diesel fuel/engine interaction and effects on exhaust emissions

part 1: diesel fuel density

part 2: heavy duty diesel engine technology

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).

P Heinze (Chairman)

P. Gadd
H. Guttmann
D. E. Hall
R. Mercogliano
N. Mann
G. Nancekievill
F. Renault

R. C. Hutcheson (Technical Coordinator)

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ABSTRACT

CONCAWE has investigated two major aspects of fuel/engine interaction and the resulting effects on exhaust emissions:

- The impact of fuel density on the particulate emissions of a light duty turbocharged passenger car fitted with an advanced engine technology/ electronic management system.
- The influence of technology change on two generations of the same model of heavy duty diesel engine.

For both investigations fuels of the EPEFE (European Programme on Emissions, Fuels and Engine Technologies) diesel fuel matrix were used. This matrix represents the optimum concept to study effects of decorrelated fuel properties (density, poly-aromatics, cetane number and T-95). The study concluded that changes in engine technology and engine management systems had a profound effect on emissions performance which far outweighed any benefits accruing from changes in fuel characteristics.

KEYWORDS

Diesel fuel, diesel fuel properties, diesel fuel density, electronic management systems, engine technology, regulated exhaust emissions, EPEFE

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ANNEX

SUMMARY

This report investigated two major aspects of fuel/engine interaction and the resulting effects on exhaust emissions: the interaction of fuel density with the electronic management system (EMS) of advanced LD engines and the interaction of fuel properties with variation of engine technology. For both investigations fuels of the EPEFE diesel fuel matrix were used. This matrix represents the optimum concept to study effects of decorrelated fuel properties (density, poly-aromatics, cetane number and T-95).

For the fuel density study an advanced technology high speed turbocharged direct injection diesel engine was used fitted in a vehicle featuring electronic diesel control, closed loop exhaust gas recirculation (EGR) and an oxidation catalyst. Engine operation was adjusted for changes in fuel density by re-setting the Eprom to obtain the same energy output of the two test fuels, varying only in density as the key fuel property. In chassis dynamometer emissions tests (ECE15 + EUDC) the major impact of fuel density on particulate emissions for advanced engine technology/engine management systems was established. A large part of the density effect on emissions (Pm, NOx) was due to physical interaction of the fuel density with the electronic management system (EMS). Limited basic bench testing of the engine showed that near complete compensation of the density effect on smoke emissions could be achieved when no advanced technology was applied.

In the technology study two generations of the same heavy duty diesel engine were used. ECE R49 emissions results demonstrated that engine technology had a much greater impact on emissions than fuel quality. Advanced engine technology reduced emissions for Pm, HC, CO by 40 to 80% versus previous generation technology. For NOx no changes were observed since the improved technology engine concept deliberately aimed at low fuel consumption within the current NOx limits. Fuel effects on specific emissions were technology/design dependent and varied from engine to engine. Advanced engine technology reduced the sensitivity to fuel property changes.

INTRODUCTION

CONCAWE AE/STF-7 task force on Diesel Fuel Emissions investigated two major aspects of fuel/engine interactions

- the influence of fuel density on exhaust emissions with special focus on the interaction between fuel density and the electronic management system (EMS)

- the influence of heavy duty engine technology on exhaust emissions and its sensitivity to fuel properties

For both investigations fuels of the EPEFE diesel fuel matrix (**Annex, Table A**) were used since they represented the optimum concept to study effects of decorrelated fuel properties:- density, poly-aromatics, cetane number and T-95.

For the density study two fuels were used which differed only in density and were tested in a direct injection turbocharged, intercooled diesel engine fitted in a passenger car and also on a bench.

In the technology study the full EPEFE diesel fuel matrix was used to investigate fuel and technology effects with two models of the same heavy duty diesel engine, but representing two generations of development. In this programme the test protocol developed for the EPEFE diesel programme was applied.

- **Part 1** of the report summarizes the findings of the programme on “Investigation of the interaction between fuel density and the electronic management system (EMS) on emissions from a light duty DI engine powered vehicle”

- **Part 2** of the report summarizes the findings on “Effects on emissions of technology changes between two generations of one heavy duty engine model”.

PART 1: INVESTIGATION OF THE INTERACTION BETWEEN FUEL DENSITY AND THE ELECTRONIC MANAGEMENT SYSTEM (EMS) ON EMISSIONS FROM A LIGHT DUTY DI ENGINE POWERED VEHICLE

1. SCOPE OF THE PROGRAMME

The influence of fuel density on exhaust emissions from diesel engines has been investigated in a number of studies,[1-7] resulting in the conclusion that particulate emissions rise with increasing density.

Advanced technology diesel engines have highly complex electronic management systems (EMS)[1] which are referenced to a chosen fuel density. CONCAWE therefore commissioned a study to investigate if the relationship between fuel density and particulate emissions applied to this technology. A high speed direct injection engine was chosen, featuring electronic diesel control, closed loop exhaust gas recirculation (EGR) and an oxidation catalyst (**Table 1**). Relevant demand data for fuel metering, injection timing and EGR are stored in Erasable, Programmable, Read-Only Memories (Eproms) within the electronic diesel control unit (ECU). Resetting the Eprom for a change in fuel density would be expected to reduce any effects on engine operation and resulting emissions performance. Therefore, in the study the Eprom was reset to obtain the same energy output from both test fuels. To exclude the influence of key fuel properties other than density (e.g. aromatics, cetane, T95), two fuels were used which vary only in density (828.8, 855.1 kg/m^3, EPEFE fuels EPD2, EPD4, **Table 2**).

The interrelationship between fuel density, exhaust emissions and advanced engine technology, including electronic diesel control, was studied in a series of chassis dynamometer tests (standard [cold start] ECE15+EUDC and hot start [limited soak] ECE15+EUDC) (**Table 3**). In addition, a limited bench test programme was conducted to confirm the basic relationship between fuel density and exhaust emissions without the advanced technology features (electronic ECU, EGR, catalyst) (**Table 4**).

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[1] General information on electronic diesel controls can be found in reference 8.

2. RESULTS

The findings are illustrated in **figures 1** to **2** and show results from cold start tests unless stated otherwise.

The findings of the study showed that:

- Increasing fuel density significantly increases particulate emissions. This is true with and without advanced emissions control features (electronic ECU, Eprom, EGR, catalyst).
- When no advanced technology features (Eprom, EGR, catalyst) were applied in bench tests, near complete compensation (93%) of the density effect on smoke emissions was achieved by adjusting the fuel injection system. In **Figure 1** the higher density fuel is adjusted to provide the same injected fuel energy as the lower density fuel.
- With advanced technology diesel control systems (electronic ECU/EMS/Eprom) fuel density affects pump setting, injection timing and EGR operation. As a consequence, the relationship between fuel density and particulate emissions is more complex. This is due to the fact that maps in the electronic control are referenced to a basic fuel mass (density). These maps control the basic emissions performance of the engine (**Figure 6**).
- When all advanced features were in operation the density adjustment of the electronic management system (EMS) provided somewhat lower compensation for particulate emissions. The shift of the pump map, injection timing and the complete EGR to the higher density profile accounted for about 48% of the total particulate emissions difference between the lower and the higher density fuel (**Figure 2**). Full compensation (as demonstrated without complex advanced technology features) could not be achieved within the limitations of the current programme. This was because it was not possible to correct the amount of EGR for equal energy output. Where the EGR-valve is fully open in the lower load ranges, air mass demand can not be corrected, and injection timing is also absolutely flat in this regime of operation. Therefore density compensation by Eprom adjustment has only limited effect in this lower load operation.
- For NOx, when all advanced features were in operation, the density adjustment of the EMS also provided a compensation of about 43% (**Figure 3**). This compensation was obtained when those results were evaluated which needed either no, or only a small correction for the humidity (observed at hot start). Data obtained mainly at cold start showed a larger range of humidity changes and resulted in a 26% increase in NOx emissions (**Figure 4**). These data had to be treated with larger correction factors to correct to standard humidity as required by the EEC regulation and the adjusted results showed a 39% over-compensation. The NOx correction equation is primarily based on results from gasoline engines and it is generally understood that engines can react differently to humidity than as specified in the regulation. Therefore results with low correction factors can be assumed to be more robust.
- Hydrocarbon and carbon monoxide emissions were not significantly affected by the Eprom adjustment (**Figure 5**).

3. CONCLUSIONS

- The major impact of fuel density on particulate emissions is confirmed and established for advanced engine technology/engine management systems.

- Substantial compensation of the density effect is possible by adjustment to the electronic control unit of the fuel injection management system for the tested vehicle/engine.

- A large part of the density effect on emissions (Pm, NOx) is due to physical interaction of the fuel density with the electronic management system (EMS).

- All details of the EMS maps could not be disclosed and full access to the control system might permit further optimisation.

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Table 1 Description of Test Engine/Vehicle

Vehicle: passenger vehicle powered by a direct injection, turbocharged and intercooled engine with electronic control unit, closed loop EGR and oxidation catalyst.

Engine	
Model year	1992
Mileage	27,000 km
Displacement	2.46 litres
Combustion system	DI/TCI
Injection system	electronic controls
Rated power	85 kW
Rated speed	4200 rpm
Peak torque	265 Nm at 2250 rpm

Table 2 Diesel Fuel Matrix Analysis

Fuel No		EPD2	EPD4
Property	Unit		
Sulphur content	% m/m	0.04	0.05
Density @ 15°C	kg/m^3	828.8	855.1
Aromatics	% mm		
mono		18.0	18.4
di		6.4	5.7
tri +		1.3	1.7
(poly)		(7.7)	(7.4)
total		25.7	25.8
Cetane Number		50.2	50.3
Cetane Index		51	49.9
Distillation			
95%	°C	349	344
Calc. net heat value	MJ/kg	42.99	42.69

Table 3 Vehicle Tests (ECE + EUDC)
(with advanced technology control systems)

NOx values shown in italics have no or low correction for humidity

1. Test Runs with Low Density Fuel (828.8 kg/m^3)
Standard EPROM Setting

	Combined ECE+EUDC Cycle Emissions (g/km)						
							Fuel Cons
Test	**HC**	**CO**	**NOx**	**NOx *)**	**CO_2**	**PM**	(l/100km)
cold	0.218	0.872	0.473	0.516	193	0.066	7.42
	0.242	0.939	0.459	0.537	192	0.068	7.39
Average	**0.230**	**0.906**	**0.466**	**0.526**	**192**	**0.067**	**7.41**
hot	0.040	0.035	0.477	0.543	173	0.062	6.62
	0.053	0.115	0.454	0.527	173	0.063	6.62
	0.062	0.083	0.446	*0.446*	163	0.041	6.20
	0.070	0.085	0.401	*0.401*	164	0.056	6.25
Average	**0.056**	**0.080**	**0.444**	**0.479**	**168**	**0.055**	**6.42**

*) humidity corrected

2. Test Runs with High Density Fuel (855.1 kg/m^3)
Standard EPROM Setting

	Combined ECE+EUDC Cycle Emissions (g/km)						
							Fuel Cons
Test	**HC**	**CO**	**NOx**	**NOx *)**	**CO_2**	**PM**	(l/100km)
cold	0.296	1.289	0.398	0.503	195	0.114	7.25
	0.276	1.177	0.421	0.421	190	0.093	7.08
Average	**0.286**	**1.233**	**0.409**	**0.462**	**193**	**0.103**	**7.17**
hot	0.040	0.065	0.403	0.497	180	0.085	6.62
	0.058	0.111	0.363	*0.363*	162	0.068	5.94
	0.071	0.229	0.398	*0.398*	165	0.089	6.08
	0.071	0.191	0.362	*0.362*	163	0.071	6.01
Average	**0.060**	**0.149**	**0.381**	**0.405**	**168**	**0.079**	**6.16**

*) humidity corrected

3. Test Runs with Low Density Fuel (828.8 kg/m^3)
Adjusted EPROM Setting (to match high density energy input)

	Combined ECE+EUDC Cycle Emissions (g/km)						
							Fuel Cons
Test	**HC**	**CO**	**NOx**	**NOx *)**	**CO_2**	**PM**	(l/100km)
cold	0.228	0.821	0.483	0.435	190	0.068	7.30
	0.235	0.936	0.480	0.440	190	0.101	7.33
Average	**0.232**	**0.879**	**0.481**	**0.437**	**190**	**0.085**	**7.32**
hot	0.025	0.016	0.454	*0.409*	168	0.082	6.43
	0.056	0.076	0.450	*0.401*	168	0.065	6.42
	0.047	0.029	0.437	*0.394*	167	0.059	6.38
	0.055	0.076	0.452	*0.403*	165	0.057	6.32
Average	**0.046**	**0.049**	**0.448**	**0.402**	**167**	**0.066**	**6.39**

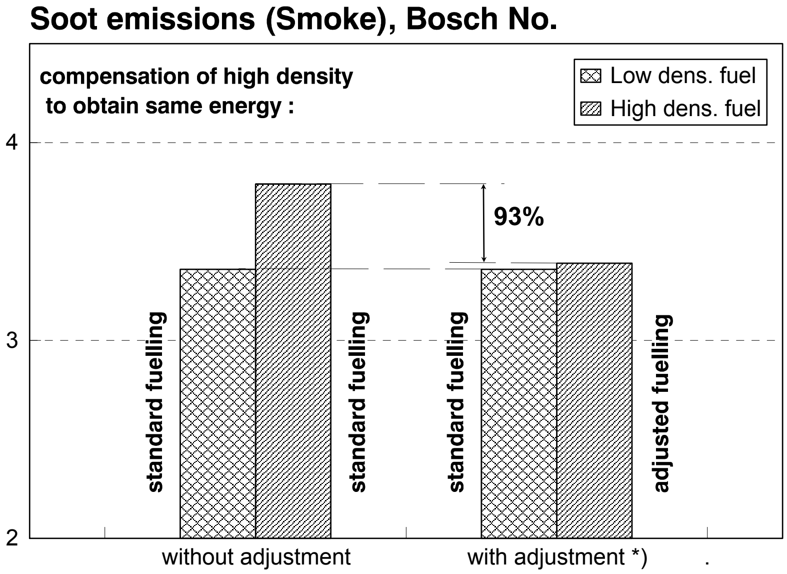
*) humidity corrected

Table 4 Bench Engine Test Runs
(without advanced technology control systems)

Operating Point				
Speed RPM	**BMEP** bar	**Fuel** **Density** kg/m^3	**Adjustment of pump sleeve position**	**Smoke** Bosch
2000	2	828.8	standard	0.58
		855.1	standard	0.62
		855.1	adjusted *)	0.58
2000	full load	828.8	standard	0.92
		855.1	standard	0.97
		855.1	adjusted *)	0.93
1250	full load			
		828.8	standard	3.36
		855.1	standard	3.79
		855.1	adjusted *)	3.39

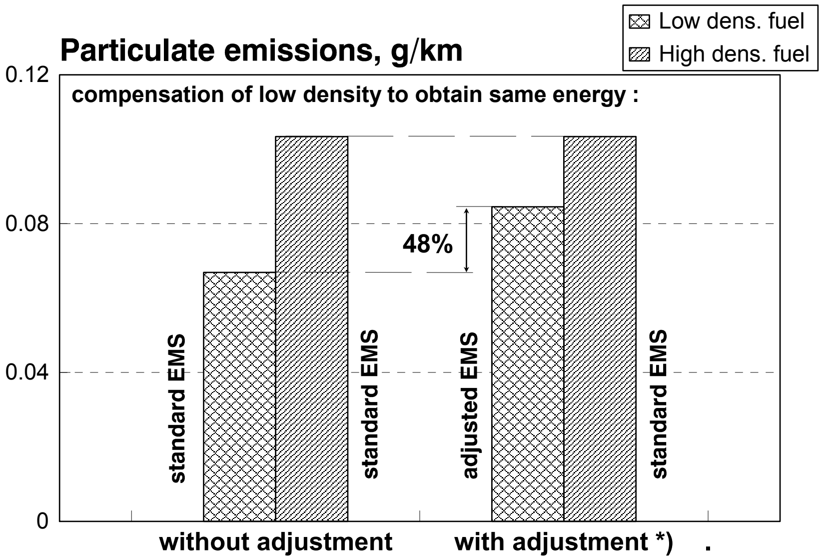
*) to achieve same BMEP as obtained with 828.8 density fuel

Figure 1 Smoke emissions (Engine bench results)
without advanced technology features (EGR, Eprom, catalyst)



*) high density fuel adjusted

Figure 2 Particulate emissions (ECE15 + EUDC results)
with advanced technology features (EGR, Eprom, catalyst)



*) low density fuel adjusted

Figure 3 Nitrogen Oxides (ECE15 + EUDC results - hot start)
(small range of humidity changes)
with advanced technology features (EGR, Eprom, catalyst)

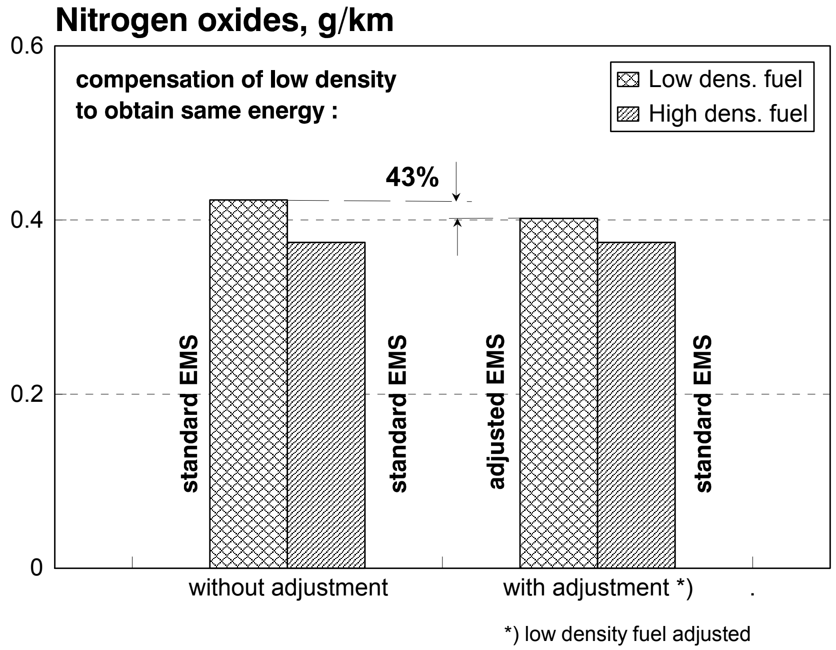


Figure 4 Nitrogen Oxides (ECE15 + EUDC results - cold start)
(larger range of humidity changes)
with advanced technology features (EGR, Eprom, catalyst)

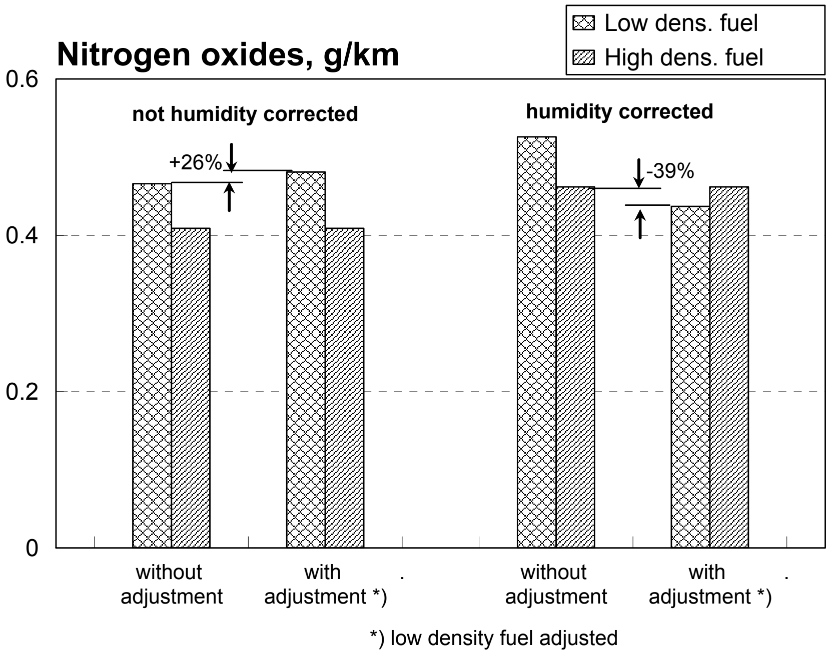
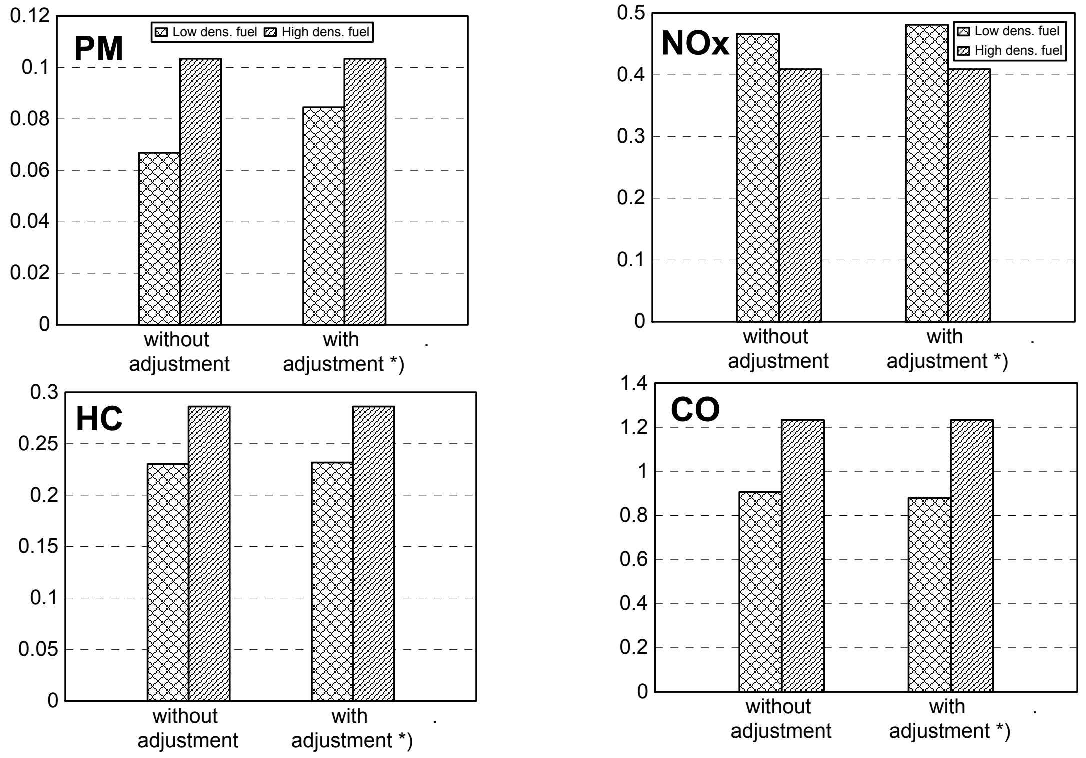
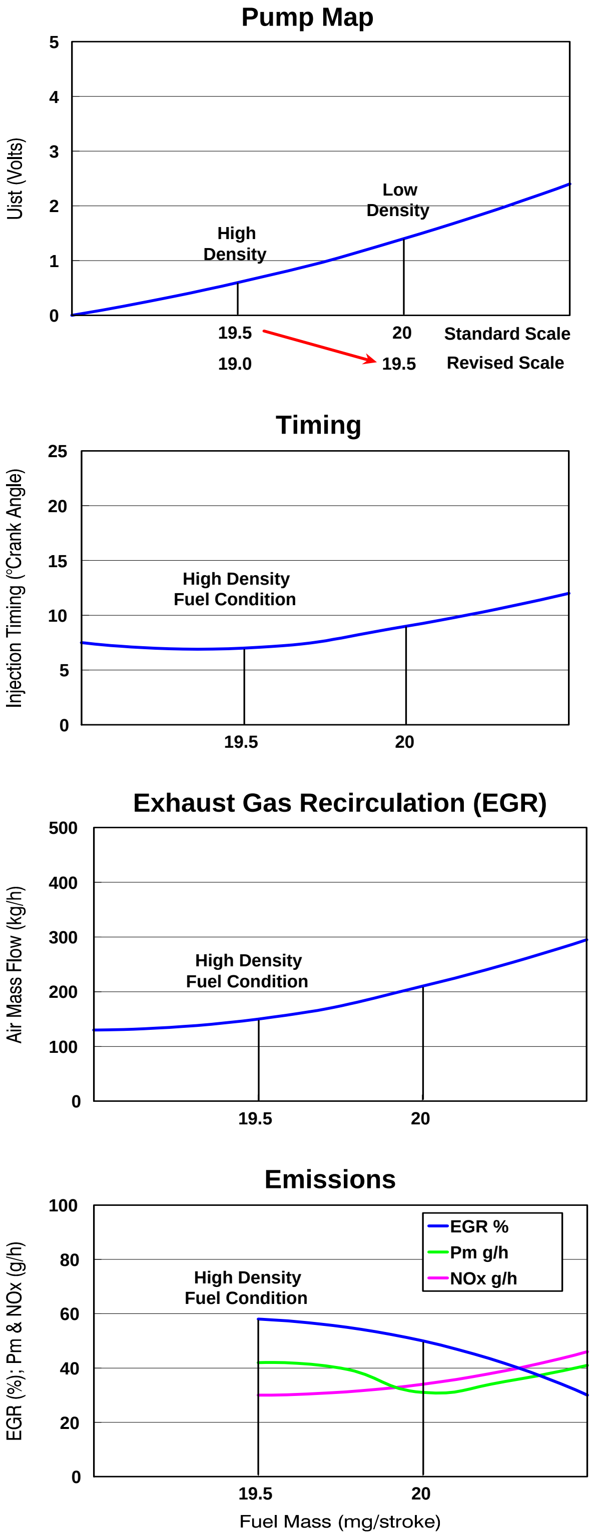


Figure 5 ECE15 + EUDC emissions, g/km
with advanced technology features (EGR, Eprom, catalyst)



*) low density fuel adjusted

Figure 6 Effect of fuel density and correction of Eprom



Timing, EGR, etc., are a function of fuel mass (mg/stroke) and represent look-up tables in the Eprom. EGR, Pm and NOx are the result of programming Uist, fuel mass, timing and air mass flow for a given standard fuel. A new scale in the pump map is employed for the low density fuel to achieve the same timing and EGR used for the high density fuel.

For a given power demand at a given speed, the high density fuel requires a smaller fuel volume (Uist) to be injected than the low density fuel.

Since fuel mass is programmed as the basis in the Eprom, a lower Uist is interpreted as a smaller fuel mass value. As the latter is the basis of all other look-up tables, timing and air mass and thus EGR, Pm and NOx are also affected.

In order to achieve the same timing and air mass flow (EGR) with the low density fuel, a new fuel mass value has to be assigned in the pump map equal to that required for the high density fuel. Thus timing and EGR maps need not be changed. **Note:** All lines shown at constant engine speed

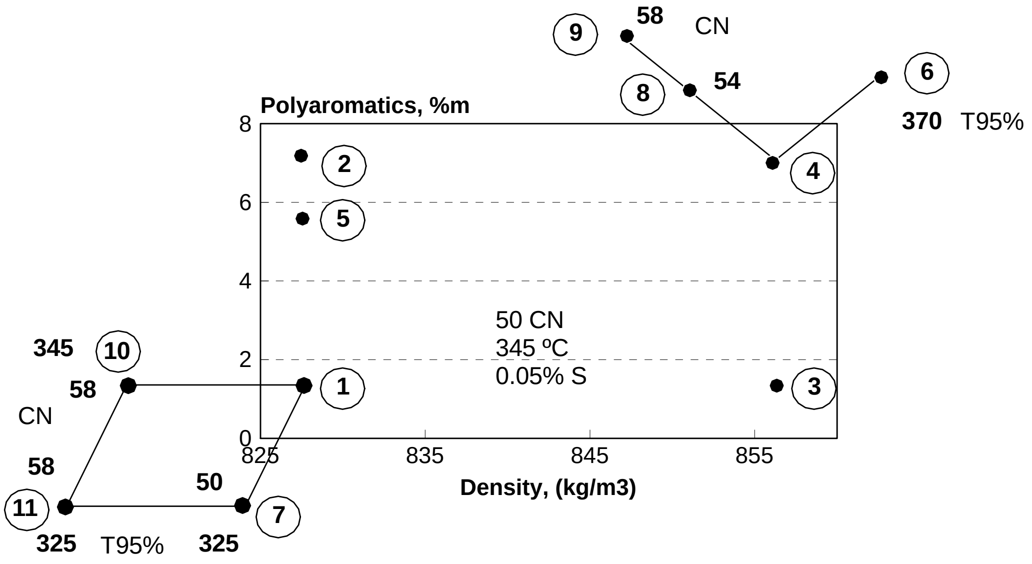
PART 2: EFFECTS ON EMISSIONS OF TECHNOLOGY CHANGES BETWEEN TWO GENERATIONS OF ONE HEAVY DUTY ENGINE MODEL

The fact that engine design has an important influence on emissions performance is well understood. The more interesting aspect of this fact arises when the effect of changes of technology on emissions is compared with the effect of changes of fuel properties on emissions. In this CONCAWE programme both aspects were investigated. Two generations (1992, 1996 plus) of one heavy duty engine model were tested on the EPEFE diesel fuel matrix, which is decorrelated with regard to the main fuel properties.

1. SCOPE OF THE PROGRAMME

Six fuels from the EPEFE eleven fuel matrix were taken to conduct the emission tests with the 1992 HD engine, defined as Engine 1. Due to volume restrictions not all fuels of the matrix could be tested on both engines. Six fuels (EPD1, EPD3, EPD4, EPD6, EPD7, EPD11) were selected to present a cross section of the fuel matrix including the extremes of the fuel properties. All eleven fuels were used to conduct the tests with the 1996 plus HD engine, defined as Engine 2. These fuels had been formulated to specifically decorrelate (1) density and poly-aromatics, (2) cetane number and (3) back end volatility, by pairwise comparisons. The inspection data for all fuels are given in **Table A** (**Annex**).

EPEFE Diesel Fuel Matrix



A dedicated batch of diesel reference fuel CEC RF-73 (**Annex**, **Table A**) made available for the EPEFE programme was used throughout the CONCAWE work.

Both heavy duty engines were from the same model line but represented two generations of development (**Table 1**). They have a displacement of about six litres, are turbocharged and intercooled and fuel injection is controlled by mechanical systems. Engine 1, a 1992 model, provides 165 kW at 2400 rpm, Engine 2, a 1996 plus model, 185 kW at 2200 rpm. The main improvements of the advanced Engine 2 involve changes in combustion chamber design, higher injection pressure and better oil control. As Engine 2 came onto the market in late 1994 the engine appears to be tuned to benefit from the then legislated NOx limit to gain even more competitive fuel consumption through the NOx/fuel consumption trade-off. All other emissions were substantially below the 1996 required levels (**Table 2** emissions with RF 73).

The same test protocol as followed in the EPEFE programme was used in this CONCAWE programme, see the final report "European Programme on Emissions, Fuels and Engine Technologies", 1995, for details.

2. RESULTS

The findings of the investigation showed:

1. **Comparison of engine technology effects on emissions**

   Advanced technology significantly reduced emissions (**Figures 1** to **6**); by about 60% for particulates, by about 40% for hydrocarbons and by about 80% for carbon monoxide. Nitrogen oxides did not vary between engines since Engine 2 appeared to be tuned to the then current legislative NOx limits to provide optimum fuel consumption. Despite an even lower fuel consumption (about 10%) the advanced technology engine showed a 12% higher power output than the previous generation model. Detailed results are given in **Table 2**.

2. **Comparison of engine technology response to fuels and fuel properties**

   Overall response to fuels

   A comparison of the response of both engines to changes of fuel properties tested with the six common fuels showed that Engine 2 not only provided lower emissions than Engine 1 (with the exception for NOx) but was also substantially less sensitive to changes in fuel quality (**Figure 7**).

   Sensitivity to individual fuel properties

   The sensitivity to density, poly-aromatics, cetane number and T95 was determined from a pairwise comparison of those fuels which varied only in this specific property. The magnitude of the individual response is expressed as percentage of change when the respective fuel property is varied over the full tested range (**Table 3**). For easier comparison the changes are described in terms of ranges of percentage (e.g. range 5 to 10%).

   A comparison of the sensitivity of both engines to changes of fuel properties provided the following findings.

   - Decreasing density (from 855 to 828) decreased particulates in the range of 10 to 20% and increased HC in the range of 10 to 20% with Engine 1. With Engine 2 decreasing density only affected HC; the direction and magnitude was the same as found with Engine 1. Density effects are highlighted in **Figure 8** where the much reduced sensitivity for Engine 2 is evident.

   - Decreasing poly-aromatic content (from 8 to 1%) had no effect on Engine 1 emissions, but decreased both particulates and NOx in the same magnitude (range 2 to 5%) with Engine 2. In addition decreasing poly-aromatics increased CO with Engine 2 in the range of 5 to 10%. With Engine 1 the same tendency was observed though its effect was statistically insignificant.

- Decreasing T95 (from 370 to 325 ºC) increased with Engine 1 NOx by up to 5% and HC in the range of 5 to 10%. With Engine 2 HC were increased by up to 2% and CO increased in the range of 2 to 5%.

- Cetane number had no effect on Engine 1 emissions. With Engine 2 increasing cetane number (from 50 to 58) decreased CO in the range of 10 to 20%.

- Fuel consumption and CO_2 were not significantly affected by any fuel property.

Overall the findings showed that the response to fuel properties varied substantially between the two engines; especially with regard to density (the advanced engine was not density sensitive for particulates) and cetane number (the advanced engine was highly sensitive for CO). In addition the advanced engine was somewhat sensitive to poly-aromatics.

3. CONCLUSIONS

- Engine technology has a much greater impact on emissions than fuel quality.
- Advanced engine technology reduced emissions for particulates, hydrocarbons, carbon monoxide emissions by 40 to 80% versus previous generation technology.
- For nitrogen oxides no changes with improved technology were observed. This fact resulted from the basic engine design concept, which was deliberately aimed at low fuel consumption. This kept nitrogen oxide emissions generally at the high end of the respective emissions limit due to the trade-off between fuel consumption and nitrogen oxides.
- Fuel effects on specific emissions were technology/design dependent and varied from engine to engine. This was particularly evident for the fuel density effect on particulates.
- Advanced engine technology reduced the sensitivity to fuel property changes.

Table 1 Description of Test Engines

	ENGINE 1	ENGINE 2
Model year	1992	1996 “plus”
Combustion system	4 stroke, direct injection	4 stroke, direct injection
Cylinders/arrangement	6, in-line	6, in-line
Swept volume per cylinder, litres	1.0	1.1
Combustion system	turbocharged / intercooled	turbocharged / intercooled
Rated power *)	165 kW	185 kW
Rated speed	2400 rpm	2200 rpm
Peak torque *)	860 Nm at 1400 rpm	1100 Nm at 1300 rpm
BSFC, g/kWh *) (at max. torque)	203	199
Specific power, kW/litre *)	27.5	28.0
Engine coolant	liquid	liquid
Fuel injection system		
- pump type	in-line	in-line
- injectors	multi-hole, separate from pump	multi-hole, separate from pump
- pump controls	mechanical	mechanical

*) Approx. values on RF 73 fuel

Table 2 Average Emissions Data and 95% Confidence Bands, g/kWh (ECE R49)

ENGINE 1

Fuel	Pm	Conf. (+/-)	NOx	Conf. (+/-)	HC	Conf. (+/-)	CO	Conf. (+/-)	CO2	Conf. (+/-)	BSFC	Conf. (+/-)
EPD1	0.229	0.019	7.30	0.22	0.419	0.021	2.38	0.31	735.1	14.9	241.4	0.6
EPD3	0.279	0.048	7.37	0.15	0.365	0.040	2.87	0.54	744.2	24.0	240.0	1.2
EPD4	0.272	0.026	7.62	0.33	0.353	0.036	2.62	0.52	751.2	29.3	240.6	0.9
EPD6	0.252	0.026	7.20	0.16	0.339	0.021	2.47	0.35	730.7	9.5	240.6	0.6
EPD7	0.232	0.024	7.14	0.42	0.506	0.081	2.45	0.50	769.8	69.7	242.0	2.1
EPD11	0.254	0.023	6.97	0.19	0.460	0.031	2.45	0.38	754.5	47.0	241.6	2.3
RF73	0.244	0.042	7.48	0.41	0.408	0.024	2.41	0.51	748.5	21.7	241.5	1.2

ENGINE 2

Fuel	Pm	Conf. (+/-)	NOx	Conf. (+/-)	HC	Conf. (+/-)	CO	Conf. (+/-)	CO_2	Conf. (+/-)	BSFC	Conf. (+/-)
EPD1	0.0855	0.0033	7.46	0.14	0.268	0.008	0.420	0.013	712.3	1.5	218.0	0.5
EPD2	0.0895	0.0033	7.65	0.23	0.268	0.008	0.418	0.008	712.8	7.2	218.4	0.8
EPD3	0.0865	0.0021	7.63	0.25	0.225	0.009	0.423	0.015	716.8	10.3	217.2	0.3
EPD4	0.0903	0.0015	8.02	0.30	0.235	0.021	0.395	0.009	716.8	4.6	217.4	0.5
EPD5	0.0920	0.0041	7.57	0.19	0.255	0.009	0.418	0.015	716.0	3.4	218.8	0.4
EPD6	0.0915	0.0032	7.86	0.36	0.235	0.024	0.393	0.009	717.2	7.1	217.3	0.5
EPD7	0.0815	0.0060	7.41	0.27	0.278	0.008	0.450	0.023	706.0	20.3	217.9	0.9
EPD8	0.0897	0.0020	8.03	0.22	0.228	0.004	0.380	0.007	717.7	4.8	217.9	0.3
EPD9	0.0928	0.0060	7.84	0.17	0.240	0.013	0.370	0.039	722.5	12.9	218.0	1.7
EPD10	0.0823	0.0015	7.52	0.26	0.238	0.008	0.388	0.015	707.8	1.5	216.9	1.2
EPD11	0.0837	0.0049	7.36	0.13	0.282	0.004	0.390	0.009	711.3	6.2	218.2	0.5
RF73	0.0926	0.0022	7.76	0.08	0.250	0.005	0.422	0.006	714.4	1.9	218.2	0.3

Table 3 Summary of pairwise comparisons
(based on test fuels commonly tested in both engines,
EPD1, EPD3, EPD4, EPD6, EPD7, EPD11)

Engine 1		**Pm**	**NO_x**	**HC**	**CO**	**BSFC**	**CO_2**
Density	**855→828 kg/m^3**	↓↓↓↓	**n.s.**	↑↑↑↑	**n.s.**	**n.s.**	**n.s.**
PolyAro	**8.0→1.0 %**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**
T95	**370→325 °C**	**n.s.**	↑↑	↑↑↑	**n.s.**	**n.s.**	**n.s.**
Cetane	**50→58**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**	**n.s.**

Engine 2		**Pm**	**NO_x**	**HC**	**CO**	**BSFC**	**CO_2**
Density	**855→828 kg/m^3**	**n.s.**	**n.s.**	↑↑↑↑	**n.s.**	**n.s.**	**n.s.**
PolyAro	**8.0→1.0 %**	↓↓	↓↓	**n.s.**	↑↑↑	**n.s.**	**n.s.**
T95	**370→325 °C**	**n.s.**	**n.s.**	↑	↑↑	**n.s.**	**n.s.**
Cetane	**50→58**	**n.s.**	**n.s.**	**n.s.**	↓↓↓↓	**n.s.**	**n.s.**

Key:

n.s.	**not significant**
-	**0 - 0.5%**
↓	**0.5 - 2%**
↓↓	**2 - 5%**
↓↓↓	**5 - 10%**
↓↓↓↓	**10 - 20%**

Figure 1 Engine Technology Effect on Particulate Emissions (ECE R49)

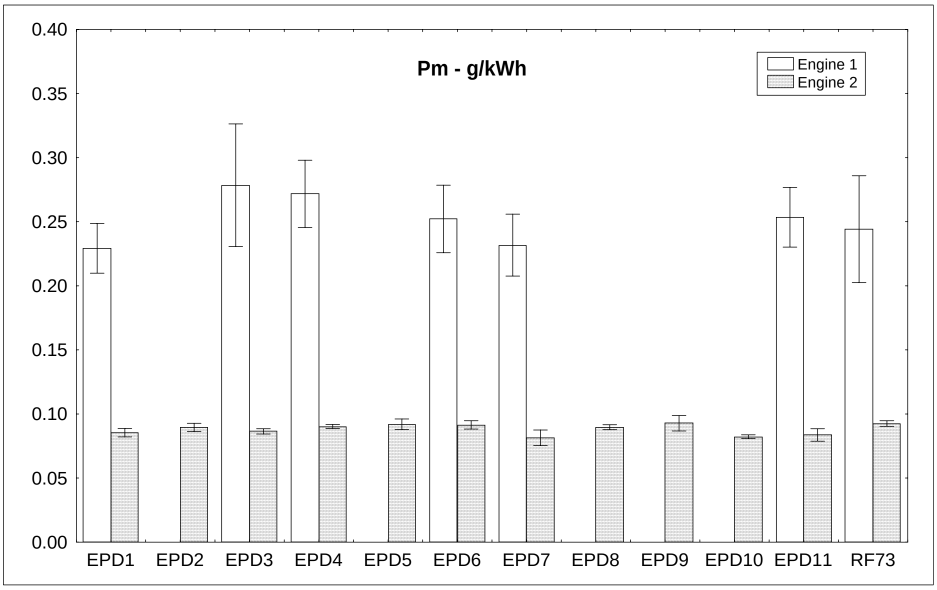


Figure 2 Engine Technology Effect on Nitrogen Oxide Emissions (ECE R49)

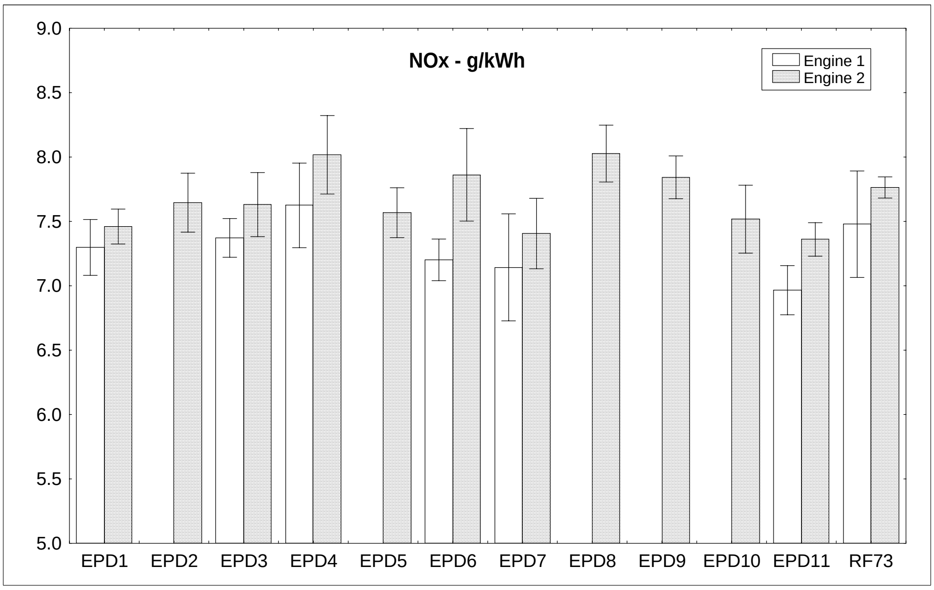


Figure 3 Engine Technology Effect on Hydrocarbon Emissions (ECE R49)

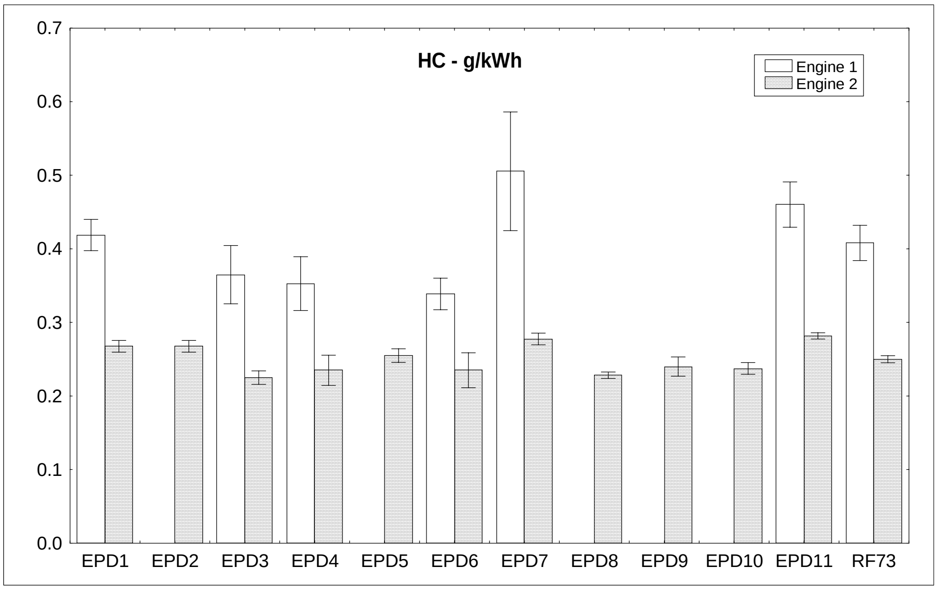


Figure 4 Engine Technology Effect on Carbon Monoxide Emissions (ECE R49)

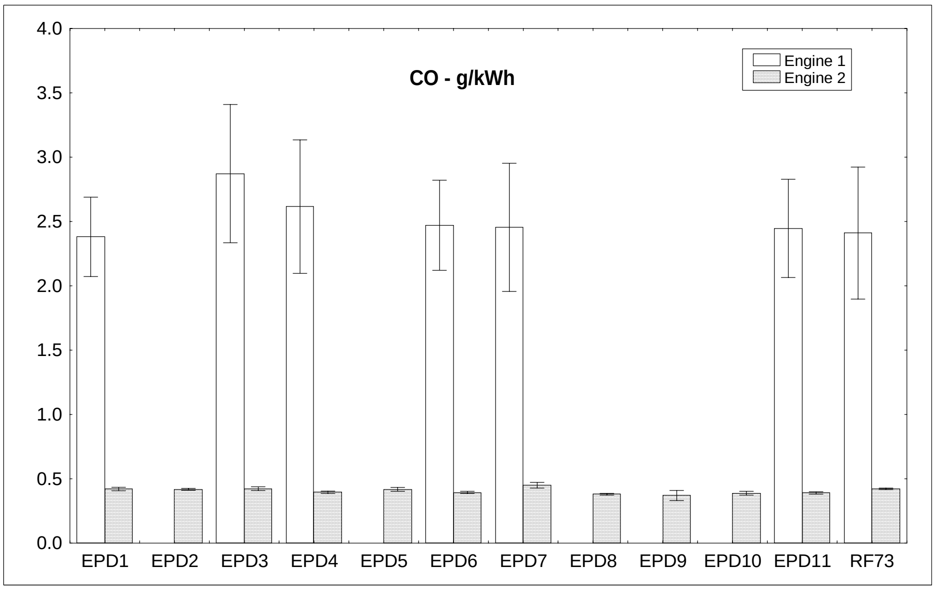


Figure 5 Engine Technology Effect on Fuel Consumption (ECE R49)

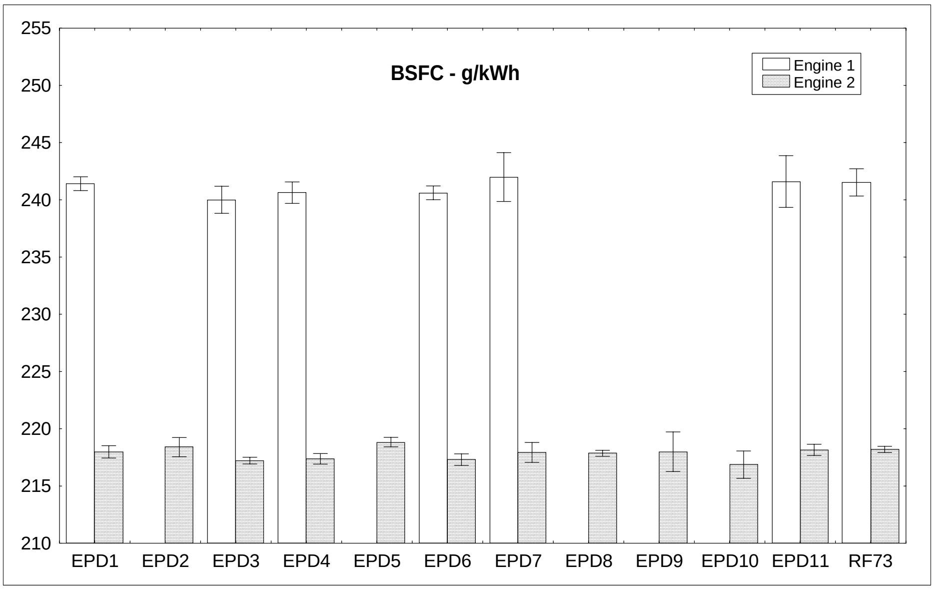


Figure 6 Engine Technology Effect on Carbon Dioxide Emissions (ECE R49)

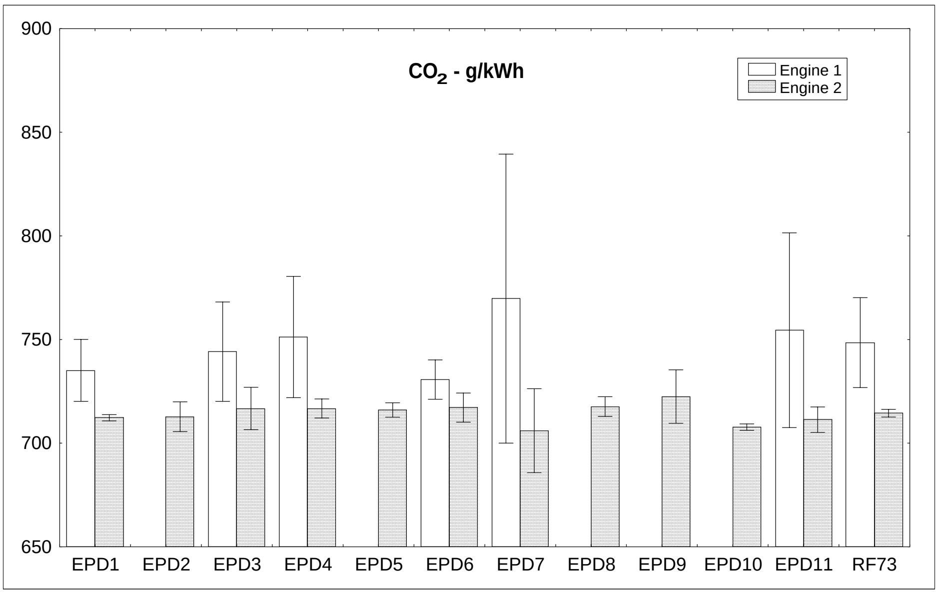


Figure 7 Comparison of engine technology response to fuel changes

Engine 2 shows substantially lower emissions for PM, HC and CO and the response to fuel changes is lower (g/kWh).
(based on test fuels commonly tested in both engines)

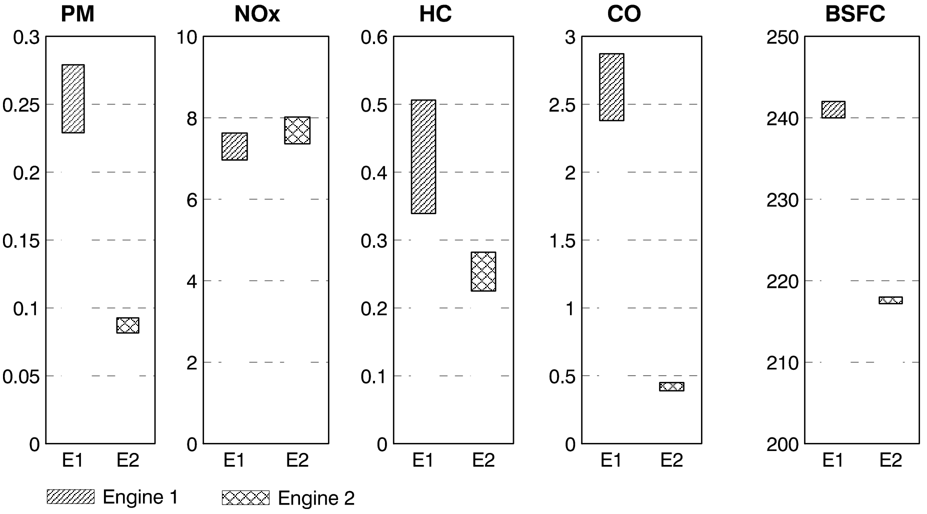
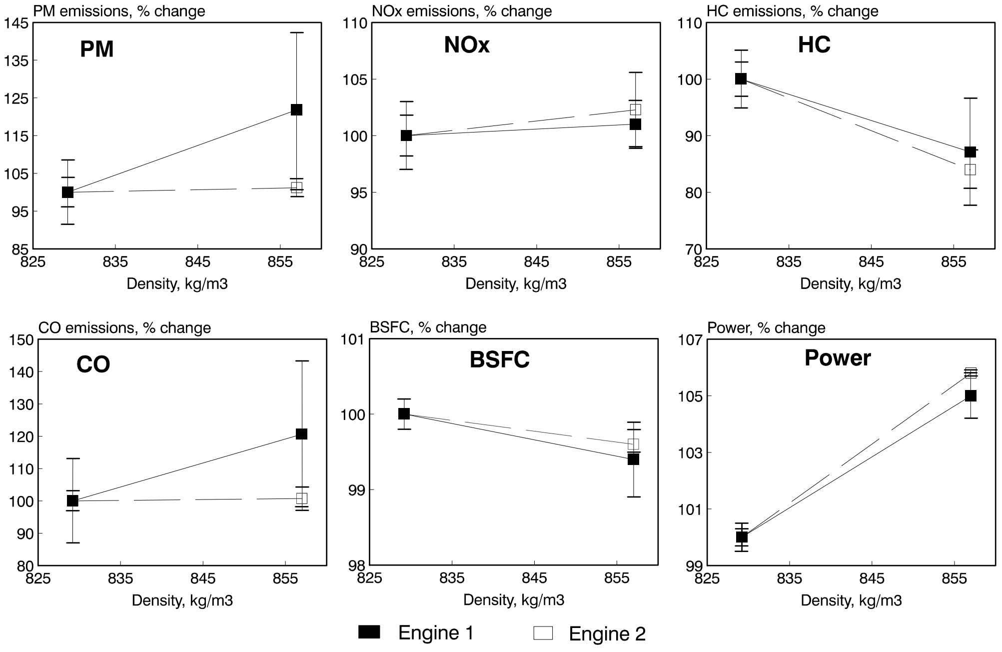


Figure 8 Comparison of engine technology response to fuel density

(the 95% confidence band is shown)



ANNEX

Table A Diesel Fuel Matrix Analysis

Fuel No		**EPD1**	**EPD2**	**EPD3**	**EPD4**	**EPD5**	**EPD6**	**EPD7**	**EPD8 ***	**EPD9 ***	**EPD10**	**EPD11 ***	**RF73**
Property	Unit												
Sulphur content	%m/m	0.04	0.04	0.04	0.05	0.04	0.04	0.05	0.04	0.05	0.05	0.04	0.04
Density @ 15°C	kg/m^3	829.2	828.8	857	855.1	828.8	855.5	826.9	855.1	855.4	826.6	827	839.8
kV @ 40°C	mm^2/sec	2.15	2.24	3.92	3.39	2.22	3.80	2.2	3.40	3.38	2.79	2.01	2.71
Flash point	°C	58	61	101	97	64	93	70	96	93	76	71	78
Cloud point	°C	-21	-12	-20	-10	-13	-10	-31	-10	-11	-9	-32	-11
CFPP	°C	-20	-15	-21	-17	-16	-16	-42	-17	-17	-19	-40	-16
Water content	mg/kg	76	66	56	61	74	60	53	55	66	60	65	60
Copper corrosion		1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a
Carbon residue	%m	0.01	0.06	0.03	0.05	0.03	0.05	0.02	0.11	0.17	0.04	0.11	0.05
Aromatics	%mm												
mono		19.7	18.0	22.7	18.4	21.7	18	17.3	19.3	19.3	17.5	17.7	25.5
di		1.0	6.4	1.0	5.7	7.0	6.0	1.0	5.7	6.4	1.0	0.9	4.9
tri +		0	1.3	0.1	1.7	0.1	1.6	0	1.6	1.6	0.1	0	0.9
(poly)		1.0	7.7	1.1	7.4	7.1	7.6	1.0	7.3	8.0	1.1	0.9	5.8
total		20.7	25.7	23.8	25.8	28.8	25.6	18.3	26.6	27.3	18.6	18.6	31.3
Cetane Number		51	50.2	50	50.3	50.6	50.2	49.5	54.8	59.1	58	57.1	49.2
Cetane Index		52.2	51	50	49.9	52.3	50.9	48.5	49.5	49.4	57.9	48.8	51.6
Distillation													
IBP	°C	160	160	224	217	162	211	177	213	211	181	177	182
10%	°C	186	197	249	247	194	245	198	245	245	214	199	219
20%	°C	200	211	259	256	207	257	206	255	255	233	206	233
30%	°C	219	225	268	264	224	266	217	263	263	251	217	247
40%	°C	244	239	277	272	244	276	227	271	271	264	228	259
50%	°C	263	252	285	280	260	286	238	279	279	275	239	271
60%	°C	275	266	294	289	275	297	249	288	288	285	250	282
70%	°C	286	282	303	298	289	310	261	298	298	297	262	294
80%	°C	300	303	314	310	308	327	276	310	310	312	276	305
90%	°C	321	330	330	328	330	351	299	327	327	331	301	319
95%	°C	344	349	348	344	346	371	326	345	344	347	329	331
FBP	°C	365	361	363	361	357	383	348	359	358	359	349	347

* contains ignition improver