Advanced combustion engines for low emissions and high efficiency

CONCAWE test programme on HCCI combustion technologies

Air pollutant emissions from motor vehicles have fallen dramatically over the past two decades as a result of continuing improvements in engine and after-treatment technologies to meet lower regulated emissions limits, and in the quality of fuel used to power these vehicles. As a result, attention is increasingly focused on vehicle efficiency and fuel consumption in order to address concerns over future energy supplies and greenhouse gas emissions while maintaining, and further reducing, exhaust emissions performance. Light-duty vehicle technology is evolving rapidly to respond to these new challenges.

In the search for both improved emissions and even lower fuel consumption, engine research is increasingly directed towards advanced combustion technologies. Highly sophisticated engines using these concepts are being developed which, if commercially successful, could combine improved engine efficiency with lower air pollutant emissions from the engine, thus reducing the demand on exhaust after-treatment systems and, potentially, overall vehicle costs. Because these advanced combustion concepts combine the best features of spark-ignition and compression-ignition combustion, the optimum fuel characteristics could be quite different from those needed by today's conventional gasoline and diesel engines.

These advanced combustion concepts are often called Homogeneous Charge Compression Ignition (HCCI) or Controlled Auto Ignition (CAI)[1]. Broadly speaking, HCCI and CAI describe a wide variety of advanced combustion sequences in which fuel and air are substantially premixed before auto-ignition and the fuel is burned without spark initiation at relatively low combustion temperatures. The temperature of combustion is usually reduced further by using high levels of cooled air and exhaust gas recirculation (EGR) which also reduces the fuel/air ratio. These approaches help to limit both soot and NO_x formation during the combustion event.

The term HCCI can be used, in its most generic sense, to describe these advanced combustion engine concepts that seek to provide:

- low engine-out emissions (especially NO_x and PM);
- low fuel consumption (comparable to, or better than, today's compression-ignition engines); and
- a stable engine operation over a wide load and speed range.

In practice, the HCCI combustion mode is most easily achieved at low engine speeds and loads, and is increasingly difficult to maintain as engine speed and load increase. For this reason, the first production engines are expected to utilise 'part-time' HCCI engines, operating under HCCI combustion conditions at lower loads and reverting to conventional diesel or gasoline operation at higher load conditions. As long as this is the case, fuels used by these engines must be compatible with both operating modes.

These combustion technologies are quite new and it is not yet possible to predict how they will develop in the marketplace. Because of their potential impact upon future fuel needs, however, CONCAWE and the consulting engineers, FEV Motorentechnik GmbH worked together to investigate what advanced combustion benefits can be achieved by practical future engine hardware and how fuel properties could influence the effectiveness of these new technologies.

CONCAWE's test programme

This study began with an assessment of engine hardware options that are likely to be needed to enable future light-duty diesel vehicles to comply with future European and US regulated emissions. A timeline for new emissions

[1] Advanced combustion for low emissions and high efficiency: a literature review of HCCI combustion concepts. *CONCAWE Report 4/08*.

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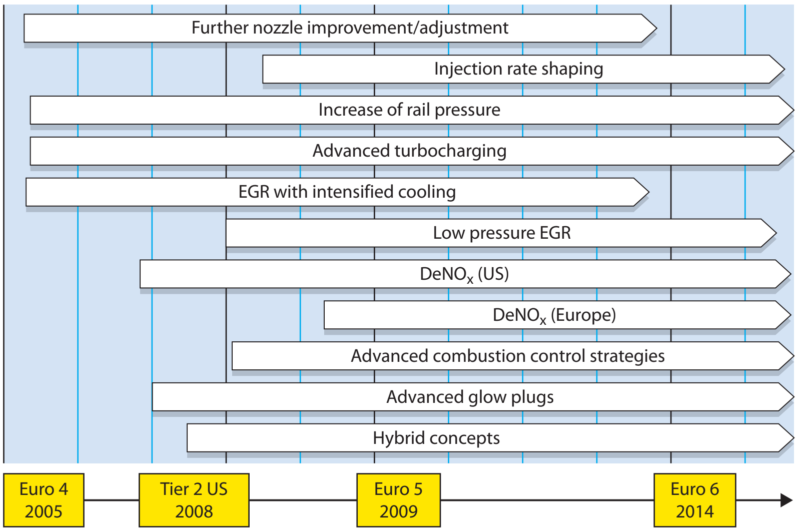
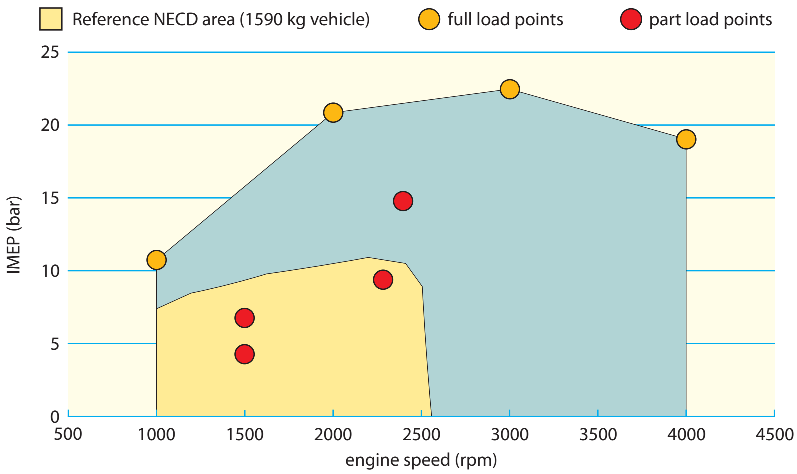
Figure 1 Potential engine hardware improvements to meet future emissions limits for light-duty diesel vehicles



limits and hardware improvements that may be important to achieve these limits is shown in Figure 1.

To explore the potential of these hardware improvements, this test programme was conducted in two parts using an advanced and highly versatile single-cylinder diesel bench engine. In the first part, different combinations of advanced engine hardware were tested in order to see how cumulative engine hardware enhancements could help to reduce engine-out emissions while, at the same time, retaining acceptable fuel efficiency and noise levels.

Figure 2 Engine speed and load points



Because this was a study anticipating engine technology in the next decade and beyond, the diesel engine was benchmarked to achieve at least Euro 6 engine-out NO_x emissions levels without the need for a separate NO_x after-treatment system. It was also assumed that Euro 5 and 6 production engines will be equipped with an HC/CO oxidation catalyst and a diesel particulate filter (DPF) to meet other emissions limits.

In the second part of the study, a broad range of fuels was investigated in the engine optimised in the first part, in order to evaluate the impact of fuel properties on overall engine performance. These fuels included practical and experimental fuels, as well as biofuel blends, and were designed to investigate fully the impact of ignition delay, volatility and molecular composition over a very wide range.

Impact of engine hardware on advanced combustion

It is generally known from the literature that HCCI combustion is facilitated by injecting fuel into the cylinder early enough in the engine cycle so that there is time to achieve thorough fuel-air mixing before combustion starts. For the first part of this study, the concept was to allow as much premixing of fuel and air as possible before combustion began, but the overall success criterion was the performance of the engine (in terms of emissions, efficiency and noise) at all speed and load conditions, not just the nature of the combustion process.

The engine and fuel studies included detailed analyses of the engine performance at eight full- and part-load conditions. The load and speed points tested in this programme are shown in Figure 2 compared to the range that is typical for the New European Driving Cycle (NEDC), the European regulated emissions cycle.

The three lower part-load points are within the range of the regulated cycle (based on a typical engine and vehicle mass) while the fourth and higher part-load point is just outside the NEDC range. This fourth point was added in order to gain information about engine performance and fuel impacts at higher loads, that may be important for real-world driving conditions and for future regulated driving cycles.

Various engine hardware enhancements were cumulatively tested in this programme for their potential to enable optimised combustion behaviour over the broadest range of engine conditions. Low engine-out emissions, fuel efficiency comparable to conventional diesel engines, and acceptable engine noise were the targets for optimised performance. All of these hardware enhancements were intended to enable more HCCI combustion by improving fuel-air mixing and simultaneously lowering the combustion temperature. These approaches included:

- a lower compression ratio;
- a higher maximum cylinder peak pressure;
- a higher maximum fuel rail pressure;
- high levels of EGR, up to 55%;
- intensified charge air cooling;
- enhanced fuel-air swirl inside the cylinder using a novel valve lift design;
- different injection nozzle configurations;
- fuel injection strategies that varied both the timing and duration of the pilot and main fuel injections; and
- adjustment of the fuel injection timing based on an in-cylinder pressure sensor.

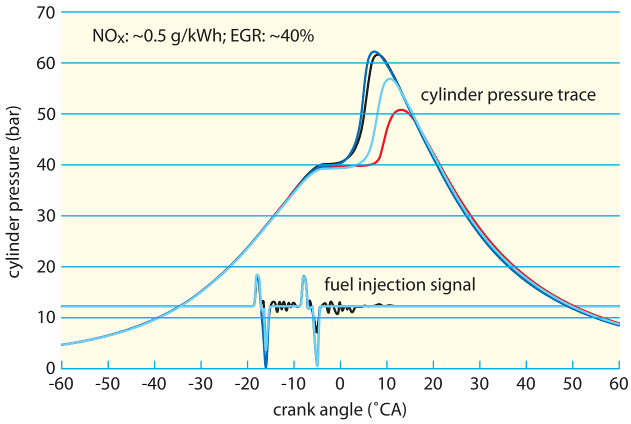
Because there were many different engine parameters to optimise simultaneously, a rigorous 'design of experiments' approach was also used to achieve optimised engine performance at each speed and load condition.

With experience, it was found that a very important optimisation requirement was a constant centre of combustion, that is, ensuring that the combustion peak pressure occurred at the same crank angle in the engine cycle. Typically, the CA50[2] was adjusted to be about 5–11 degrees crank angle (°CA) after top dead centre.

The centre of combustion was brought to the same optimum position by adjusting the fuel injection timing using the readout from an in-cylinder pressure sensor. This approach provided the best and most consistent engine efficiency and simulated the behaviour of a future engine operating with closed loop combustion control (CLCC). Figure 3 shows, for example, the effect that different fuel properties had on the centre of combustion at the same start-of-injection timing (Figure 3a) and at different start-of-injection timing (Figure 3b) for four different fuels.

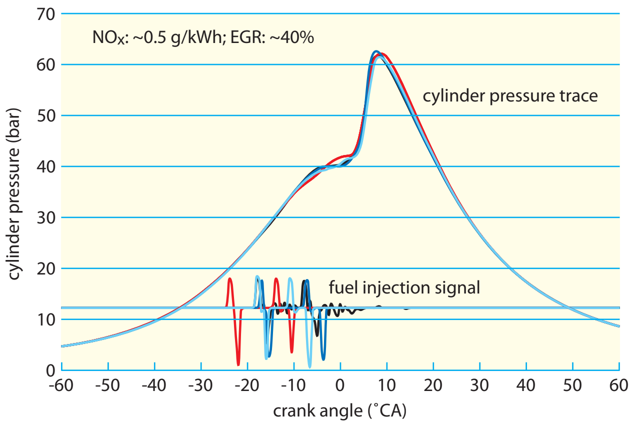
Figure 3 Pressure traces at one speed and load condition for four test fuels

a) Constant start-of-injection timing for all fuels



Lowering the fuel's cetane number delays the peak combustion pressure.

b) Different start-of-injection timing for different fuels



Adjusting the injection timing for each fuel optimises the combustion pressure.

As the cetane number of the fuel was reduced from 53 (typical of European diesel fuel) to 44 (typical of US diesel fuel), the same start-of-injection timing resulted in the combustion peak pressure occurring at a later crank angle (Figure 3a). This is to be expected, since a lower cetane number will lengthen the time between injection and the start of auto-ignition. However, an uncontrolled variation in the combustion peak pressure significantly complicates the analysis of engine versus fuel effects.

[2] *CA50 is the point where 50% of the injected fuel mass has been converted to heat.*

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In order to harmonise the combustion peak pressure for all fuels regardless of the cetane number, the start-of-injection was adjusted (Figure 3b). With this adjustment, the pressure traces now overlap for all four fuels, ensuring that fuel effects are not confounded with engine calibration effects.

Using the constant centre of combustion approach, four diesel and kerosene fuels were tested in order to study the response of the engine hardware enhancements, at optimised combustion conditions, to the fuel's ignition delay (as indicated by cetane number), volatility and molecular composition.

All of the results taken together showed that the various engine hardware enhancements enabled a significant improvement of the emissions behaviour and engine efficiency without deterioration in the engine noise. Compared with these improvements, fuel properties were found to have only a small impact on emissions, efficiency and noise.

What have we learned about engine hardware and advanced combustion?

This part of the study demonstrated that the fully warmed-up single-cylinder diesel engine could be run successfully at all full- and part-load engine operating conditions on a narrow range of four test fuels. When the centre of combustion was harmonised for all fuels, essentially the same indicated efficiency could be achieved at the same speed and load conditions.

This is an important observation because it demonstrates that the engine performance can be robust to a range of market fuel properties. Translating this strategy into future engines seems quite feasible using a CLCC approach.

At higher engine speeds and loads, conventional diesel combustion was observed for all fuels, in which the PM increased rapidly as the NO_x level was reduced. At lower engine speeds and loads, however, this behaviour was not always observed, especially for the lower cetane number and more volatile fuels. In these cases, characteristic HCCI combustion was observed, in which the PM was reduced as the NO_x level was reduced. This observation demonstrated that the hardware configuration used in this study could successfully achieve HCCI combustion, especially at lower speeds and loads. As the speed and load increased, however, all fuels tended to revert to a classic diesel combustion performance.

Using high EGR levels, very low NO_x emission levels were achieved out of the engine. In fact, the NO_x emissions were low enough that a NO_x after-treatment system would not be needed to meet Euro 6 emissions limits. PM, HC and CO were also maintained at levels that could be acceptably treated by a standard oxidation catalyst and diesel particulate filter. Other parameters of interest (noise and efficiency) were also at acceptable levels for all fuels at the full- and part-load operating points.

Impact of fuel properties on advanced combustion

Previous studies have suggested that three fuel properties are especially important to promote HCCI combustion:

- lower cetane number, in order to lengthen the ignition delay and provide time for fuel-air mixing;
- increased volatility, in order to reduce the time needed to achieve fuel-air mixing before auto-ignition occurs; and
- fuel composition, to promote combustion and reduce engine-out emissions.

Although these fuel properties were varied over a narrow range in the first part of this study, the test fuels in the second part of this study were varied over a much wider range. Because fuel parameters tend to be highly correlated, it was not possible to produce a fully orthogonal fuel matrix for all fuel properties of interest. Instead, fuel properties were changed one at a time, keeping the other properties of interest as constant as possible. The effects of fuel property changes could therefore be evaluated by comparing selected pairs of fuels.

The complete fuel matrix is shown in Figure 4 where the derived cetane number (DCN) is plotted versus the total aromatics content. In addition to marketplace fuels, specially blended and reference fuels were also tested to investigate the potential impact of fuel properties.

These fuels included a wide range of both practical and experimental fuels that were designed to investigate the impact of ignition quality (cetane number), volatility, and molecular composition on engine-out emissions and performance. Experimental fuels in the gasoline boiling range were included that are not traditionally associated with diesel engines. Two low-level biofuel blends and a blend of marketplace gasoline and diesel were also tested to look for short-term advantages and disadvantages.

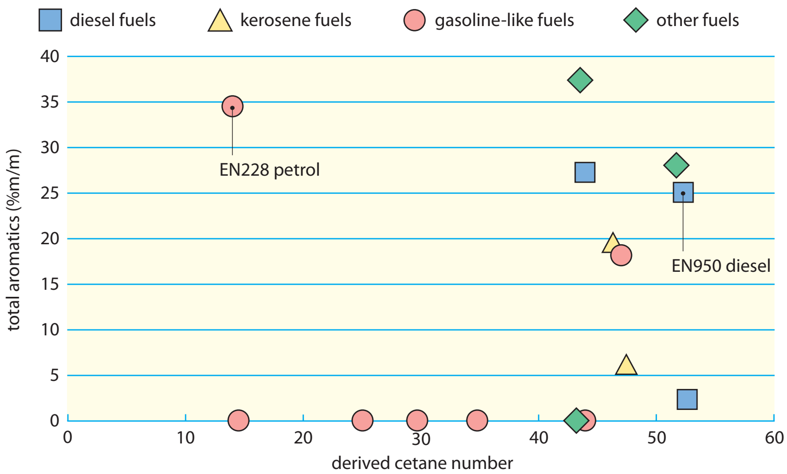
What have we learned about fuel properties and advanced combustion?

All of the results taken together showed that the optimised engine could produce acceptable engine-out emissions, efficiency and noise using a much broader range of fuel properties than tested in the first part of the study. Fuels having DCN values as high as 53 and as low as 25 could be successfully run in the optimised engine at all full- and part-load conditions. Fuel volatility changes from diesel to kerosene to gasoline-like were also accepted without engine modifications.

Because reducing PM emissions is very important for light-duty diesel engines, however, special attention was given to the impact of fuel properties on PM emissions. The results showed that the relative influence of the fuel's ignition delay, volatility and molecular composition on PM emissions appears to be different at different speed/load points. In general, increasing the ignition delay (by lowering the DCN value) was beneficial at the lower part-load points for diesel fuels but had only a moderate effect for the gasoline-like fuels.

Increasing fuel volatility from the diesel to the kerosene boiling range generally lowered PM emissions as well. Additional volatility increases from kerosene to gasoline-like fuels reduced PM emissions at the low part-load points but gave some increases at the highest part-load point. Reducing aromatics in the fuel consistently lowered the PM emissions. Although the absolute PM emissions were very low for all fuels, sizeable differences were found between the relative PM emissions for different fuels at higher EGR levels.

Figure 4 Test fuels matrix: derived cetane number (DCN) versus total aromatics



Overall conclusions

In this study, the single-cylinder diesel engine optimised with enhanced hardware and operating under simulated CLCC conditions was found to be surprisingly tolerant of fuel properties. This was the case even though the engine operated under HCCI-like conditions at low speeds and loads and under conventional diesel combustion conditions at higher speeds and loads.

This is an important observation because it suggests that a special fuel may not be essential to enable acceptable performance and Euro 6+ emissions performance on advanced combustion technology engines. When combined with the CLCC optimisation approach, engine hardware that is already in use on today's production engines in combination with commercial after-treatment technology may be sufficient. With such an engine configuration, marketplace fuels may be suitable to meet the performance needs of both today's light-duty fleet and future engines.

This study only investigated engine performance and emissions on a fully warmed-up engine and more work will be needed to ensure satisfactory engine performance under cold start and transient conditions. If these observations are validated, however, at least one critical barrier to the broad introduction of advanced combustion technology may be reduced, namely the need for a very special fuel and its associated supply and distribution infrastructure.