Running high-octane petrol in a suitably adapted engine

Concawe's modelling and vehicle testing study shows that fuels and vehicles can be optimised together to take advantage of higher-RON fuels, and achieve significant improvements in efficiency and CO_2 emissions.

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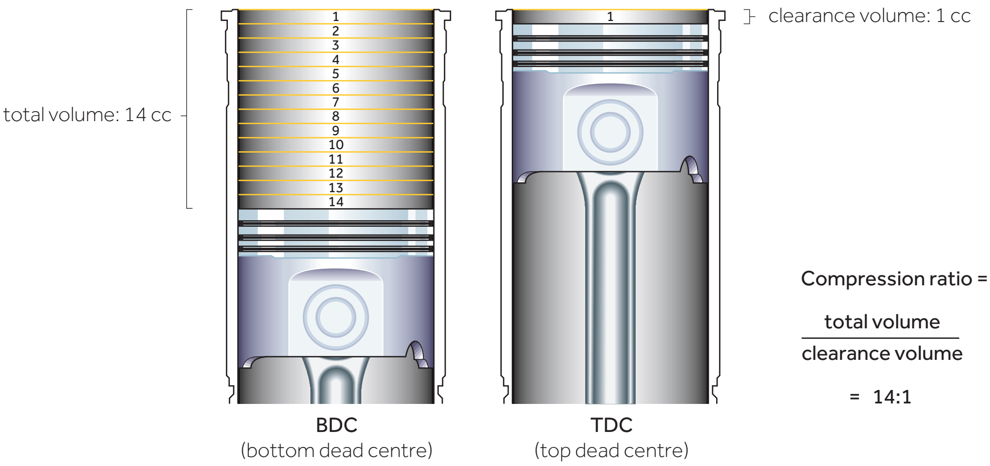
Background

Gasoline combustion has traditionally been measured using Research Octane Number (RON) and Motor Octane Number (MON) which describe the fuel's resistance to auto-ignition (commonly known as 'knock') under different conditions. All modern European gasoline cars must be capable of running on the regular 95 RON grade petrol. However, some vehicles are calibrated to be able to take advantage of higher-octane fuels available in the market, typically by advancing spark timing or increasing boost pressure, which can produce more power and, potentially, better fuel consumption. An article in the last edition of the Concawe *Review* discussed the possibility of producing higher-octane fuels from a refinery perspective using Concawe's refinery planning model.[1] The current article is the second in the series, and focuses on a modelling and vehicle testing programme conducted by Concawe to demonstrate improvements in fuel consumption for a range of higher-octane fuels in a specially adapted vehicle beyond the calibration aspects mentioned above.

In the future, gasoline engines with higher or variable compression ratios (VCRs) may be made available. While such engines are not commercially available at the present time, the concept is well-understood and demonstration engines exist.

Figure 1: Engine compression ratio — an example



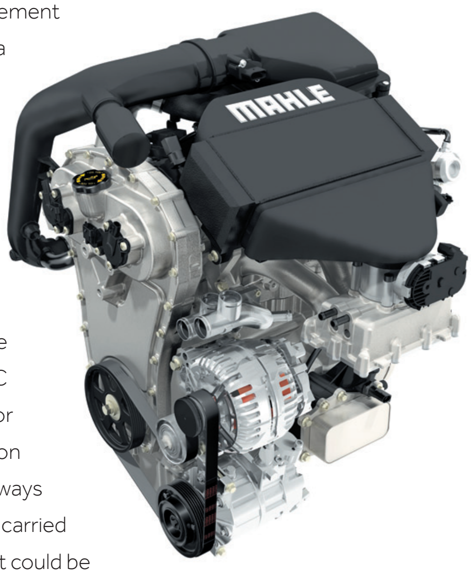
Compression ratio is calculated by dividing the total volume of the cylinder when the piston is at BDC by the clearance volume when the piston is at TDC. In the example on the right, the compression ratio would be expressed as 14:1.

The compression ratio (CR) is a measure of the compression of the air inside a vehicle piston, and is calculated by dividing the total volume of the cylinder when the engine piston is at bottom dead centre (BDC) by the volume when the piston is at the top of the stroke, i.e. at top dead centre (TDC). There are many studies in the literature which suggest that engines with higher compression ratios can take full advantage of improved thermal efficiency when run with higher-octane fuel, leading to improved fuel consumption. The downsized high-compression ratio engine used in this study was used in a previous study[2,3] and was loaned to Concawe for the programme by BP. The engine was a downsized version of a 2.0 litre engine, with a final swept volume of 1.2 litres and a compression ratio of 12.2:1 compared to that of the original engine, which was 10.2:1. The engine details are shown in Table 1 on page 5.

Table 1: Properties of the downsized high-compression engine used in the study

Number of cylinders	3
Capacity	1,199.5 cm^3
Bore	83 mm
Stroke	73.9 mm
Compression ratio	12.2:1
Maximum brake mean effective pressure (BMEP)	30 bar
Peak power	120 kW (at 5,000–6,000 rpm)
Peak torque	286 kW (at 1,600–3,500 rpm)

The results of the original BP work showed an improvement in efficiency of ~5% with a 102 RON fuel compared to a 95 RON fuel over a range of test cycles when the two compression ratios were also varied. BP's work showed that this improvement of ~5% was split into two parts: for example, in real driving conditions, a contribution of 4% was due to the RON increase while a contribution of 1.3% was due to the compression ratio increase. Interestingly, this work also showed that, when the driving conditions are less dynamic (typically the NEDC or WLTC), the RON's contribution decreases more or less as much as the compression ratio's contribution increases, so that the efficiency improvement is always ~5% whatever the driving cycle. The current study was carried out to gain a better understanding of the benefits that could be obtained with intermediate octane fuels in between the range that had been studied previously, using the same fuel formulations as those used in the aforementioned refining blending study (Concawe *Review*, Vol. 28, No. 1), i.e. 95, 98, 100 and 102 RON. A second goal of this study was to further validate these simulation results (based on engine test data) with a full vehicle demonstration.



Left: the downsized high-compression ratio engine used in the study.

Image courtesy of MAHLE Powertrain

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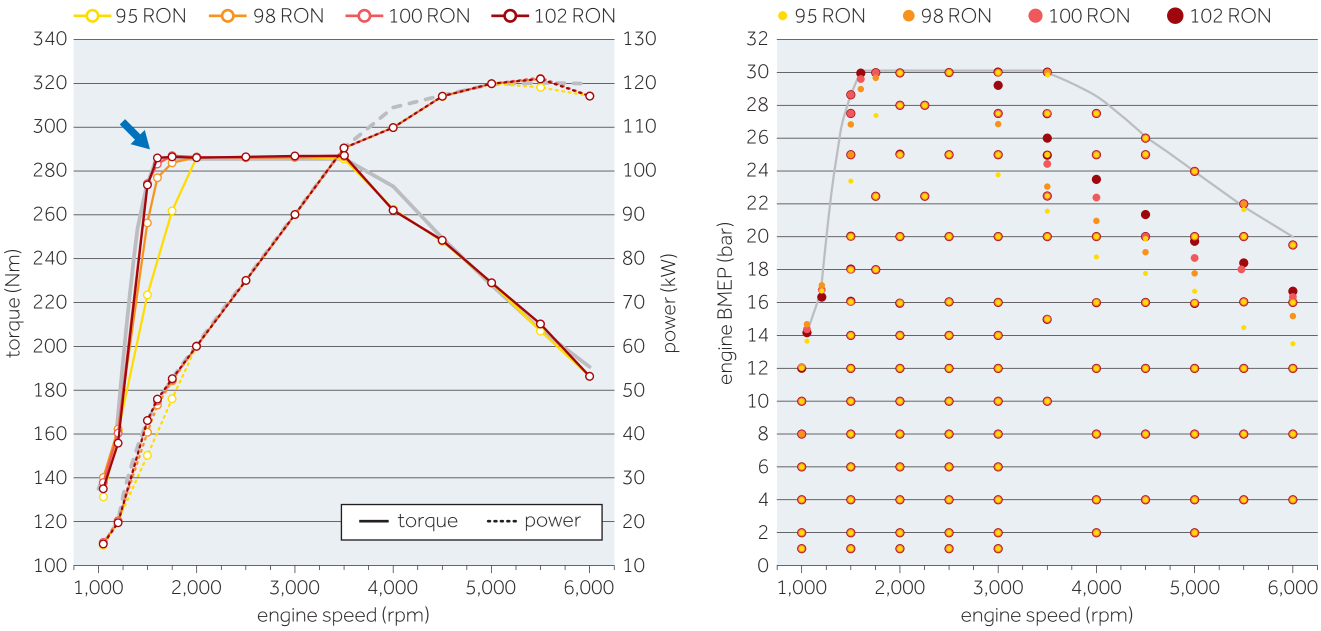
Engine testing and calibration

To ensure that the engine performs at its best with each fuel tested, it was calibrated for each fuel over the full range of speed and load points. The speed-load curves for all of the fuels are superimposed on Figure 2a, where load is expressed in terms of torque, from which it can be seen that the fuels are well matched. Figure 2b shows the speed-load points measured for each of the fuels, where load is expressed in terms of BMEP; these were kept the same wherever possible, except when fuel differences did not allow for this.

Figure 2: Speed-load curves and measured points for each of the fuels tested

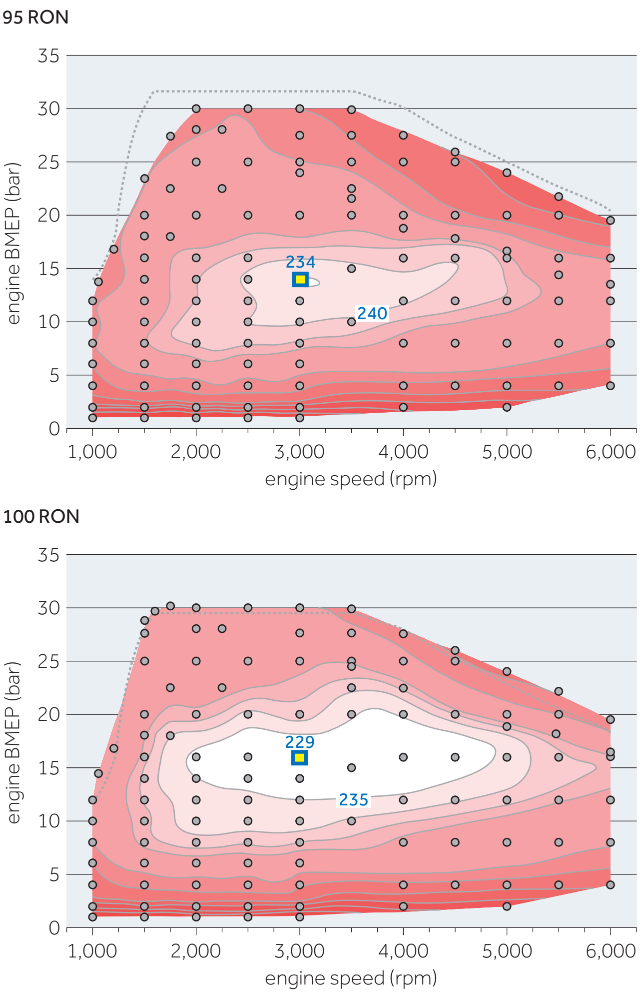
a) Speed-load curves

b) Measured speed-BMEP points



The main goal of the study was to understand the effect of octane on fuel efficiency. The contour plots shown in Figure 3 demonstrate the benefits. In this figure, the iso-contours represent the iso-BSFC (brake specific fuel consumption, expressed in g/kWh) areas. The darker tints on the figure indicate poorer efficiency (higher BSFC) and the lighter tints better efficiency (lower BSFC). As load increases and the engine becomes more susceptible to knock, by maintaining optimum spark timing over more of the operating range the higher-RON fuels enable efficient operation over a larger portion of the range. This improvement in thermal efficiency can be clearly seen by comparing the size of the central area of best efficiency shown on Figure 3 for each fuel grade. On viewing the upper right portion of each chart, it is apparent that RON plays a key role in improving efficiency at high engine speeds and loads, due to earlier ignition timing. While overfuelling is used in the engine to protect exhaust system components, advancing the ignition timing reduces the extent to which this option needs to be used.

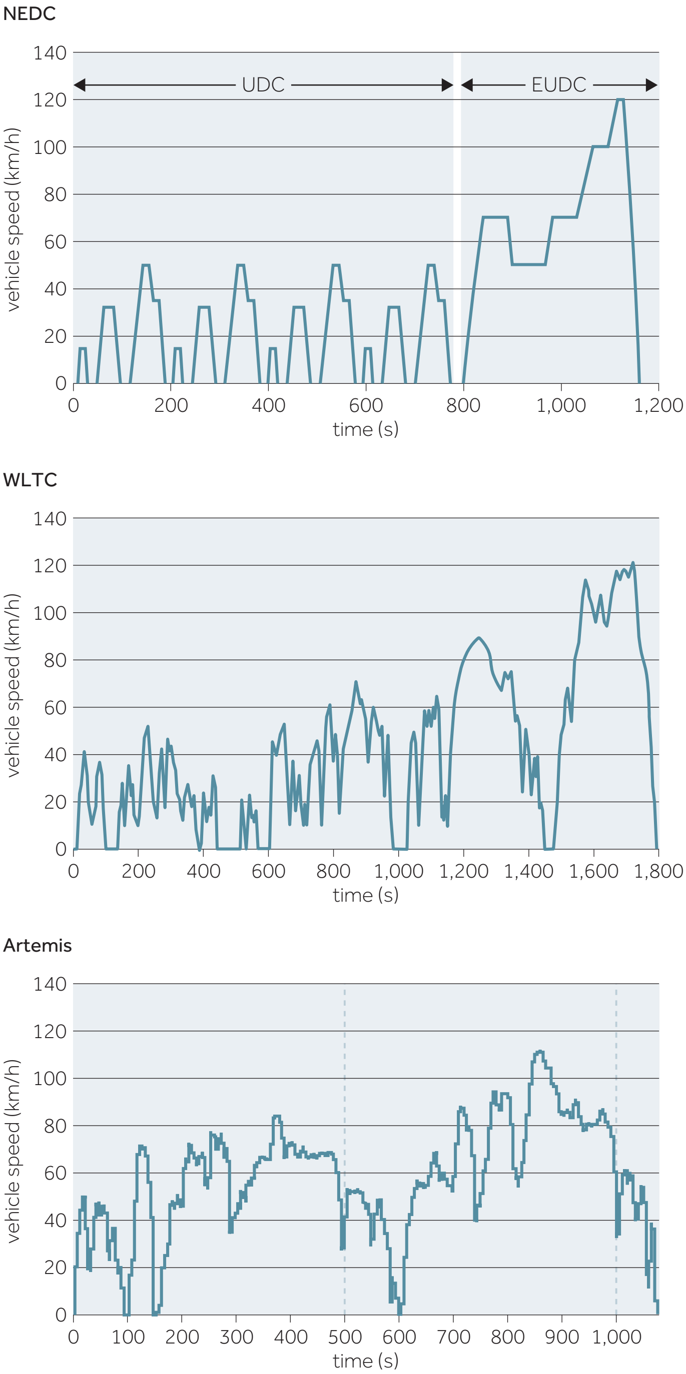
Figure 3: Contour plots of BSFC for different fuels



Drive cycles and modelling

Four test cycles were chosen for modelling. The NEDC (New European Drive Cycle) is the test cycle which, historically and until recently, was used for the homologation of vehicles. It consists of two parts—the urban drive cycle (UDC), and the extra-urban drive cycle (EUDC) which has higher speeds and less transience than the UDC. The Worldwide harmonized Light-duty Test Cycle (WLTC) contains a mix of far more realistic driving characteristics and range of speeds than the NEDC, and has been developed to replace the NEDC in vehicle homologation testing. In addition to these two test cycles, two higher-load test cycles were used: (i) the Real Driving Emissions (RDE) test cycle performed on a chassis dynamometer, which mimics a real route on roads around Northampton UK, the home of the MAHLE Powertrain headquarters; and (ii) the Artemis cycle, an older cycle that was also designed to mimic the more transient operation of on-road use. The NEDC, WLTC and Artemis cycles are shown in Figure 4 on page 8.

Figure 4: The NEDC, WLTC and Artemis chassis dynamometer test cycles

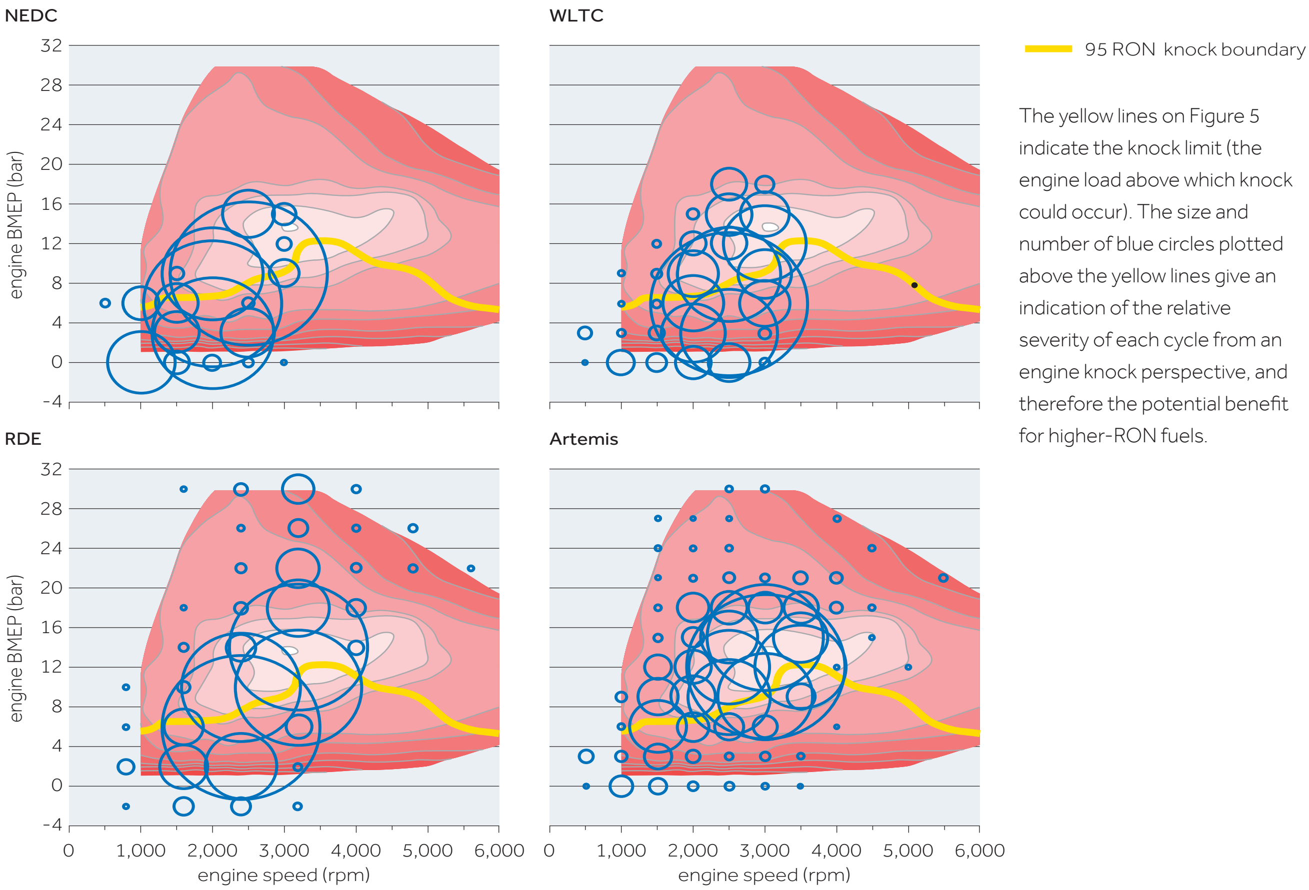


A vehicle simulation was performed using GT-Drive software, a dynamic model which was an updated version of the model used in a previous study.[4] The software enables virtual 'vehicles' to be built and tested over different drive cycles to evaluate fuel consumption and pollutant emissions. To produce a representation of the engine, the GT-Drive model uses the map of measured fuel flow rate against engine speed and load. This map is obtained from dynamometer measurements on the real engine taken during steady-state operation, under fully warm engine conditions, as described above. Full-load and friction curves are also measured and implemented as a function of accelerator position. A 'virtual driver' was constructed and used to generate the required system inputs such as throttle, brake, clutch and gear selection signals, to follow the time-speed profiles of the various drive cycles investigated. This 'virtual driver' looks one time-step ahead (around 0.25 seconds) and calculates the torque necessary to achieve the required vehicle acceleration in order to match the requested future vehicle speed. The calculated torque request is passed on to the engine or brake parts of the model. To account for changes in speed and cold-start fuelling characteristics of the real engine, a number of correction tables and equations are implemented into the model.

The inputs required for the creation of the model combine parameters related to vehicle specifications used for driving resistance and powertrain data for efficiency, torque and energy flow while delivering the power demanded. Vehicle specifications were either obtained via manufacturers' information or from direct measurements, and were finely adjusted so that road loads, such as aerodynamic drag and wheel rolling resistance, could be accurately represented. To capture the actual energy losses for the vehicle under evaluation, a vehicle coast-down test was performed, and the measured driving resistance employed in the correlated model for the technology and fuel assessment over the selected drive cycles.

The speed-load plots in Figure 5 demonstrate the benefits that can be achieved through the use of higher-octane fuels. The yellow lines indicate the knock limit (the engine load above which knock could occur with standard gasoline), and the position (speed-load coordinate of the operating point) and size (frequency of occurrence) of blue circles plotted above the line give an indication of the relative severity of each cycle from an engine knock perspective, and therefore the potential benefit for higher-RON fuels. These benefits translate to the drive-cycle fuel efficiency for each fuel and cycle combination presented in Table 2.

Figure 5: Speed-load plots for different test cycles



The yellow lines on Figure 5 indicate the knock limit (the engine load above which knock could occur). The size and number of blue circles plotted above the yellow lines give an indication of the relative severity of each cycle from an engine knock perspective, and therefore the potential benefit for higher-RON fuels.

Table 2: Simulated fuel consumption for each fuel and driving cycle

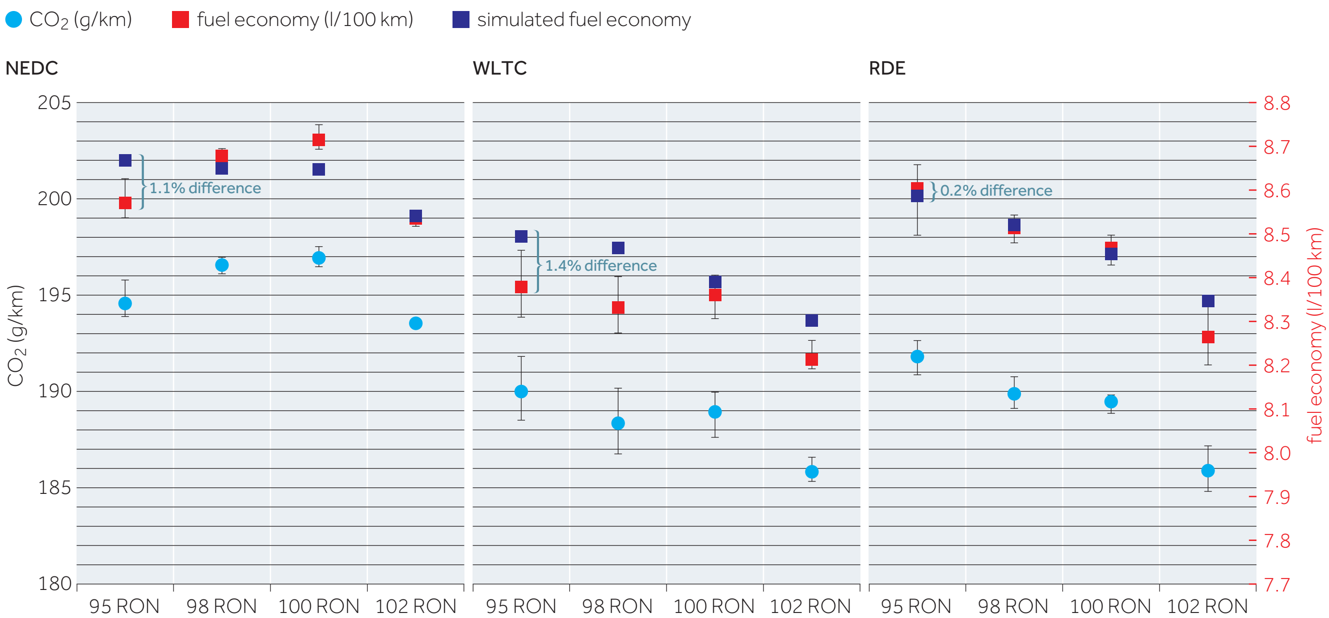
	95 RON	98 RON	100 RON	102 RON	95 RON	98 RON	100 RON	102 RON
Drive cycle	litres/100 km				% improvement vs 95 RON			
NEDC	7.078	7.062	7.019	6.954	-	0.22	0.83	1.75
WLTC	7.663	7.640	7.552	7.486	-	0.29	1.44	2.3
RDE	8.129	8.022	7.927	7.827	-	1.32	2.48	3.72
Artemis	8.34	8.245	8.168	8.075	-	1.14	2.06	3.17

Fuel economy benefits associated with an increase in RON from 95 to 102 of between 1.75% and 3.72% were simulated, with the lowest benefit being seen over the NEDC drive cycle, and the greatest over the chosen RDE cycle. For the NEDC cycle, the engine operates at BMEP levels below the knock limit threshold for most of the cycle, and therefore the effect of higher RON fuels is relatively small. The WLTC cycle is operated at slightly higher loads, although the greater part of the cycle is still below the 95 RON knock limit. In addition, both the RDE cycle and the Artemis cycle operate at significantly higher loads compared to the NEDC or the WLTC cycles and, therefore, showed fuel economy improvements when higher RON fuels were used due to less overfuelling needed than for lower RON fuels. These results are qualitatively and quantitatively consistent with those obtained in BP's work. They also demonstrate that the efficiency gain increases continuously with the RON increase, meaning that each step increase in RON between RON 95 and RON 102 is beneficial to fuel consumption for this high compression ratio engine. As far as the real driving conditions are concerned, a gain of 1.3% can be added due to the compression ratio increase from 10.2:1 to 12.2:1 as demonstrated in BP's work, leading to a ~5% fuel consumption benefit, which is again consistent with BP's results.

Vehicle testing

Following the completion of the engine test-bed testing and modelling phase, the engine was fitted within the chassis of a D/E segment car for chassis dynamometer testing. This vehicle was originally equipped with a 2.0 litre, turbocharged direct-injection engine of similar performance to the test engine. The vehicle was tested using three out of the four simulated test cycles—NEDC, WLTC and RDE—on the chassis dynamometer (rolling road). The RDE test cycle chosen was the same as that used for the modelling exercise for direct comparison, and was chosen as it represented an average cycle in terms of those available for all the fuels tested. Figure 6 shows the carbon dioxide (CO_2) and fuel economy results for the measured test cycles.

Figure 6: Measured CO_2 and fuel economy results versus simulated fuel economy results



In each case, the results shown are the average of each of three repeats, and the bars show the range of data round the average points. Both the WLTC and the RDE showed downward trends as RON increased, with no overlap between the results from the 102 RON fuel and the other fuels. The NEDC results were less clear, but were consistent with the modelling, and in line with the residency maps including the amount of time spent in low-load versus high-load conditions. The modelled fuel economy results are also superimposed on the charts, and it can be seen that the NEDC modelled result at 95 RON appears to follow the same trend as the others. In general the difference between the modelled and measured results was around 1.5% and below, which was considered to be very good, with the lowest difference in the RDE results and the biggest difference with the WLTC, which was more similar to the NEDC.

Conclusion

These results add to an increasing body of data which shows that when fuels and vehicles are optimised together to take advantage of higher-RON fuels, significant improvements in efficiency and CO_2 emissions can be demonstrated, particularly under high-load and real-driving conditions. They also add to our understanding of how vehicles and fuels together can play a role in meeting future CO_2 targets.

Acknowledgements

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References

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