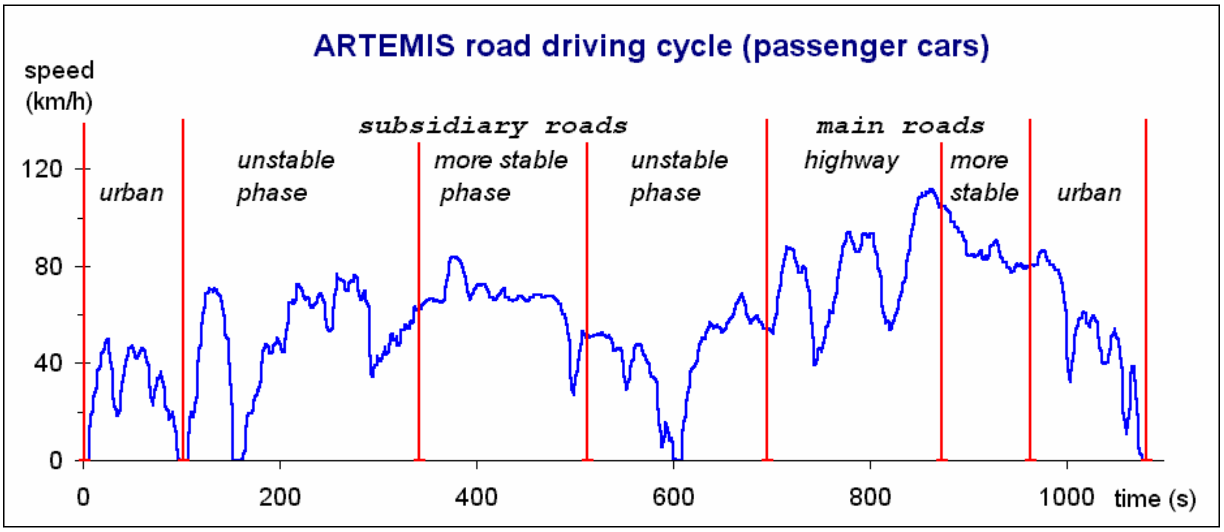
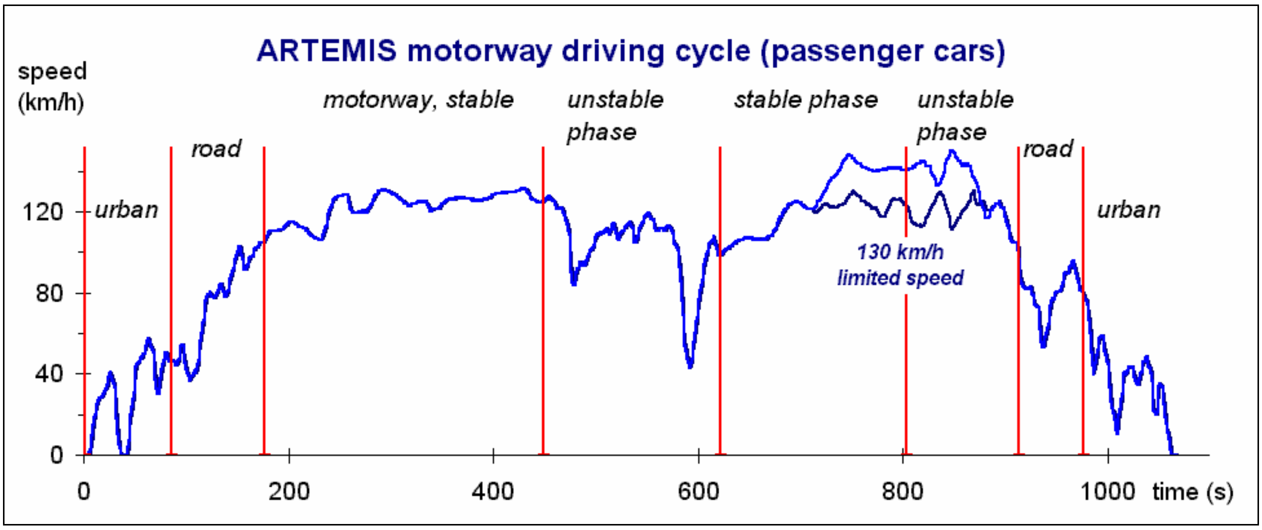


Figure A.1.3


ARTEMIS motorway driving cycle (passenger cars)
speed
(km/h)
motorway, stable
unstable
phase
stable phase
unstable
phase
road
road
urban
urban
130 km/h
limited speed
120
80
40
0
0
200
400
600
800
1000
time (s)

APPENDIX 2 MEAN EMISSIONS DATA, HEAVY-DUTY ENGINES

Cycle	Engine	Fuel	CO (g/kWh)		NOX (g/kWh)	HC (g/kWh)	PM (g/kWh)
			Original	Corrected	Original	Original	Original
Overall ESC	Euro 3	D2	0.431		4.907	0.262	0.0680
Overall ESC	Euro 3	D3	0.427		4.938	0.257	0.0627
Overall ESC	Euro 3	D4	0.427		4.925	0.257	0.0593
Overall ESC	Euro 3	D5	0.485		4.459	0.306	0.0487
Overall ESC	Euro 3	D6	0.421		5.133	0.267	0.0680
Overall ESC	Euro 3	D7	0.424		4.984	0.254	0.0600
Overall ESC	Euro 4	D3	0.039		2.808	0.008	0.0100
Overall ESC	Euro 4	D4	0.039		2.867	0.007	0.0093
Overall ESC	Euro 4	D5	0.040		2.514	0.010	0.0067
Overall ESC	Euro 4	D7	0.041		2.878	0.007	0.0087
Overall ESC	Euro 4	D8	0.031		2.515	0.006	0.0073
Overall ESC	Euro 5	D3	0.068		2.022	0.000	0.0130
Overall ESC	Euro 5	D4	0.088		1.962	0.000	0.0120
Overall ESC	Euro 5	D5	0.095		1.480	0.000	0.0120
Overall ESC	Euro 5	D7	0.078		2.153	0.000	0.0123
Overall ESC	Euro 5	D8	0.083		1.513	0.000	0.0083
ETC Overall	Euro 3	D2	1.121		5.406	0.300	0.0887
ETC Overall	Euro 3	D3	1.087		5.483	0.298	0.0845
ETC Overall	Euro 3	D4	1.062		5.468	0.302	0.0810
ETC Overall	Euro 3	D5	0.869		4.937	0.364	0.0662
ETC Overall	Euro 3	D6	1.057		5.647	0.306	0.0922
ETC Overall	Euro 3	D7	1.040		5.454	0.290	0.0878
ETC Overall	Euro 4	D3	0.202	0.211	2.582	0.013	0.0103
ETC Overall	Euro 4	D4	0.088	0.086	2.692	0.010	0.0072
ETC Overall	Euro 4	D5	0.038	0.042	2.393	0.012	0.0065
ETC Overall	Euro 4	D7	0.061	0.055	2.673	0.009	0.0072
ETC Overall	Euro 4	D8	0.054	0.033	2.284	0.009	0.0070
ETC Overall	Euro 5	D3	0.071		2.353	0.000	0.0192
ETC Overall	Euro 5	D4	0.088		2.261	0.000	0.0177
ETC Overall	Euro 5	D5	0.115		1.710	0.000	0.0123
ETC Overall	Euro 5	D7	0.085		2.616	0.000	0.0147
ETC Overall	Euro 5	D8	0.086		1.703	0.000	0.0137

Mean emissions data, heavy-duty engines (cont.)

Cycle	Engine	Fuel	CO_2 (g/kWh)		FC (g/kWh)		FC (l/kWh)		Efficiency (%)	
			Original	Corr.	Original	Corr.	Original	Corr.	Original	Corr.
Overall ESC	**Euro 3**	**D2**	665.0	664.8	208.5	208.5	0.247	0.247	40.3%	40.3%
Overall ESC	**Euro 3**	**D3**	663.9	663.9	208.5	208.4	0.247	0.247	40.3%	40.3%
Overall ESC	**Euro 3**	**D4**	663.3	662.9	208.2	208.2	0.247	0.247	40.3%	40.3%
Overall ESC	**Euro 3**	**D5**	651.4	650.9	206.6	206.5	0.255	0.255	39.9%	40.0%
Overall ESC	**Euro 3**	**D6**	670.6	670.7	209.9	209.9	0.245	0.245	40.2%	40.2%
Overall ESC	**Euro 3**	**D7**	661.4	662.6	209.6	209.7	0.248	0.248	40.2%	40.2%
Overall ESC	**Euro 4**	**D3**	709.8		220.8		0.261		38.0%	
Overall ESC	**Euro 4**	**D4**	710.0		219.9		0.260		38.2%	
Overall ESC	**Euro 4**	**D5**	698.6		218.4		0.270		37.8%	
Overall ESC	**Euro 4**	**D7**	708.8		220.8		0.261		38.2%	
Overall ESC	**Euro 4**	**D8**	683.7		214.9		0.274		37.9%	
Overall ESC	**Euro 5**	**D3**	618.7		196.9		0.233		42.6%	
Overall ESC	**Euro 5**	**D4**	618.9		197.0		0.233		42.6%	
Overall ESC	**Euro 5**	**D5**	606.3		195.1		0.241		42.3%	
Overall ESC	**Euro 5**	**D7**	617.9		197.9		0.234		42.6%	
Overall ESC	**Euro 5**	**D8**	594.3		192.3		0.245		42.4%	
ETC Overall	**Euro 3**	**D2**	649.8		208.3		0.247		40.3%	
ETC Overall	**Euro 3**	**D3**	646.9		208.1		0.246		40.4%	
ETC Overall	**Euro 3**	**D4**	648.7		208.2		0.247		40.3%	
ETC Overall	**Euro 3**	**D5**	637.4		206.5		0.255		40.0%	
ETC Overall	**Euro 3**	**D6**	655.9		209.6		0.245		40.2%	
ETC Overall	**Euro 3**	**D7**	647.1		209.2		0.247		40.3%	
ETC Overall	**Euro 4**	**D3**	719.5		225.7		0.267		37.2%	
ETC Overall	**Euro 4**	**D4**	709.7		223.6		0.265		37.5%	
ETC Overall	**Euro 4**	**D5**	705.6		223.8		0.276		36.9%	
ETC Overall	**Euro 4**	**D7**	711.9		229.5		0.271		36.7%	
ETC Overall	**Euro 4**	**D8**	686.4		219.9		0.280		37.1%	
ETC Overall	**Euro 5**	**D3**	648.1		198.9		0.235		42.2%	
ETC Overall	**Euro 5**	**D4**	647.9		199.0		0.236		42.2%	
ETC Overall	**Euro 5**	**D5**	633.6		197.0		0.243		41.9%	
ETC Overall	**Euro 5**	**D7**	649.0		202.5		0.239		41.6%	
ETC Overall	**Euro 5**	**D8**	622.5		193.7		0.247		42.1%	

Euro-3 arithmetic mean values with linear trend corrections to the CO_2, FC and efficiency (ESC) data (in the original g/kWh, l/kWh and percentage scales)

Euro-4 arithmetic mean values with a linear trend correction to the CO (ETC) data (on the log emissions scale)

Euro-5 arithmetic mean values - all HC measurements were either zero or negative

ETC pairs of back-to-back measurements were averaged before calculating arithmetic means. ETC CO_2 data not used, see also p.21.

APPENDIX 3 MEAN EMISSIONS DATA, LIGHT-DUTY VEHICLES

Cycle	Car	Fuel	CO (g/km)	NOx (g/km)		HC (g/km)	PM (g/km)
			Original	Original	Corrected	Original	Original
NEDC	**A**	**D2**	0.0862	0.260		0.0143	0.0284
NEDC	**A**	**D3**	0.0902	0.252		0.0152	0.0272
NEDC	**A**	**D4**	0.1004	0.255		0.0154	0.0279
NEDC	**A**	**D5**	0.0584	0.254		0.0086	0.0243
NEDC	**A**	**D6**	0.1508	0.266		0.0265	0.0331
NEDC	**A**	**D7**	0.0828	0.254		0.0148	0.0271
NEDC	**A**	**D8**	0.0130	0.263		0.0078	0.0244
NEDC	**B**	**D2**	0.1569	0.412	0.415	0.0225	0.0007
NEDC	**B**	**D3**	0.1722	0.404	0.406	0.0304	0.0011
NEDC	**B**	**D4**	0.1332	0.428	0.435	0.0208	0.0006
NEDC	**B**	**D5**	0.0991	0.399	0.401	0.0145	0.0002
NEDC	**B**	**D6**	0.2104	0.415	0.418	0.0317	0.0004
NEDC	**B**	**D7**	0.1303	0.413	0.406	0.0199	0.0006
NEDC	**B**	**D8**	0.0165	0.397	0.389	0.0089	0.0008
Motorway	**A**	**D2**	0.0000	0.607		0.0028	0.0688
Motorway	**A**	**D3**	0.0000	0.582		0.0022	0.0411
Motorway	**A**	**D4**	0.0000	0.594		0.0015	0.0387
Motorway	**A**	**D5**	0.0000	0.578		0.0039	0.0232
Motorway	**A**	**D6**	0.0000	0.612		0.0031	0.0674
Motorway	**A**	**D7**	0.0000	0.598		0.0020	0.0339
Motorway	**A**	**D8**	0.0000	0.593		0.0021	0.0227
Motorway	**B**	**D2**	0.0155	0.850		0.0035	0.0153
Motorway	**B**	**D3**	0.0106	0.841		0.0030	0.0010
Motorway	**B**	**D4**	0.0118	0.833		0.0028	0.0016
Motorway	**B**	**D5**	0.0095	0.776		0.0028	0.0010
Motorway	**B**	**D6**	0.0168	0.843		0.0043	0.0251
Motorway	**B**	**D7**	0.0149	0.828		0.0030	0.0018
Motorway	**B**	**D8**	0.0039	0.765		0.0019	0.0007

Mean emissions data, light-duty vehicles (cont.)

Cycle	Car	Fuel	CO_2 (g/km)		FC (g/km)		FC (l/100km)		FC (MJ/100km)	
			Original	Corr.	Original	Corr.	Original	Corr.	Original	Corr.
NEDC	**A**	**D2**	136.9		43.11		5.105		184.8	
NEDC	**A**	**D3**	135.9		42.81		5.069		183.5	
NEDC	**A**	**D4**	136.8		43.08		5.100		184.7	
NEDC	**A**	**D5**	133.5		42.58		5.260		185.8	
NEDC	**A**	**D6**	139.7		43.87		5.124		187.3	
NEDC	**A**	**D7**	134.9		42.74		5.051		182.5	
NEDC	**A**	**D8**	132.1		42.42		5.402		187.4	
NEDC	**B**	**D2**	171.7		54.09		6.405		231.9	
NEDC	**B**	**D3**	167.9		52.94		6.268		226.9	
NEDC	**B**	**D4**	171.8		54.12		6.408		232.0	
NEDC	**B**	**D5**	165.0		52.66		6.504		229.8	
NEDC	**B**	**D6**	173.2		54.42		6.356		232.3	
NEDC	**B**	**D7**	170.4		53.97		6.379		230.5	
NEDC	**B**	**D8**	161.6		51.91		6.611		229.3	
Motorway	**A**	**D2**	135.0		42.46		5.027		182.0	
Motorway	**A**	**D3**	135.9		42.75		5.061		183.2	
Motorway	**A**	**D4**	135.6		42.67		5.052		182.9	
Motorway	**A**	**D5**	131.3		41.86		5.171		182.7	
Motorway	**A**	**D6**	136.3		42.71		4.989		182.3	
Motorway	**A**	**D7**	133.0		42.09		4.974		179.7	
Motorway	**A**	**D8**	132.7		42.59		5.424		188.1	
Motorway	**B**	**D2**	159.6	159.3	50.20	50.11	5.944	5.933	215.2	214.8
Motorway	**B**	**D3**	159.7	159.5	50.23	50.17	5.948	5.940	215.4	215.1
Motorway	**B**	**D4**	159.8	159.2	50.26	50.08	5.951	5.929	215.5	214.7
Motorway	**B**	**D5**	154.9	154.7	49.39	49.33	6.101	6.094	215.5	215.2
Motorway	**B**	**D6**	161.0	160.8	50.44	50.38	5.892	5.884	215.3	215.1
Motorway	**B**	**D7**	158.6	159.3	50.18	50.39	5.931	5.957	214.3	215.2
Motorway	**B**	**D8**	151.7	152.5	48.72	48.96	6.205	6.234	215.2	216.2

Car A arithmetic mean values calculated after the rejection of the third test on fuel D8 (14/10/2002) and the exclusion of the 2 extra tests on fuel D3 at the start of the test programme and the 4 extra tests at the end

Car B arithmetic mean values with linear trend corrections to the NOx (NEDC), CO_2 and FC (motorway) data (in the original g/km, l/100km and MJ/100km scales)

APPENDIX 4 STATISTICAL DATA ANALYSIS

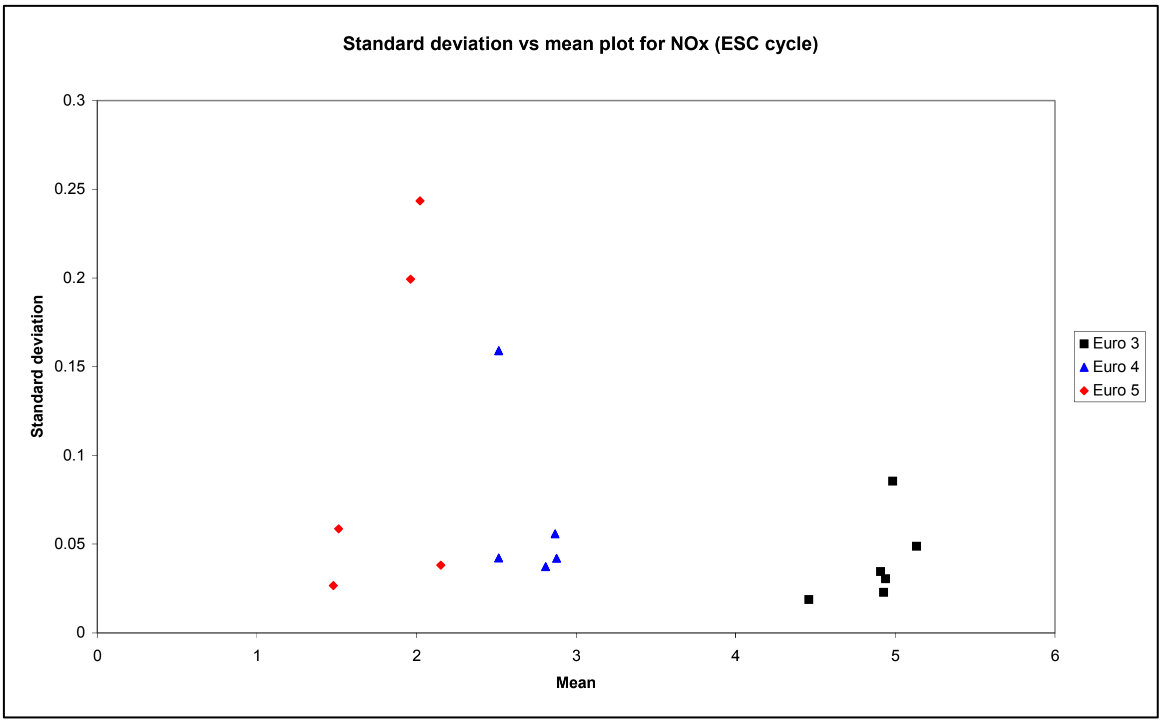
This appendix provides additional information on the statistical data analyses discussed in **Sections 5 and 6**.

Standard deviation vs. mean plots

The distributions of sets of repeat measurements of automotive emissions or atmospheric concentrations are typically asymmetric or "skewed" and bear little resemblance to the standard bell-shaped normal or "Gaussian" distribution. In the EPEFE gasoline project [6] and other previous emission studies [7-9,12-14], the variability in emissions measurements has been found to follow the lognormal distribution with the degree of scatter increasing as the emission level increases.

Figure A.4.1 is a typical standard deviation vs. mean graph plotting the S.D. of the three NOx measurements for each of the 16 engine × fuel combinations in the present study against the mean. Looking at each engine in turn, there is too little variation in mean emissions to determine whether the S.D. increases with the mean or is constant. In the absence of evidence to the contrary, it is assumed that the measurements in the present study do follow the lognormal distribution as mechanistically this is the most plausible model for emissions data.

Figure A.4.1 Typical S.D. vs. mean plot



Arithmetic means and standard errors

In this report, arithmetic means are used to summarise the average emissions using each fuel in each vehicle, in line with EPEFE [6]. Geometric means are sometimes used in emissions studies as they give excellent comparisons between fuels on a percentage basis. However, they have the disadvantage of underestimating total emissions to the atmosphere.

Each vehicle/engine × cycle × emission data set was analysed separately. The standard errors of the arithmetic mean emissions for the various fuels were estimated from a weighted analysis of variance in which each emission measurement was assigned a weight equal to

$$\text{weight} = 1 / (\text{mean emission for that fuel and vehicle})^2$$

to take account of the lognormality in the data (see [6], Annex 05).

In some tests, two ETC measurements were made within a short time of one another. These were averaged before computing the overall mean. For example, if two measurements were taken in the first test, one in the second and one in the third, then the overall mean would be

$$\text{Overall mean} = \frac{(\text{Test 1 Result 1} + \text{Test 1 Result 2}) / 2 + \text{Test 2 Result} + \text{Test 3 Result}}{3}$$

In several of the figures in section 6, "error bars" are shown around the average emissions for the various fuels. These have been constructed so that when two fuels are significantly different from one another at $P < 5\%$, their error bars will not overlap, as in EPEFE (see [6], Annex 05). We can be 84% confident that the true mean lies within the limits shown.