Advanced vehicles and fuels

Some recent emissions results

The recent update to the EU Fuels Directive specifies a maximum sulphur content of 50 mg/kg in gasolines and diesel fuels from 2005, with 'appropriately balanced geographic availability' of sulphur-free[1] fuels from the same date, progressing to 100% coverage of sulphur-free fuels by 2009 (this date being subject to a further review for diesel).

Sulphur-free fuels are being introduced to enable advanced engine and exhaust after-treatment technologies to meet increasingly stringent exhaust emissions regulations, with best fuel efficiency and long-term durability. As these new fuels and vehicles are introduced, the potential for further improvements in air quality through changes to fuel properties can be expected to diminish.

Nevertheless, the EU Fuels Directive calls for a further review of other fuel properties to be completed by end 2005. In order to update knowledge on fuel effects on emissions, CONCAWE has continued to evaluate new engine/vehicle technologies as they approach the market. In two recent test programmes, on which full reports will be published soon, emissions from advanced gasoline vehicles and advanced diesel engines and vehicles have been measured using a wide range of fuels. This article gives a summary of the results and implications.

Diesel programme

Two advanced light-duty diesel vehicles and three heavy-duty diesel engines were tested with a wide range of fuels. The main objectives of the programme were to assess:

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

Only the regulated emissions are described in this article.

Engines/vehicles tested

The two diesel passenger cars selected for testing were chosen as examples of advanced technologies available in the European market in 2002. These included a medium sized DI diesel car with an oxidation catalyst (car A) and a large DI diesel car with an additised particulate filter (car B).

The heavy-duty engines were selected to cover the range of technologies likely to be used to meet the future exhaust emissions standards. A commercial Euro-3 engine without after-treatment provided the base case, compared to prototype Euro-4 (using EGR and CRT) and Euro-5 engines (using SCR/urea but no particulate filter).

Diesel fuels

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 provide a major part of the total diesel fuel volume, even by the year 2020, they provide a means to assess the maximum possible fuel effects.

Test fuels are coded D2 to D8. D2 to D4 were based on a common conventional but sulphur-free fuel with other properties close to average year 2000/05 levels, and designed to study the sulphur effect, from 300 to 50 to 10 ppm. Swedish Class 1 diesel fuel is designated as D5, and Fischer-Tropsch diesel fuel as D8. A second conventional diesel fuel (D6) at the 300 ppm sulphur level, but with higher density and aromatics content, was also tested to provide the other extreme of fuel composition. Finally, fuel D7 was a blend of fuel D4 with 5% RME.

Test methodology

The programme mainly focused on tests over the standard regulated test cycles, namely the NEDC for light-

[1] *With maximum sulphur content of 10 mg/kg*

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duty vehicles and the ESC/ETC for heavy-duty engines. In addition some steady-state tests and 'real-world' drive cycles, defined under the EU's 'ARTEMIS'[2] programme, were included. Only some key examples of the results can be illustrated in this article. Full results will be found in the CONCAWE reports.

For both light-duty and heavy-duty testing, a consistent fuel change, conditioning and testing sequence was followed in order to obtain comparable results for the different fuel/engine combinations. The test programmes were constructed using the principles of statistical experimental design, with each fuel tested three times in each vehicle/engine.

Results and discussion

The diagrams show the average emissions results from the different engines/cars grouped by fuel, versus the relevant Euro emissions limits. Non-overlapping error bars indicate a statistically significant difference between those fuel/engine combinations.

Light-duty diesel vehicles

For CO emissions, both cars performed well within the Euro-4 limit. HC emissions from both cars were very low.

Particulate mass (PM) and NO_x are the more critical emissions from diesel engines. For PM emissions, car A, although certified to Euro-3, produced PM emissions close to the Euro-4 limit. Fuel D6 gave the highest PM emissions in this car. Swedish Class 1 (D5) and FT diesel (D8) gave the lowest PM emissions. The addition of RME to D4 did not significantly affect PM emissions.

The more striking effect was that of the particulate filter, car B producing extremely low PM emissions, below 10% of the Euro-4 limit on all fuels. In this car, the differences between fuels in PM emissions over the NEDC were not significant (Figure 1).

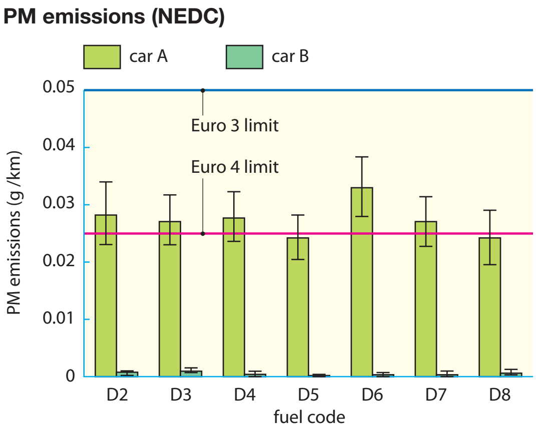
Sulphur had a larger effect on PM emissions under more severe test conditions, in particular the 'ARTEMIS' motorway cycle.

For NO_x emissions, car A almost satisfied the Euro-4 limit, while car B performed within its Euro-3 certification limit. Fuel effects were generally not significant on the NEDC, though directionally fuels D5 and D8 gave lowest NO_x emissions in car B (Figure 2).

NO_x emissions roughly doubled for both cars under the more severe conditions of the 'ARTEMIS' motorway cycle. On this cycle, fuels D5 and D8 gave significant reduction in NO_x emissions in car B, though not in car A.

Heavy-duty diesel engines

CO emissions, even for the Euro-3 engine, were well below the Euro-5 limit and fuel effects were small rela-



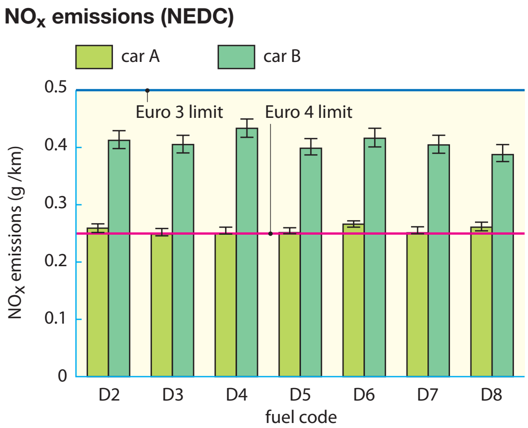


Figure 1 (left)
Car B with a particulate filter produced extremely low PM emissions, less than 10% of the Euro-4 limit.

Figure 2 (right)
Fuel effects on NO_x emissions were small over the NEDC.

[2] *Assessment and Reliability of Transport Emission Models and Inventory Systems*

tive to the regulatory limit. The Euro-4 and Euro-5 engines which both include oxidation catalysts gave extremely low CO emissions. HC emissions were around half of the applicable limit for the Euro-3 engine, even lower for the Euro-4 engine and not detectable for the Euro-5 engine. Swedish Class 1 fuel (D5) gave the highest HC emissions in the Euro-3 engine. Other fuel effects on HC emissions were not significant.

For particulate mass (PM), all three engines performed well within their respective PM emissions limits (Figure 3). The Euro-4 engine with particulate filter 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. Fuels D2 and D6, with comparable sulphur contents but differing in other fuel properties, gave similar emissions. The addition of 5% RME did not change PM emissions. Swedish Class 1 (D5) and Fischer-Tropsch diesel (D8) performed similarly and gave lower PM emissions than the other fuels. In the advanced Euro-4 and Euro-5 engines, the effects versus conventional sulphur-free fuels were very small in absolute terms.

The Euro-4 engine performed well within its NO_x limit on all fuels. NO_x emissions from the Euro-3 and Euro-5 engines were very close to their respective ESC test limits (Figure 4). Considerable progress in control of NO_x emissions from Euro-3 to Euro-5 engines is evident. However, even the Euro-5 NO_x emissions levels are still relatively high compared to the US heavy-duty limits for 2007 and 2010. Further progress can therefore be expected as control of engine-out emissions improves and NO_x after-treatment technology matures.

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

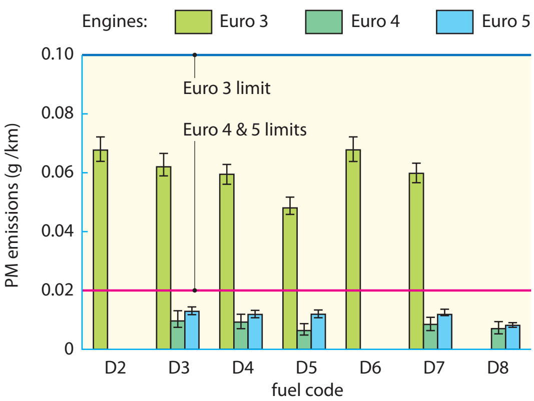
In the prototype Euro-5 engine, NO_x after-treatment was by SCR/urea. In this system, there was potential to further reduce NO_x emissions with all fuels, if a higher urea injection rate was used.

Diesel programme conclusions

Large improvements in exhaust emissions control are being accomplished through advanced diesel engine technologies and after-treatment systems in combination with low sulphur fuels.

- HC and CO emissions from the advanced diesel engines and vehicles were well below the prescribed emissions limits.
- PM emissions were dramatically reduced in engines/vehicles equipped with diesel particulate filters.

PM emissions (ESC)



NO_x emissions (ESC)

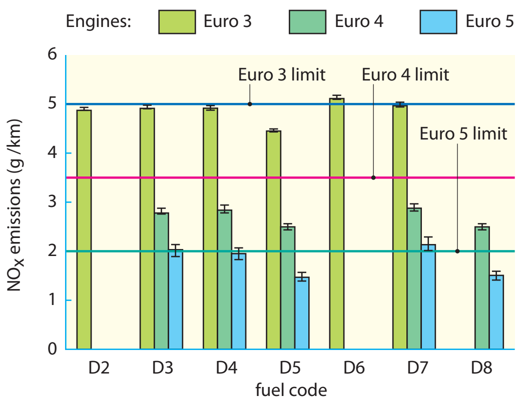


Figure 3 (left)
Substantial improvements can be seen in PM emissions control.

Figure 4 (right)
Clear progress is also evident in the control of NO_x emissions.

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- Clear progress in control of NO_x emissions was demonstrated with the advanced diesel engine technologies. Further improvements can be expected as control of engine-out emissions improves and NO_x after-treatment technology matures, with the availability of sulphur-free fuels.

Gasoline programme

A range of advanced gasoline engine technologies and exhaust after-treatment technologies are being introduced to meet more stringent emissions requirements together with CO_2 reduction. The introduction of sulphur-free fuels is an important step, allowing regenerative devices such as NO_x storage catalysts to be introduced with acceptable durability and best fuel efficiency.

In this programme CONCAWE evaluated the impact of fuel quality on exhaust emissions from advanced gasoline vehicle technologies available in the market in 2002, covering three DI cars and one advanced MPI car. The fuel parameters of interest were evaluated by preparing two independent fuel sets: the first to examine the short-term effect of sulphur content (reported previously, CONCAWE report 5/03); the second to examine the effect of other key fuel properties: aromatics, olefins, volatility and final boiling point (described here).

Test vehicles

Four vehicles were evaluated, selected on the basis of new technologies judged likely to take a significant share of the European car population in the near term. Three examples of DI technologies, one stoichiometric (car A) and two lean-burn (cars C and D), and one advanced MPI system (car B) were tested. Two of these vehicles (A and C) were certified to Euro-3 emissions limits and two (B and D) to Euro-4.

Test fuels

The fuel matrix was designed to evaluate the effects of aromatics, olefins, volatility and final boiling point (FBP) on exhaust emissions. In order to maximise the chance to identify fuel effects, a wide range in the fuel parameters of interest was investigated, covering olefins from 14 to 5% v/v, aromatics from 38 to 26% v/v, E70 from 38 to 22% v/v and FBP from 197 to 176 °C. To reduce the number of emissions tests required, a statistically designed half-factorial matrix of eight fuels was blended, which treated volatility as the combined effects of E70 and E100. The sulphur content of all fuels was kept nominally constant. The key fuel properties are shown in Table 1.

Test methodology

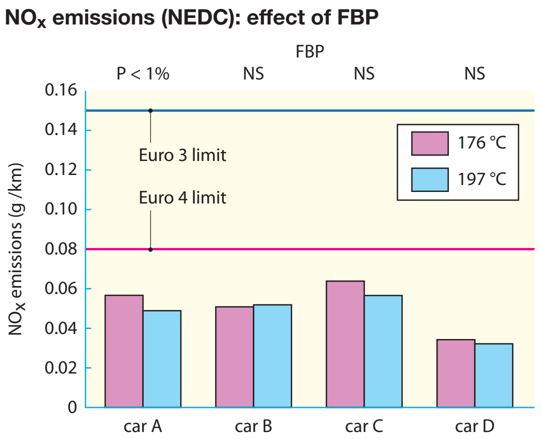
Vehicles were tested according to the current legislated NEDC test procedure and the legislated exhaust emissions—CO, HC, NO_x—were measured. Test order was based on a randomised statistical block design with at least three repeat tests on each fuel/vehicle combination. Multiple regression techniques were used to relate emissions to the four fuel design variables (E70, FBP, aromatics, olefins) described above.

Results and discussion

The results are described below by emission with key illustrative graphs. In these graphs, the data are plotted with common scales for a given emission, with the maximum of the scale set just above the respective Euro-3 emissions limit. Within each graph, there are two bars for each vehicle, showing the mean emissions for the 'low' and 'high' level of the fuel parameter. The

Table 1 Key fuel properties *(The higher levels of each parameter are shaded grey)*

	Units	Fuel code							
		F1	F2	F3	F4	F5	F6	F7	F8
FBP	°C	174	180	174	177	195	202	195	196
E 70 °C	% Vol	19.1	33.4	39.2	20.5	41.2	24.5	22.8	39.0
E 100 °C	% Vol	48.2	61.9	62.9	46.7	62.2	48.0	47.4	62.5
Olefins	% Vol	5.5	3.0	12.7	14.1	4.9	5.3	13.0	14.2
Aromatics	% Vol	25.0	37.8	27.7	39.9	28.6	38.5	24.1	35.9



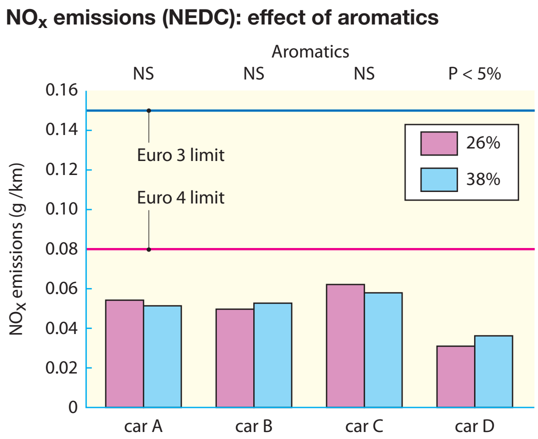


Figure 5 (left)
All four cars performed within the Euro-4 NO_x limit. Lower FBP gave a small increase in NO_x emissions in the DI cars, significant only in car A.

Figure 6 (right)
Aromatics effects on NO_x emissions were small, only car D showing a significant effect.

significance of the effects is denoted by the text above the bars: P < 1% = the probability that an effect could be observed by chance when no real effect exists is less than 1%, i.e. we are 99% confident that the effect is real. Likewise P < 5% = 95% confidence and P < 0.1% = 99.9% confidence. NS = Not significant (< 95%).

NO_x emissions

All four cars met the Euro-4 NO_x emissions limit of 0.08 g/km. Car D gave consistently lower NO_x emissions across all fuels.

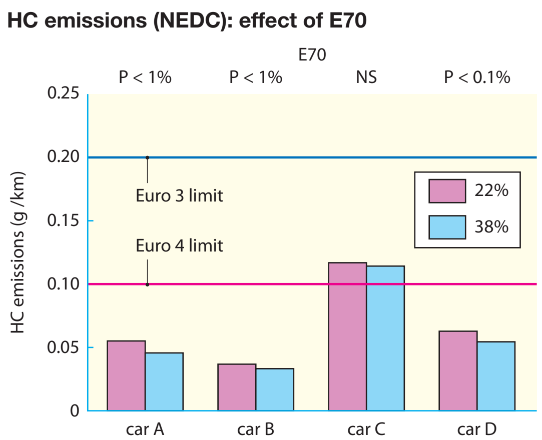
Front/mid range volatility (E70) only had a significant effect on car A, the stoichiometric DI; NO_x increasing with higher volatility. Lowering FBP directionally increased NO_x emissions in the three DI cars, although significant only in car A (Figure 5). There was no significant effect of FBP in the MPI car B.

Reducing aromatics showed conflicting trends (Figure 6). The effects were not significant on NO_x emissions in three cars. Car D, a lean DI, showed a small but significant decrease in NO_x emissions with lower aromatics. Reducing olefins yielded no significant effect on NO_x emissions in any car.

HC emissions

HC emissions for three of the four vehicles were well below the Euro-4 limit of 0.1 g/km. Car C operated well below the Euro-3 limit against which it was certified. The other Euro-3 vehicle (car A) had very low HC emissions, in line with the two Euro-4 vehicles. For all four vehicles, the emissions from the ECE phase dominated the NEDC HC emissions.

Decreasing front/mid range volatility (E70 from 38% to 22%) increased HC emissions in all four vehicles, and was



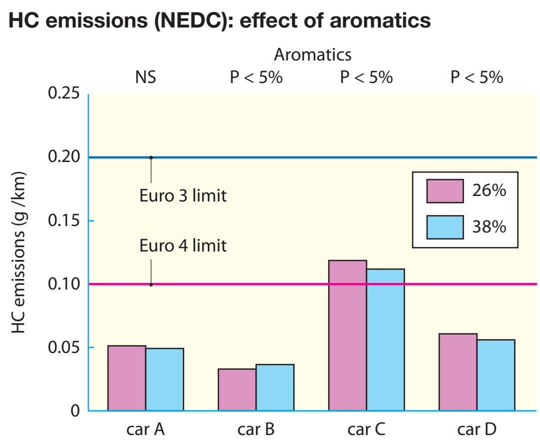


Figure 7 (left)
Three of the four cars performed within the Euro-4 HC limit. Decreasing E70 gave a small increase in HC emissions in all four vehicles.

Figure 8 (right)
Reducing aromatics gave a small increase in HC emissions in the DI cars, whereas the advanced MPI car (B) showed the opposite effect.

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significant in three cases (Figure 7). The overall average increase was 0.006 g/km (10%).

Reducing FBP (from 197 °C to 176 °C) reduced HC emissions in all four cars, and was significant in two cases. The overall average decrease was 0.006 g/km (9%).

Reducing aromatics (from 38% v/v to 26% v/v) increased HC emissions in all three DI cars, and was significant in two cases (Figure 8). The overall average increase in the DI cars was 0.004 g/km (5%). Car B, the advanced MPI car, showed a significant effect in the opposite direction. Reducing olefins had no significant effect on HC emissions in any of the four vehicles.

CO emissions

CO emissions for all four vehicles were well below the Euro-4 limit of 1.0 g/km. Car A gave consistently lower CO emissions across all fuels.

Decreasing front/mid range volatility gave a significant reduction in CO emissions in the lean DI car C and in the advanced MPI vehicle. It had no effect in the other two vehicles. Reducing FBP directionally increased CO emissions in all four vehicles but the effect was significant only in cars B and C.

Changing aromatics content had no effect on CO emissions in any of the cars. Olefin effects on CO emissions were small. Only the advanced MPI vehicle (car B) showed a significant effect, with CO emissions increasing with lower olefins content.

Gasoline programme conclusions

All four gasoline vehicles achieved their respective emissions certification limits, and in most cases measured emissions were lower than the Euro-4 limits.

- A reduction in fuel volatility, representing the combined effects of vapour pressure, E70 (38% v/v to 22% v/v) and E100, had no consistent effect on NO_x emissions, increased HC across all vehicle technologies (10%), but decreased CO emissions in two cars.
- A reduction in FBP from 197 °C to 176 °C increased NO_x emissions in one car but had no significant effect in the others. HC emissions were directionally reduced (9%) and CO emissions directionally increased (20%), with significant effects in both cases in two cars.
- A reduction in aromatics content from 38% v/v to 26% v/v showed conflicting effects, increasing NO_x emissions in two cars, decreasing in the others, but the effects were only significant in one vehicle. Reducing aromatics increased HC emissions in the two lean DI cars but showed the opposite effect in the MPI car.
- A reduction in olefins content from 14% v/v to 5% v/v gave no significant improvement in NO_x, HC or CO emissions in any of the cars.

Summary/outlook

It is clear that very low emissions can be achieved by advanced engine/vehicle technologies operating on sulphur-free fuels, and this will bring substantial improvements in European air quality as the vehicle fleet is replaced. For diesel vehicles, particulate filters have the potential to reduce diesel PM emissions by more than an order of magnitude, and capability for substantial improvements in control of NO_x emissions is also evident. Gasoline vehicles are already achieving very low regulated emissions and the future challenge is to continue to improve fuel efficiency.

The potential for additional air quality benefits from further changes to EU fuel specifications appears to be minimal. It should be borne in mind that any such changes would increase refinery processing, hence CO_2 emissions, and could also limit available fuel volumes. Nevertheless, the EU Fuels Directive review still has some important items to consider, including the end date for 100% market coverage of 10 mg/kg sulphur diesel fuel, gasoline vapour pressure limits with respect to ethanol blending, metallic additives, and non-road diesel fuel requirements.