Fuels for advanced combustion engines

Better performance by engine and fuel working together

Over the past two decades, air pollutant emissions from motor vehicles have fallen dramatically as a result of continuing improvements in vehicle, engine and aftertreatment technologies aided by the widespread introduction of sulphur-free fuels.

While air pollutants are still important, today's priority is to improve engine efficiency and fuel consumption in order to address new concerns regarding future energy supplies and greenhouse gas emissions. These new targets must be met while further reducing air pollutant emissions. Manufacturers of engines and engine equipment are rapidly responding to meet these new challenges. Fuel manufacturers are also interested in knowing what fuels might enable these engine improvements and are ready to contribute to vehicle studies that help to clarify the performance of future fuel and biofuel blends.

Considerable research is focused today on enhancing the combustion performance of compression-ignition (CI) passenger car engines. Compared to spark-ignition (SI) engines, CI engines are already very efficient so today's challenge is to maintain or improve the CI engine's efficiency while further reducing its air pollutant emissions. Engines using advanced combustion concepts are being developed that achieve improved efficiency with lower engine-out emissions, thus reducing the demand on exhaust aftertreatment systems and, potentially, also their cost. Because these concepts typically combine features of both SI and CI combustion, the best fuel characteristics could be quite different from those that are needed by today's petrol and diesel engines.

In general, these advanced combustion concepts are designed to substantially homogenise the fuel-air mixture before it is combusted in the engine at relatively low combustion temperatures. This approach helps to simultaneously reduce soot and NO_x formation, two important air pollutant emissions from diesel engines. Achieving this result requires more sophisticated engine technology to better disperse the fuel while simultaneously lowering the oxygen content of the fuel-air mixture and the combustion temperature. Any improvements in engine-out emissions can reduce the demands on the vehicle's exhaust aftertreatment system.

In the engine, the use of higher injection pressures, cooled exhaust gas recirculation (EGR), and advanced injection nozzle designs are just a few of the hardware enhancements that improve performance. In addition, a robust and rapidly-responding combustion controller is increasingly important in order to better control the fuel injection timing and optimize the combustion process on a cycle-by-cycle basis. These concepts are rapidly moving from research into production engines. If successfully marketed in most new vehicles, these approaches have the potential to impact the types of fuels that may be needed in the future.

As reported in CONCAWE *Review* Vol. 17, No. 2, CONCAWE and FEV Motorentechnik in Aachen, Germany have explored these engine technologies using an advanced combustion single-cylinder bench engine and found that similar and very acceptable engine efficiency, exhaust emissions and noise could be obtained using a very broad range of fuels[1]. Compared to a bench engine running at steady-state speeds and loads, achieving the same level of performance and emissions in an advanced combustion vehicle operating over a European driving cycle is a substantially bigger challenge and was the next major milestone for the CONCAWE and FEV collaboration.

FEV's demonstrator vehicle

Through their own research, FEV had already developed a 'demonstrator vehicle' (Figure 1) equipped with a novel high-efficiency combustion system (HECS)[2] and were

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[1] *SAE 2008-01-2404 and 2008-01-2405*

[2] *17th Aachen Colloquium, October 5–7, 2008. Aachen, Germany*

interested in testing this vehicle concept on CONCAWE's fuel set. The objective of the study was similar to the previous bench engine study: to investigate what performance could be achieved in an advanced combustion vehicle and how changes in fuel properties would influence the overall results[3]. Unlike the bench engine study, the performance hurdle was the demonstrator vehicle's driveability, fuel consumption and tailpipe emissions over the European regulatory cycle.

The FEV vehicle was equipped with a 4-cylinder high-speed direct injection (HSDI) diesel engine. A downsized 1.6-litre engine replaced the vehicle's standard 2.0-litre engine, providing the same power output and much lower pollutant emissions. Tests were completed over the New European Driving Cycle (NEDC).

The vehicle's engine was equipped with the same upgrades that had previously been used on the bench engine and are likely to be needed to meet future exhaust emissions regulations. These included a high-pressure common rail fuel system, piezoelectric fuel injectors, EGR cooling and 2-stage charge air boosting. This 2-stage strategy used both low- and high-pressure turbocharging and allowed recirculation of high amounts of exhaust gas while achieving good driveability and fast engine transient response. Although a diesel oxidation catalyst and diesel particulate filter (DPF) were used to control some emissions, tailpipe NO_x emissions were controlled by the engine combustion and EGR process alone, and a special NO_x aftertreatment system was not used.

Pressure sensors were also inserted into the cylinders in order to provide cycle-by-cycle feedback to a sophisticated engine management system (EMS). The EMS was responsible for automatically adapting to changes in fuel properties without limiting vehicle driveability and acceleration. The control strategy included an injection pre-controller that provided fast and precise fuel injection timing information to the EMS in order to maintain a constant centre of combustion from cycle-to-cycle. This so-called 'closed loop combustion control' (CLCC) approach was found to be especially important to achieve fuel flexibility while maintaining exceptional engine performance.

Figure 1 FEV demonstrator vehicle

What fuels were tested?

Previous studies[4] have suggested that three fuel properties are especially important to enable advanced combustion:

1. lower cetane number (CN), to lengthen the ignition delay and provide time for more fuel-air mixing;
2. higher volatility, to increase fuel-air mixing before auto-ignition occurs; and
3. fuel composition, to promote combustion and reduce engine-out emissions.

Six fuels were tested that covered a broad range of these properties (see Figure 2, overleaf), and included some fuels that could be imagined to fuel a growing

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[3] *SAE 2010-01-0334*

[4] *CONCAWE Report 4/08 and CONCAWE* Review *Vol. 17, No. 1*

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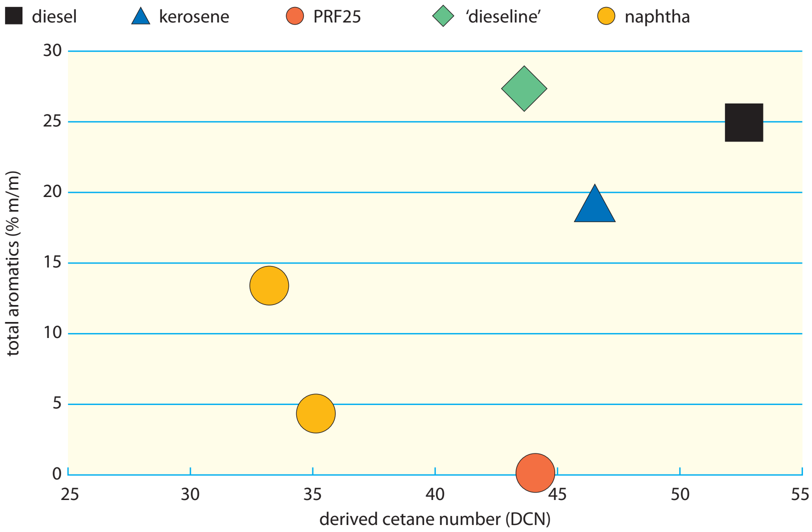
Figure 2 Fuels evaluated in the study



fleet of advanced combustion vehicles. The fuels included both conventional and experimental blends. In addition to a typical European diesel fuel and commercial kerosene, a 'dieseline' blend of diesel and gasoline fuels and two naphtha fuels sampled from refinery process units were tested. A Primary Reference Fuel (PRF25), blended from pure chemicals boiling in the gasoline range, was also tested.

Vehicle performance

With the vehicle hardware and EMS described above, emissions tests were completed over the NEDC. Vehicle driveability was evaluated, especially cold engine starting and responsiveness to acceleration and high load operations. Most importantly, regulatory procedures were followed to evaluate how closely the vehicle would come to meeting future (Euro 6) exhaust emissions limits for a 1700-kg vehicle.

Remarkably, good vehicle driveability performance was achieved for all six test fuels. Regardless of the fuels' properties, the vehicle operated successfully over the NEDC with few or no hesitations in engine performance. Even with the refinery naphthas, having the lowest cetane numbers in the fuel set, the demonstrator vehicle was able to complete the full NEDC regulatory protocol.

Exhaust emissions, with a focus on NO_x and particulate matter (PM), were also measured to see whether the vehicle would meet the Euro 6 limits. The NO_x emissions versus engine-out particle emissions are shown in Figure 3a for two different tests on each fuel. The NO_x and PM tailpipe limits are also shown although the PM limits only apply to tailpipe emissions and not to engine-out emissions.

Figure 3a Tailpipe NO_x versus engine-out particle emissions over the NEDC

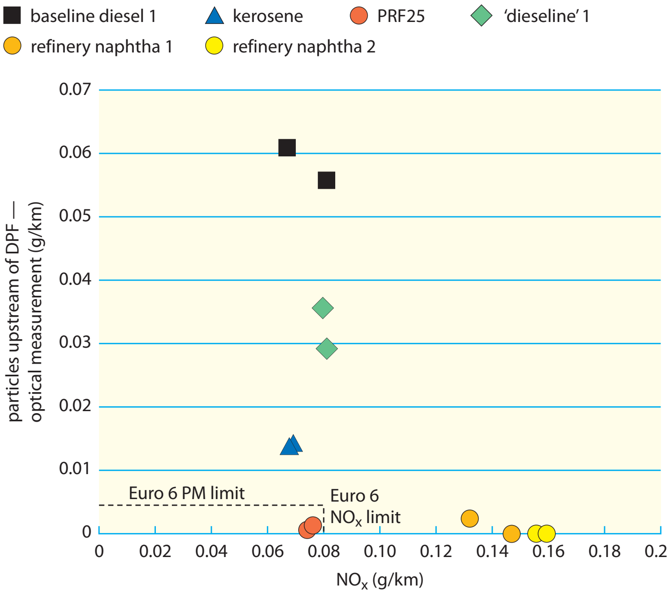
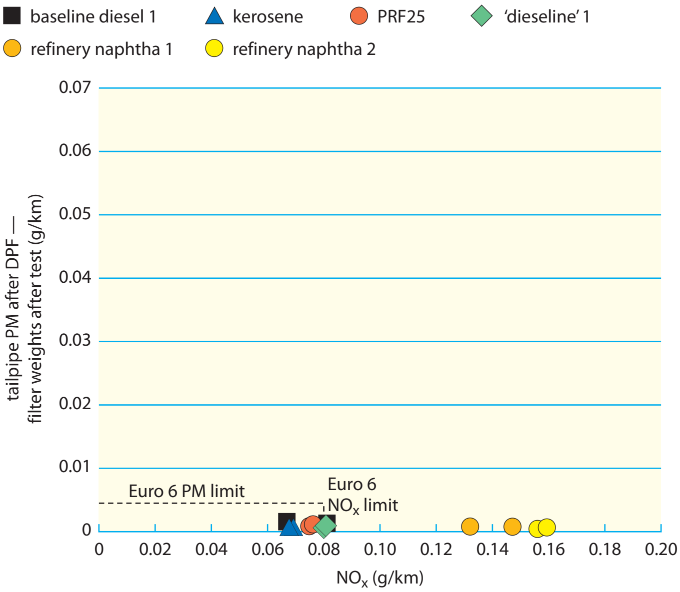


Figure 3b Tailpipe NO_x versus PM emissions over the NEDC



The engine-out particle emissions varied widely between the fuels and were generally in line with the aromatics contents and volatilities of the six fuels. Nevertheless, the PM emissions measured at the tailpipe by standard procedures were all within the Euro 6 PM regulatory limits when using a conventional DPF aftertreatment device (see Figure 3b).

Because of the high EGR rates used in this engine, four fuels gave NO_x emissions that were within the Euro 6 limit. The two refinery naphthas produced higher NO_x emissions over the NEDC, primarily due to higher emissions during the cold engine portion of the driving cycle.

Very good performance was also observed for CO_2 emissions (Figure 4), again with two results on each fuel obtained on different test days. Over the NEDC, four fuels showed similar performance, between 132–148 g CO_2/km. These emissions values were in line with the study targets and well below those of a comparable 2.2-litre engine. The two naphtha fuels gave slightly higher CO_2 emissions, between 148–158 g/km.

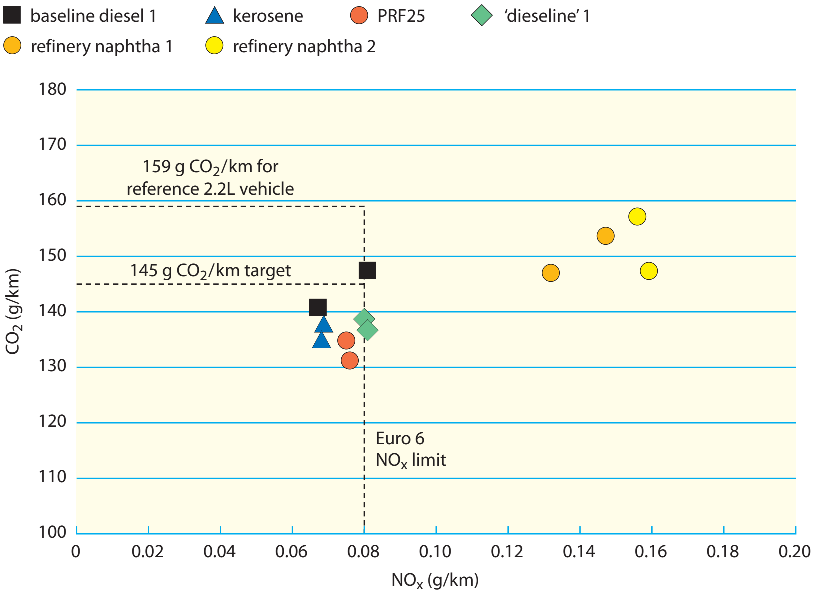
Although four fuels gave very acceptable exhaust emissions over the NEDC, the two naphtha fuels did not perform as well, especially during the cold engine portion of the driving cycle and at the lower engine load points. Higher noise emissions were also recorded for these two fuels due to longer ignition delays and a rapid pressure increase in the cylinder after auto-ignition of the fuel-air mixture. The combustion performance of these fuels is being investigated further.

What did we learn?

Although the six fuels tested in the demonstrator vehicle covered a wide range of chemical and physical properties, the advanced engine hardware and sophisticated EMS controller provided good driveability over the EU regulatory cycle, with excellent test-to-test performance on the same fuel.

All of the engine enhancements played their part, but the CLCC approach was especially important to provide fuel flexibility and consistent vehicle performance.

Figure 4 Tailpipe NO_x and CO_2 emissions over the NEDC



Controlling the centre of combustion on a cycle-by-cycle basis allowed the engine to quickly adapt to changes in fuel properties, meeting future NO_x emissions limits without a dedicated NO_x aftertreatment system. Engine-out particle emissions were also low enough to be handled by a standard exhaust system DPF. The versatility of the demonstrator vehicle on a range of fuel types suggests that a sophisticated EMS controller, perhaps utilising in-cylinder pressure sensors, could be essential hardware for future advanced combustion engines.

In the light of today's priorities for better fuel consumption and emissions, the overall performance of the demonstrator vehicle over the NEDC was very exciting. These results suggest that even better performance and lower emissions can be achieved by ensuring that the engine, fuel and vehicle work together to meet future targets.