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Testing and modelling the effect of high octane petrols on an adapted vehicle

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Testing and modelling the effect of high octane petrols on an adapted vehicle

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ABSTRACT

Gasoline combustion has traditionally been measured using Research Octane Number (RON) and Motor Octane Number (MON) which describe antiknock performance under different conditions. All European gasoline cars must be capable of running on the 95 RON petrol grade, 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 allows more power and perhaps also better fuel consumption. In the future vehicles may be made available which have increased or variable compression ratio which can fully take advantage of higher octane but these are not commercially available at present. This engine modelling and vehicle testing study was carried out to understand the effect of high octane fuels on the efficiency of a downsized higher compression ratio engine.

KEYWORDS

Octane, RON, higher compression ratio, modelling

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SUMMARY

Concawe has previously undertaken and published the results of two studies aimed at understanding the relationship between octane and the performance and efficiency of mainstream Euro 4 to Euro 6 vehicles. Whilst the performance and efficiency of these vehicles showed some small relationship to octane, it was important to note that most of these vehicles were not calibrated to take full advantage of fuels with a Research Octane Number (RON) in excess of 95.

To assess the full potential for higher octane fuels to lower vehicle CO_2 output and fuel consumption when measured over current legislative drive-cycles, a test-bed and vehicle study was carried out using a highly downsized (30 bar BMEP), high compression ratio (12.2:1) engine with a series of 4 fuels with RON numbers ranging from 95 to 102. This high compression ratio is higher than the one of the baseline engine (10.2:1), and is enabled by the antiknock properties of the high RON fuels.

Prior to measurement, the engine was calibrated specifically on each fuel over the full engine map. This ensured that the engine would experience the maximum benefit from changes in fuel properties. Based on these test-bed data, a GT-Drive model has been used to predict the CO_2 emission and fuel consumption over the New European Drive Cycle (NEDC), the Worldwide harmonised Light-duty Test Cycle (WLTC) and multiple Real Driving Emissions (RDE) cycles of differing severity.

The engine was subsequently fitted to a D-segment vehicle and NEDC, WLTC and RDE cycles were performed in order to validate modelled efficiency improvements. These vehicle tests demonstrated:

- A fuel consumption benefit of up to 3.9% for the RON 102 fuel relative to the baseline 95 RON fuel in real driving conditions on the high compression ratio engine;
- A linear improvement in the fuel consumption benefit between RON 95 and RON 102, meaning that each RON increase between these two values is beneficial to fuel consumption.

Adding the benefit of the compression ratio increase from 10.2:1 to 12.2:1 allowed by the fuel's antiknock behaviour, the fuel consumption benefit reaches up to ~5% according to data found in the literature.

1. INTRODUCTION

1.1. GENERAL BACKGROUND AND OBJECTIVES

Gasoline knocking tendency has traditionally been measured using Research Octane Number (RON) and Motor Octane Number (MON) which describe antiknock performance under different conditions. All European gasoline cars must be capable of running on the 95 RON petrol grade. However, some vehicles are calibrated to be able to take advantage of higher octane fuels available in the market, typically by advancing spark timing and/or increasing boost pressure which increases potential torque production per work stroke and perhaps also improves fuel consumption. In the future, more vehicles may be made available which have increased or variable compression ratio which can fully take advantage of higher octane. These are starting to be commercialized in some markets. Historically, increasing both RON and MON have been considered beneficial. However, a large body of more recent literature suggests that while increasing RON still gives benefits in modern production cars, MON is less important and in fact lowering MON at the same RON level could improve vehicle performance [12].

It is now generally recognised that minimising energy consumption and CO2 emissions in transportation needs consideration of both fuel production and vehicle efficiency, combining these factors into a 'well-to-wheels' approach. For the future, higher octane fuels could potentially be used by engine designers to improve fuel efficiency using higher compression ratios, boost pressures, and other techniques. This needs to be balanced against the additional energy needed in the refinery to produce higher octane. For this reason, the optimum octane number for future fuels will come under discussion and the correct balance between RON and MON is clearly part of this process. However, such consideration of future vehicle possibilities cannot be addressed by testing vehicles in the market. Concawe carried out a study to address these considerations, the first phase of which was reported during 2016 and the subject of several papers [1], [2] and a Concawe report published in 2016 [3].

The first phase of this study was to investigate the effect of RON and MON on the power and acceleration performance of two Euro 4 gasoline vehicles under full throttle acceleration conditions. Fifteen fuels covering RON levels 95 to 103 and sensitivities (RON minus MON) up to 15 were blended and tested in the vehicles on the chassis dynamometer. Both pure hydrocarbon and oxygenate blends containing ethanol or ETBE were included so that any specific effects of oxygenates could be identified. Three additional fuels, covering RON as low as 86, were blended using primary reference fuels. The results confirm the findings of previous studies on older vehicles that MON is not a good predictor of vehicle acceleration performance and in fact high MON levels increase acceleration time under full throttle conditions. Both vehicles were tolerant of fuels in the 95-98 RON range, but reductions in performance were seen on lower octane fuels.

It was found that neither RON nor MON had an effect on the efficiency of the vehicle on the NEDC cycle, suggesting that either knock does not occur under these lighter load conditions, or that adaptations to knock are not severe enough to impact engine efficiency. Under more extreme full throttle acceleration conditions, efficiency deteriorated with the lowest RON fuels tested as expected as the engine adapts to knock. It was also observed that efficiency increased as RON of the fuels increased for both vehicles.

A follow-on study screened a wider range of more modern Euro 5 and Euro 6 vehicles [4], [5]. Two vehicles were selected for further evaluation of the full set of 22 fuels, again measuring acceleration performance at full load on a modified version of the test cycle used for the previous study. Both vehicles showed a strong appetite for octane in the range 86 < RON <95, with one vehicle also showing some further benefit beyond 95. Fuel consumption improvements were observed with increasing RON with this particular vehicle under steady state conditions see figure 1. Other researchers have also made similar observations for other vehicles [6]. In that study, in Euro 4 vehicles, there was an average increase of 0.35% in efficiency per RON number increase under slow speed/medium load conditions and 0.75% per RON number increase under high speed/high load conditions. The most responsive vehicles showed efficiency improvements of more than twice these averages. The fuels tested in this study ranged from 92 to 98 RON and the recommended RON of the vehicles ranged from 93 to 97 RON.

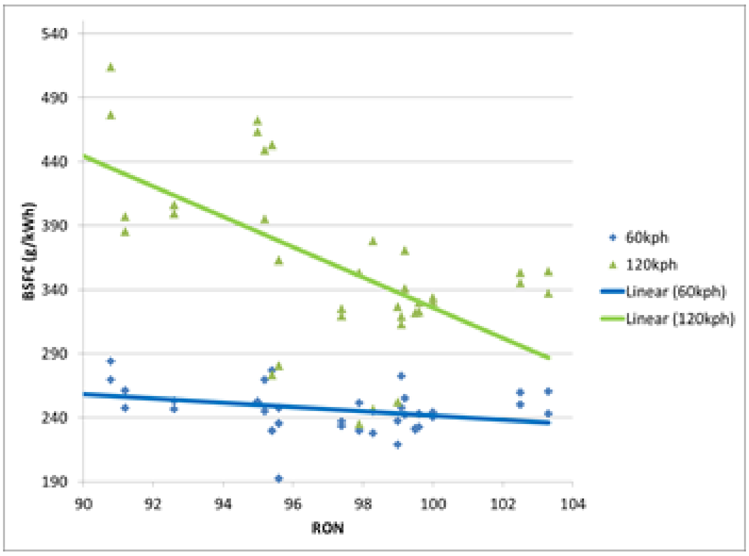


Figure 1. Brake Specific Fuel Consumption (BSFC) versus RON for two steady state conditions

The one Concawe vehicle mentioned above which showed a benefit beyond 95 RON was also tested for efficiency and regulated emissions on the WLTP and the US06 legislative test cycles. The vehicle was tested over the two legislative drive cycles on three fuels, to understand how the benefits, attributed to octane, at full-load would translate to vehicle efficiency over a representative drive cycle. Directional improvements were seen beyond the expected octane benefit, particularly for the WLTP test cycle where the vehicle appeared to show benefits up to beyond 99 octane. For the US06, some benefit was also seen up to 98 octane.

A criticism of these previous studies was that as marketplace vehicles are typically calibrated for 95 RON or occasionally 98 RON fuels, benefits of fuels with higher RON values would not be expected to show any further benefit in terms of power or efficiency. However, as described above in the Concawe programme, at least one vehicle, under one test cycle, and under the steady state segments of another appeared to show an improvement and multiple vehicles showed improvement in other work. In the current study, to test the maximum efficiency benefit afforded by an increase in octane, a downsized engine with high compression ratio was tested on a series of 4 test fuels after being calibrated specifically on each fuel.

1.2. TECHNICAL BACKGROUND ON OCTANE

Octane number is a measure of a fuel's resistance to auto-ignition. Gasoline spark-ignited engines need a high octane fuel under certain operating conditions to avoid knock. This is in contrast to diesel engines, which rely on auto-ignition and so require a low octane (or high cetane number) fuel. The octane number of a fuel is measured in a special test engine known as a CFR engine, which is a single cylinder test engine with variable compression ratio dating from 1928. Although the test has been progressively improved over the years, the basic engine configuration and test conditions remain the same. Tests in the early 1930s demonstrated that the knocking behaviour of fuels in vehicles of that era did not correlate with the measured Research Octane Number, therefore a new, more severe, Motor Octane Number was developed. Both methods are still in use today.

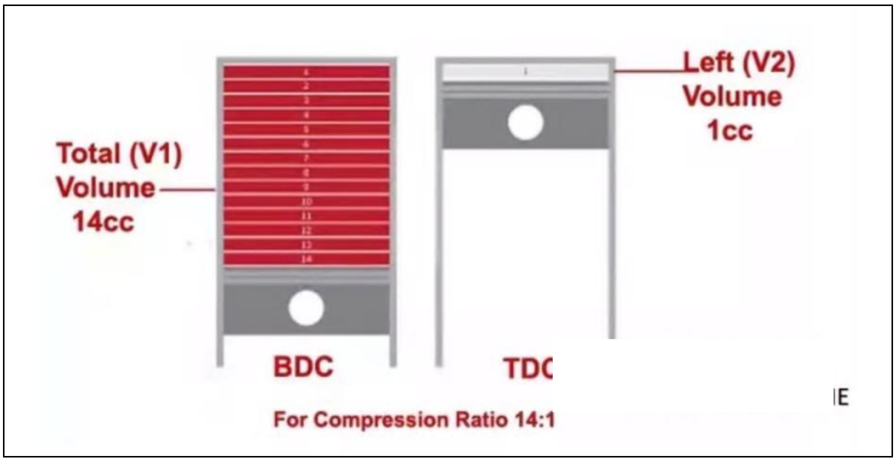
Research Octane Number (RON) is measured at a speed of 600rpm with a specified intake air temperature of 52°C and is traditionally associated with mild to moderate driving conditions [7]. Motor Octane Number (MON) was introduced to simulate more severe higher load conditions and uses a higher engine speed of 900rpm and a governed charge temperature of 149°C. The MON of a fuel is typically about 10 numbers lower than its RON, although the difference between RON and MON varies with fuel composition [8].

A fuel's octane number is determined by comparing its performance in the engine with a blend of pure compounds: iso-octane, defined to be 100 octane and n-heptane, defined to have zero octane number. Although the engine test conditions, especially the engine speed, seem far from typical of today's engines, octane number has proved a valuable measure of fuel quality up to the present. Fuel specifications usually set minimum requirements for both RON and MON. In most parts of the world, RON is the primary measure of gasoline octane at the point of sale. In the USA, Canada and some other countries, a different system is used where the octane measure displayed at the point of sale is the Anti-Knock Index, defined as (RON+MON)/2.

How an individual road vehicle responds to octane number depends on the details of its engine design and calibration. The 'octane requirement' of a vehicle has traditionally been determined by testing under acceleration or steady speed full load conditions, either on the road or on a chassis dynamometer. By running on a series of specially blended test fuels of varying octane number, the lowest octane number that will run in the vehicle without knock can be determined. In the past, large numbers of vehicles were tested in co-operative industry programmes in Europe and the USA to build up a picture of the road vehicle fleet, so that the octane number of fuels sold could be matched to the needs of the vehicle fleet. More recently, the octane numbers are determined purely by the fuel specification and vehicles are developed to operate on them. However, a growing body of vehicle test data shows that the traditional expectation that RON correlates with mild operating conditions and MON with more severe driving no longer holds particularly in boosted downsized engines which may be representative of future vehicles [9], [10], [11].

1.3. OCTANE APPETITE AND COMPRESSION RATIO

In the future more vehicles may be made available which have increased or variable compression ratio (VCR). These engines are starting to become commercially available in some markets. Compression ratio (CR) is a measure of the compression of the air inside a vehicle piston by calculating the ratio of the total volume when the engine piston is fully extended at bottom dead centre (BDC), compared to the remaining volume when the piston is fully at the top of the stroke or top dead centre (TDC) i.e. CR = V1/V2.



Source: Based on Jalopnik.com

Figure 2. Description of compression ratio

There are many studies in the literature that show that increasing compression ratio generally increases thermal efficiency, but will also increase the appetite for RON. These efficiency benefits may grow, should the engine calibration be modified to take full advantage of higher RON fuels. CRC published an extensive literature study in 2011/12 [12], [13] which suggests that improvements of 1.8 – 4% vehicle efficiency for port fuel injected and direct injected engines can be obtained on the basis of a compression ratio increase of 1.0 number and fuel with increase of 4 – 5 octane numbers. The same study suggested that turbocharging could give even greater benefits (5 – 7%) although increasing the compression ratio is more cost effective as suggested by an ICCT publication [14]. A US modelling study [15] makes the assumption that one unit increase in compression ratio coupled with an increase in RON from 98 to 102 would result in 4.45% improvement in fuel economy for non-turbocharged SI engines and up to 7.34% for turbocharged engines. These assumptions were made from a combination of GT-Power modelling substantiated by a literature review. Other studies suggest the relationship between efficiency and octane number is linear for turbo-charged engines. More recent work using a higher compression engine was done as part of an EC-funded programme and reported in June of 2019 [16]. This programme was focused on the technical feasibility of E20 or E25 although there were some lower oxygenate fuels tested for reference. Three of the four vehicles were Euro 6 in series-production configuration, the fourth vehicle was a prototype having increased compression ratio and adapted calibration to utilize the full potential of high-RON, high Ethanol fuel grade, and of the same make as one of the series-production vehicles. The conclusions from that work was that, in terms of CO_2 emissions reduction, majority of test results on both, the series-production vehicles as well as the prototype vehicle, indicate a 1% improvement potential. Only few WLTC test cycle measurements indicated a 4 % improvement using RON 102 gasoline (E20) on series production vehicles calibrated for 95 RON (actual market vehicles) in comparison with the RON 95 E10 reference fuel. It was stated that the efficiency benefit could only be increased to up to 7% if the vehicle had an increased compression ratio and optimum calibration for 102 RON and operating under more demanding RDE driving conditions. Most of the fuels tested contained high levels of oxygenates, although the non-oxygenate containing fuel of 102RON also showed improvements with the adapted vehicle when compared with the reference fuel and on one of the other non-adapted vehicles.

The downsized, high compression ratio engine used in the current Concawe study was used in a previous study [17, 18] and was loaned to Concawe for the programme by BP. In the previous programme conducted by Mahle (based in Northampton, UK who also conducted the current programme) an efficiency improvement of ~5% was measured over a variety of test cycles for a 102 RON fuel and an engine compression ratio of 12.2:1 compared to a 95 RON fuel with an original compression ratio of 10.2:1. BP's work showed that the 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 to the engine's efficiency improvement decreases more or less as much as the compression ratio's contribution to its efficiency increases, so that the efficiency improvement is always ~5% whatever the driving cycle. For instance, on a NEDC, which is the less dynamic driving cycle, the RON increase contributes to an improvement of the fuel consumption by 1.8% (lower than the 4% demonstrated in real driving conditions) and the compression ratio increase by 3.4% (higher than the 1.3% in real driving conditions), with still an overall gain of ~5%. In that programme the two fuels tested had 1.7 and 2.3% oxygen content respectively so were both within the current EN228 E5 specification. The current programme was designed to extend work into fuels in between the upper and lower RON values used in the previous programme.

2. TEST PROGRAMME

The objective of the current programme was to study the effect of RON on a downsized, high compression ratio engine using fuels with RON from 95 to 102. The programme was to involve engine modelling and fired-engine and vehicle testing over a range of simulated and real driving test cycles to understand and validate the linearity of the octane response between the lower and upper octane range. A second objective of this study was to further validate previously developed simulation results (based on engine test data) with a full vehicle demonstration.

2.1. PROGRAMME OVERVIEW

In the current study, testing took place in two distinct stages. Firstly, the engine was fitted by Mahle to a test-bed, where it was calibrated and its efficiency and emissions were measured over a range of operating conditions. These data were then used as inputs in a vehicle drive-cycle simulation. Multiple cycles of increasing severity were calculated.

In the second segment of testing, the engine was fitted into a D segment vehicle. This vehicle was subsequently tested over the same drive cycles to validate the simulation model.

2.2. ENGINE SELECTION AND CONSIDERATIONS

A 3-cylinder, turbocharged, direct-injection engine was chosen to undertake this study. This engine had been used in previous studies [19], [20], [21] and had shown itself to be sensitive to RON. Since it uses a fully flexible engine control unit (ECU), it was possible to calibrate the engine for optimum performance on each fuel.
A compression ratio of 12.2:1 was considered to be appropriate for a future-looking engine with >30bar BMEP. The engine was fitted with a solenoid actuated, multi-hole direct injector and cam phasers on intake and exhaust.

Cylinders	-	3
Capacity	cm^3	1199.5
Bore	mm	83
Stroke	mm	73.9
Compression Ratio	-	12.2:1
Maximum BMEP	bar	30
Peak Power (speed)	kW	120 (5000-6000 rpm)
Peak Torque (speed)	Nm	286 (1600-3500 rpm)

Table 1. Key engine specifications

2.3. TEST FUELS DEFINITION AND BLENDING

This test programme was run in parallel with a refinery study carried out by Concawe which will be published as a separate report. In that study the consequences for an average refinery, in terms of producing petrols of various RON and MON were studied including use of the Concawe LP blending model.

Four fuels were selected for use in this programme, these fuels were blended to meet RON and MON targets whilst other physical properties were kept consistent wherever possible. The LP model was used to define the components for “virtual” fuels, the blend recipes for which were mimicked in producing the “real” fuels. These fuels were consistent with EN228, the European specification for forecourt gasoline. The target RON ranged from 95, typical for regular grade gasoline in Europe, through 98, 100, and 102, which is the highest RON fuel currently available at an EU forecourt. As the focus for the study was octane rather than oxygenates, the blends were kept at an E5 equivalent level of oxygen content, which is about the average value used in Europe at the moment.

Properties	95RON	98RON	100RON	102RON
Specific gravity	0.7520	0.7531	0.7509	0.7515
RON	95.4	98.3	99.9	102.0
MON	86.2	88.3	88.9	90.7
Olefins, vol%	2.3	4.4	3.3	6.7
Aromatics, vol%	33.1	33.1	33.1	34.2
Benzene, vol%	0.91	0.92	0.92	0.86
Oxygen, wt%	2.09	2.07	2.06	2.09
RVP, kPa	55.7	57.3	56.7	52,5
Evap. @70°C, vol%	29.5	27.1	26.4	26.4
Evap. @100°C, vol%	53.6	49.8	47.5	47.4
Evap. @150°C, vol%	94.4	94.3	93.9	94.1
LHV, GJ/T	42.2	42.3	42.1	42.3

Table 2. Key fuel properties

3. TEST METHODOLOGY

3.1. ENGINE CALIBRATION AND TESTING

To ensure best performance was achieved on each fuel, the engine was fully calibrated over a range of steady-state speed and load points. Parameters optimised at each mapping point included spark-timing, cam-phasing, boost-level and lambda.

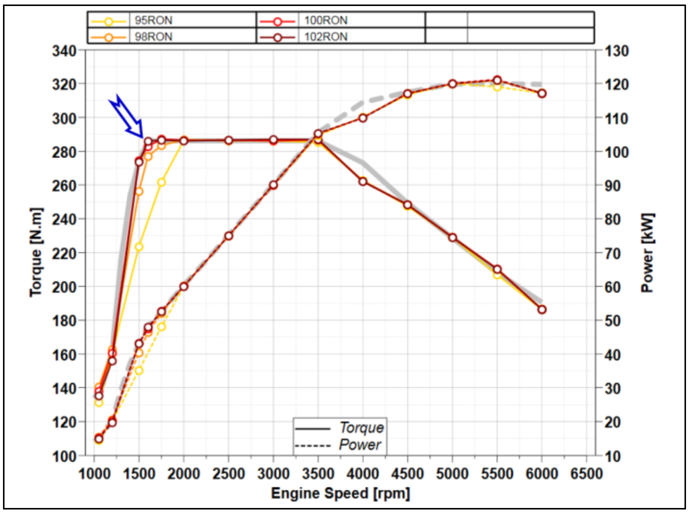


Figure 3. Chart of power and torque output for all fuels.

A requirement for this study was to ensure that similar vehicle performance was achievable on each of the test fuels. Figure 3 shows the power and torque curves for the engine with each fuel, the grey lines show the coding i.e. dashed lines for power and solid lines for torque. The only noticeable deviation can be seen during low speed, high load operation, where the 95 RON fuel became knock-limited and thus was unable to achieve the same operation points. At higher load and speed conditions, particular care was required to ensure that the exhaust gas temperature did not exceed the material constraints of any of the exhaust system components.

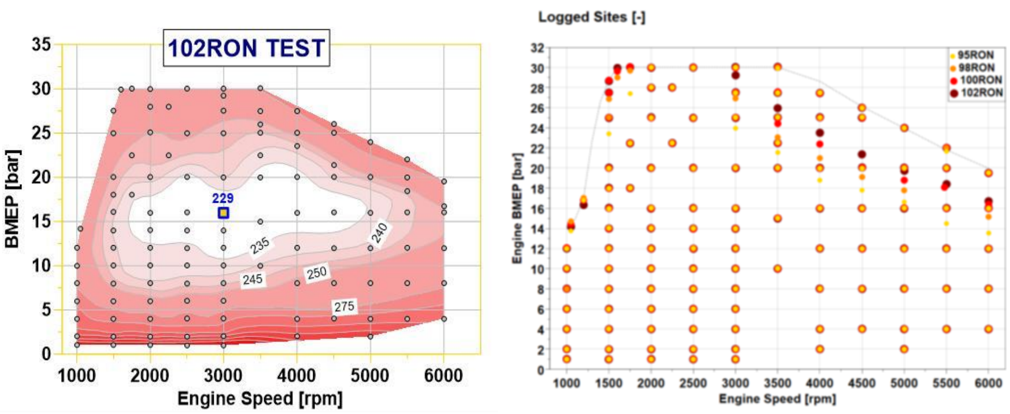


Figure 4. Speed vs Load map of a) calibration and b) logging points for all fuels.

Wherever possible, the performance of each fuel was measured at the same speed and load point, as shown in the right chart of Figure 4. It was only when a significant difference in knock-susceptibility was experienced that it became inappropriate to measure data at identical test conditions. Measurements included key engine temperatures and pressures, together with heat-release analysis on all cylinders.

Regulated emissions measurements (i.e. NOx, PM, HC, CO, CO_2,) were also recorded but are not reported here. Using this data, speed-load maps were created for each fuel type, which could then be used within a 1-D model to predict vehicle fuel consumption over a variety of drive cycles.

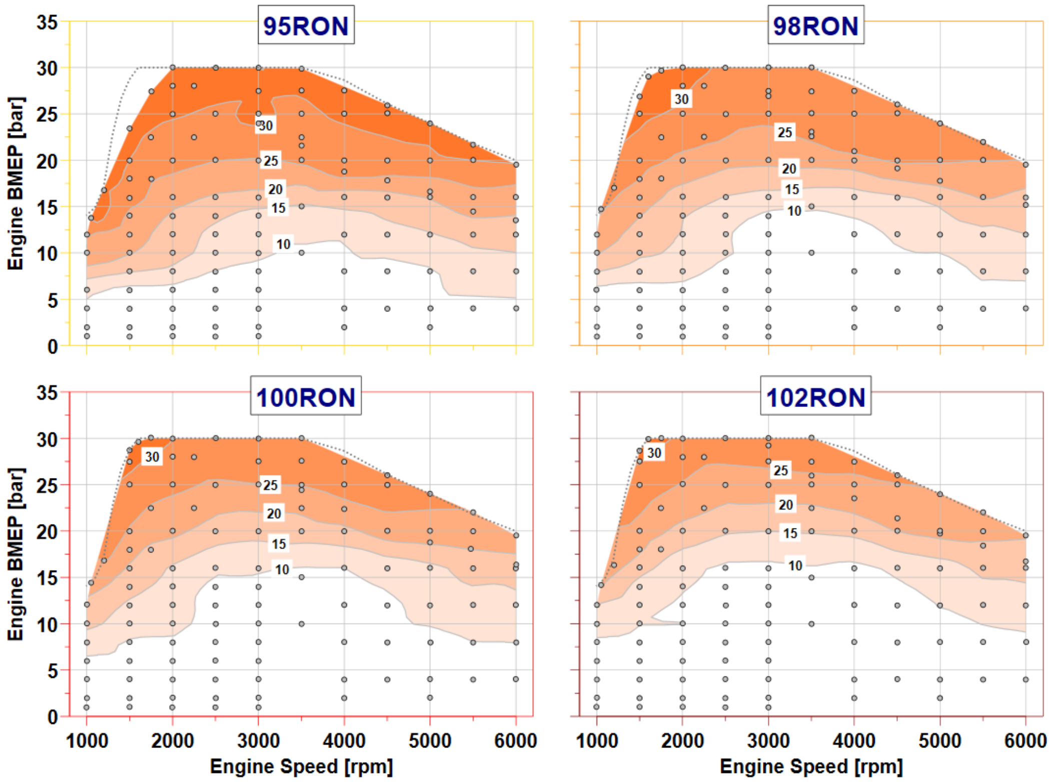


Figure 5. Speed vs Load maps of combustion phasing (CA50) for each fuel

Figure 5 displays a contour plot of the optimised CA50 combustion phasing for each fuel. CA50 is the crank-angle after TDC where 50% of the heat from combustion has been released. Generally, advancing CA50 by advancing the ignition timing towards an engine's ideal timing will increase the thermal efficiency. However, the maximum advance will be limited by engine-knock and thus is dependent upon a fuel's knock-resistance.

In the charts above, the ideal engine timing is depicted by the white section (CA50 below 10 CAD after TDC). Once outside of this area, the other portions of the contour are areas where combustion phasing is retarded further after TDC, shown in 5 CAD increments, and corresponding to degraded cycle efficiency. It is important to note how the white section, corresponding to optimal combustion phasing, grows as RON increases. Also, note that the darkest orange section of latest CA50 timing, corresponding to lowest thermal efficiency, which forms a significant portion of the 95 RON case is entirely eliminated in the 102 RON case.

3.2. VEHICLE MODELLING

A vehicle simulation was performed using GT-Drive software. This dynamic (forward-facing) model was an updated version of the model used in a previous study by Bisordi et al [19].Based on a library of multi-physics elements, the software enables vehicles and drivelines to be built and tested over drive-cycles to estimate fuel consumption and pollutant emissions.

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 timestep ahead and calculates the torque necessary to achieve the required vehicle acceleration in order to match the target future vehicle speed.

The calculated torque request is passed on to the engine or brake objects. In the case of a torque request for the engine object that is greater than the fuel cut threshold, the model will look up the instantaneous fuel flow from a 3-dimensional look-up table in a quasi-static manor.

To account for transient and cold start fuelling characteristics of the real engine, a number of correction tables and equations are implemented into the model.

The above method relies on the timestep to be small enough to be quasi static, usually on the order of 0.25s results in sufficiently accurate instantaneous fuel flow rates.

As the engine is turbo charged, the transient time to full torque at any given engine speed is not instantaneous. Therefore, turbo transient behaviour is also modelled via equations and look up tables based on test data. In highly dynamic drive cycles where the engine is operated transiently most of the time, the above corrections have to be incorporated into the model to ensure a sufficient correlation to test data.

The inputs required for model creation combine parameters related to vehicle specifications used for driving resistance representation and powertrain data for efficiency, torque, and energy flow whilst delivering the power demanded.

Vehicle specifications were either obtained via manufacturer’s information or from direct measurements and were finely adjusted so road loads such as aerodynamic drag and wheel rolling resistance could be accurately represented.

In order to capture the actual losses associated with vehicle friction and wind resistance for the vehicle under evaluation, a vehicle coast down test following 70/220/EEC guidelines was performed, and the measured driving resistance curve was employed later in the correlated model for the technology and fuel assessment over the drive-cycles selected.

For engine representation, the GT-Drive model uses a map of measured fuel flow rate against engine speed and load. This map is obtained from dynamometer measurements taken during steady-state operation, under fully warm engine conditions. Full load and motored curves are also measured and implemented as a function of accelerator pedal position.

The transient effects, such as increased fuelling during warm-up, can be accurately estimated due to the repetitive nature of the NEDC. A fuel multiplier trendline is fitted to a modified Arrhenius equation, in which elapsed cycle time is the main variable. This method was applied to all measurements performed on the selected fuels tested in the baseline vehicle. No appreciable differences were found between the fuel types investigated. Therefore, a single warm-up correction model for all fuel types is used. The same warm-up correlation is also used for both the WLTC and RDE cycle simulations.

3.3. VEHICLE TESTING

Following the completion of the engine test-bed calibration and modelling phase, the engine was fitted in the chassis of a D segment car for chassis dynamometer testing. The 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 NEDC, WLTC and RDE simulated test cycles on the chassis dynamometer. The RDE test cycle chosen was the same as that used for the modelling exercise for direct comparison, and it represented an average cycle in terms of those available for all the fuels tested. The Artemis cycle was not run on the vehicle as it was not expected to be too different from the RDE cycle. However, the cycle was modelled for comparison with previous studies for completeness.

3.3.1. NEDC

The NEDC (New European Drive Cycle) is the test cycle that, until recently, was used for the homologation of vehicles. It consists of two parts: the urban drive cycle (UDC) or also known as ECE; and the extra urban drive cycle (EUDC), which has higher speeds and less transience than the UDC.

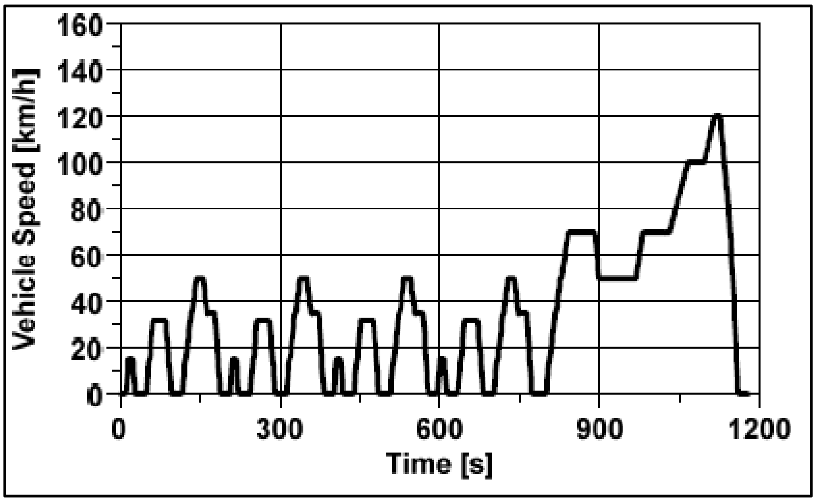


Figure 6. The NEDC test cycle

3.3.2. WLTC

The Worldwide harmonized Light duty Test Cycle (WLTC) contains a mix of real-world driving characteristics, and a wider range of speeds and transients than the NEDC, which it has been developed to replace in vehicle homologation testing. Figure 7 shows the profile of the test cycle, which takes around 30 minutes to complete, and covers 23 km.

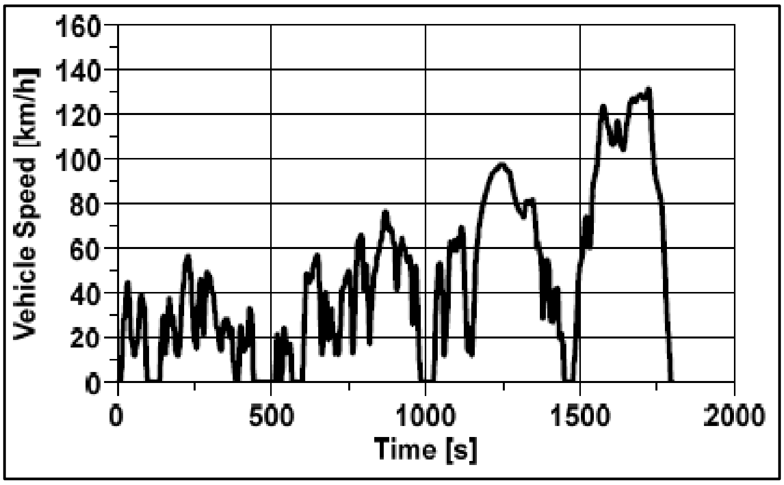


Figure 7. Speed time chart for WLTC

3.3.3. RDE

Mahle have a wide range of RDE routes/cycles available to them in the Northampton area, so one particular cycle was chosen for the modelling which could be replicated on the road so that modelled and real results could be compared (Figure 8).

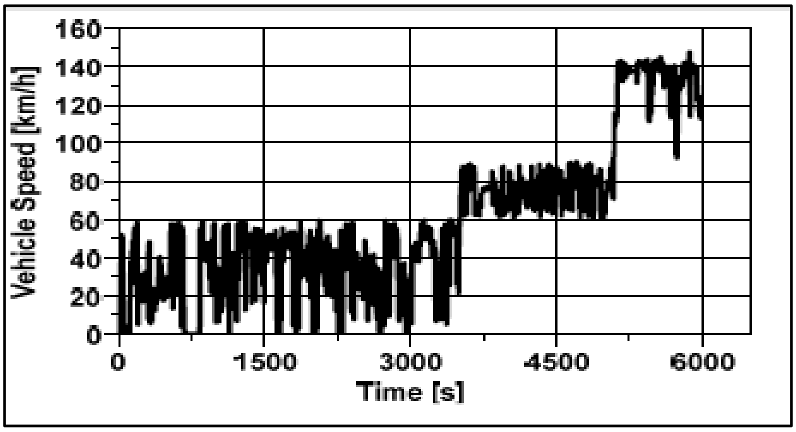


Figure 8. Speed time graph for RDE cycle used

3.3.4. ARTEMIS

The Artemis cycle is highly transient, with higher average load than either the NEDC or the WLTC. This cycle was modelled in the previous BP programme, so was modelled again for comparison purposes (Figure 9).

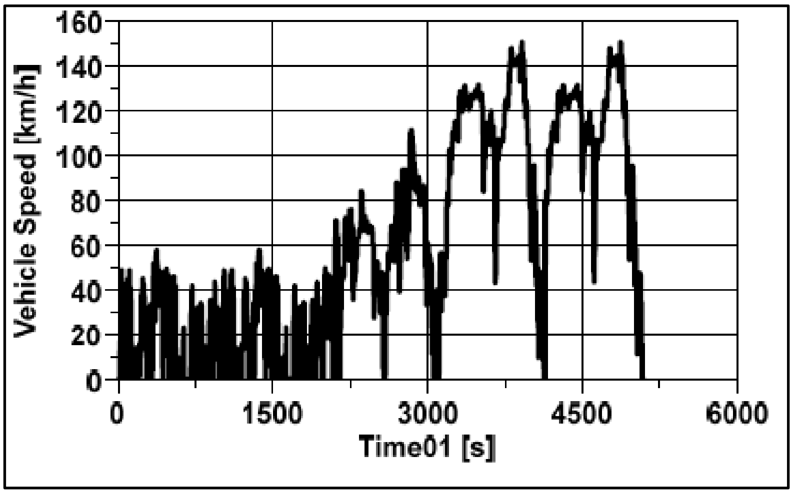


Figure 9. The Artemis test cycle used for this work

4. RESULTS AND DISCUSSION

4.1. BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)

The contour plots in Figure 10 demonstrate the fuel efficiency benefits associated with increasing RON, as the load increases and the engine becomes more susceptible to knock. By maintaining optimum spark timing across more of the operating range, the higher RON fuels increase efficiency over a large portion of the operating range. This improvement in thermal efficiency is particularly noticeable in the size of the central island of peak efficiency. 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. This improvement in efficiency will be discussed later.

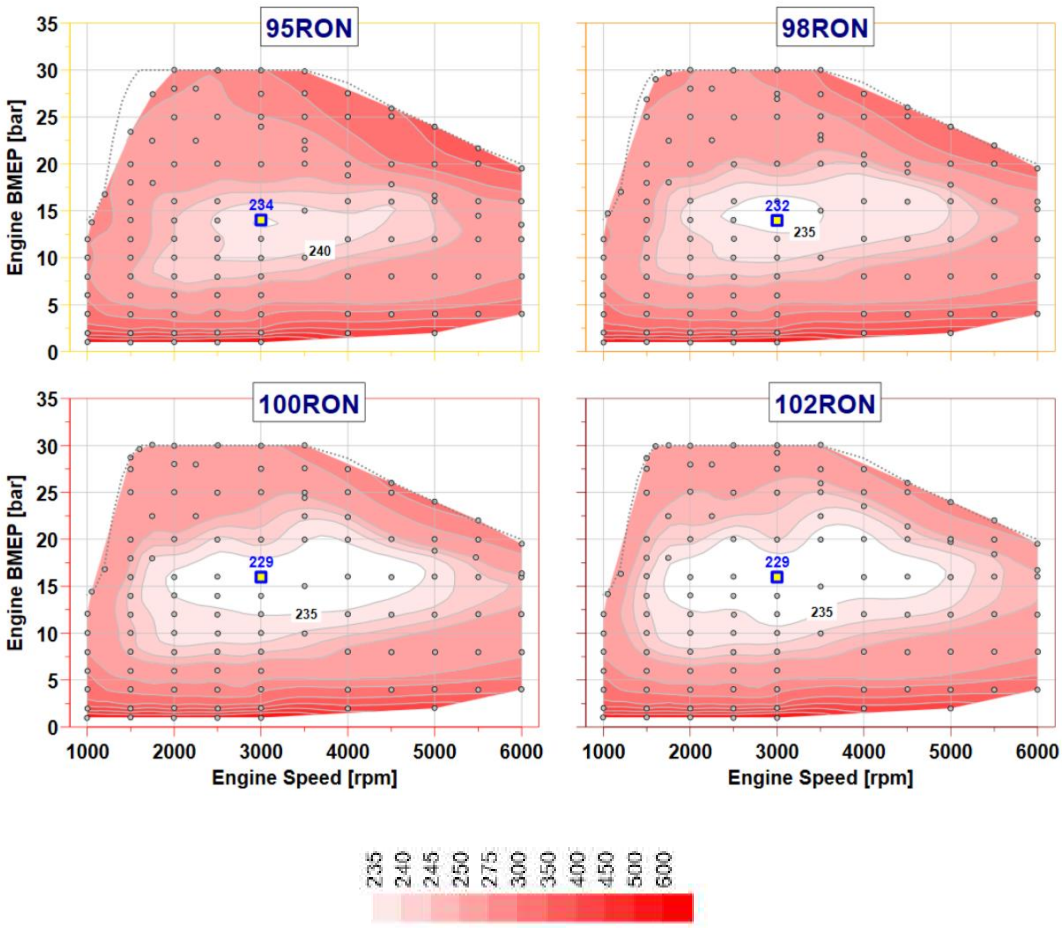


Figure 10. Contour plots for brake specific fuel consumption

4.2. EXHAUST GAS TEMPERATURE

As depicted in Figure 11, in order to protect the exhaust and turbine system components, the engine exhaust gas temperature profile on each fuel was controlled to be largely similar, deviating primarily at the higher load and speed points where lower RON fuels lead to higher exhaust gas temperatures over a larger segment of the operation range. The is due to a retardation in spark timing and the subsequent delayed combustion which allows less cooling time before the exhaust valves open. The intensity of the red coloration gives an indication of the higher exhaust gas temperature. The yellow, orange, red and brown lines on this and on

Figure 11 show where lambda (air fuel ratio) is equal to 1.0 and this corresponds closely with the 975ºC iso-line which is below the maximum turbine inlet temperature of 980ºC and the target for over-fuelling with a tolerance of +/-5ºC. The closeness of the lines shows the accuracy of testing.

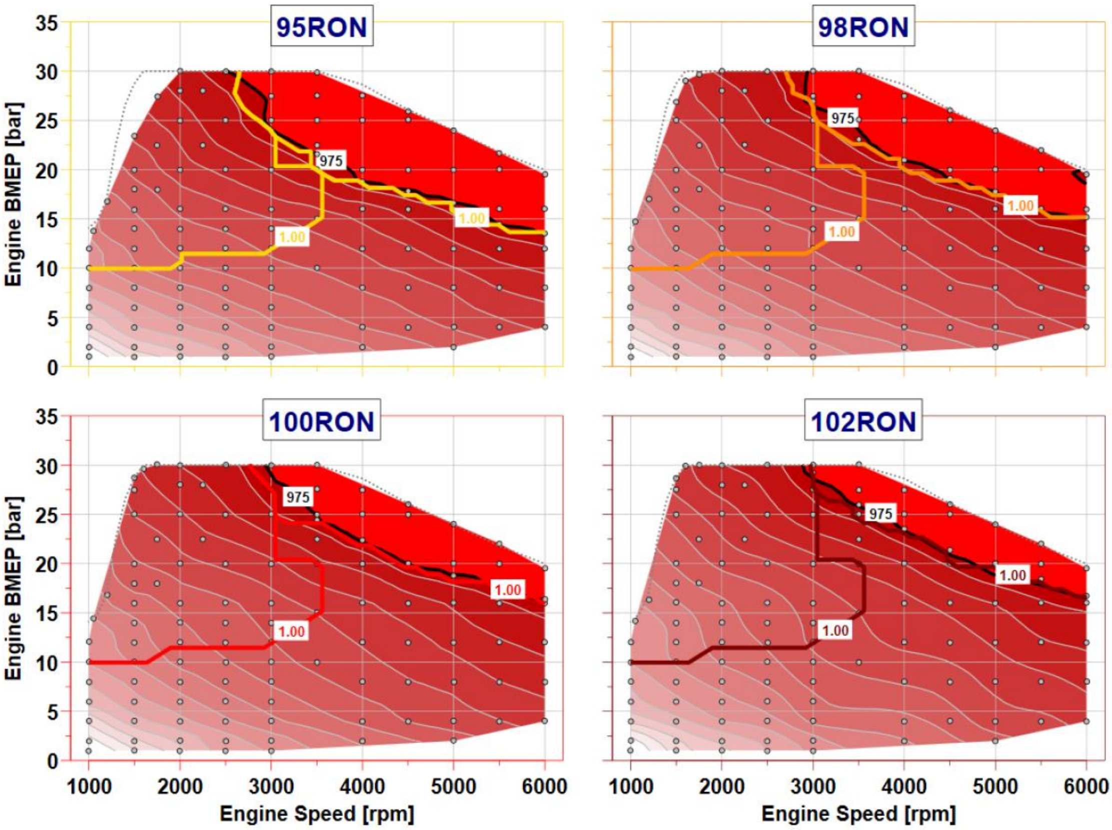


Figure 11. Contour plots for exhaust gas temperature

Under these conditions, over-fuelling is employed to compensate for the increase in temperature due to retarded ignition employed to avoid knocking combustion. This point is further illustrated in Figure 12 below, where the magnitude of over-fuelling required for each fuel can be clearly seen. In the figure, red coloration represents over-fuelling, and blue coloration underfuelling, based on air-fuel ratio. High RON fuels result in less over-fuelling resulting in improved efficiency due to the reduced temperature as illustrated above.

It should be noted that whilst this engine can be considered compliant with Euro 6c, for Euro 6d TEMP compliance, over the RDE cycle, it is likely that this engine would need recalibration to reduce the area of lean engine operation that exists at lower engine speeds and mid to high load and ensure that in particular NOx specifications would be met.

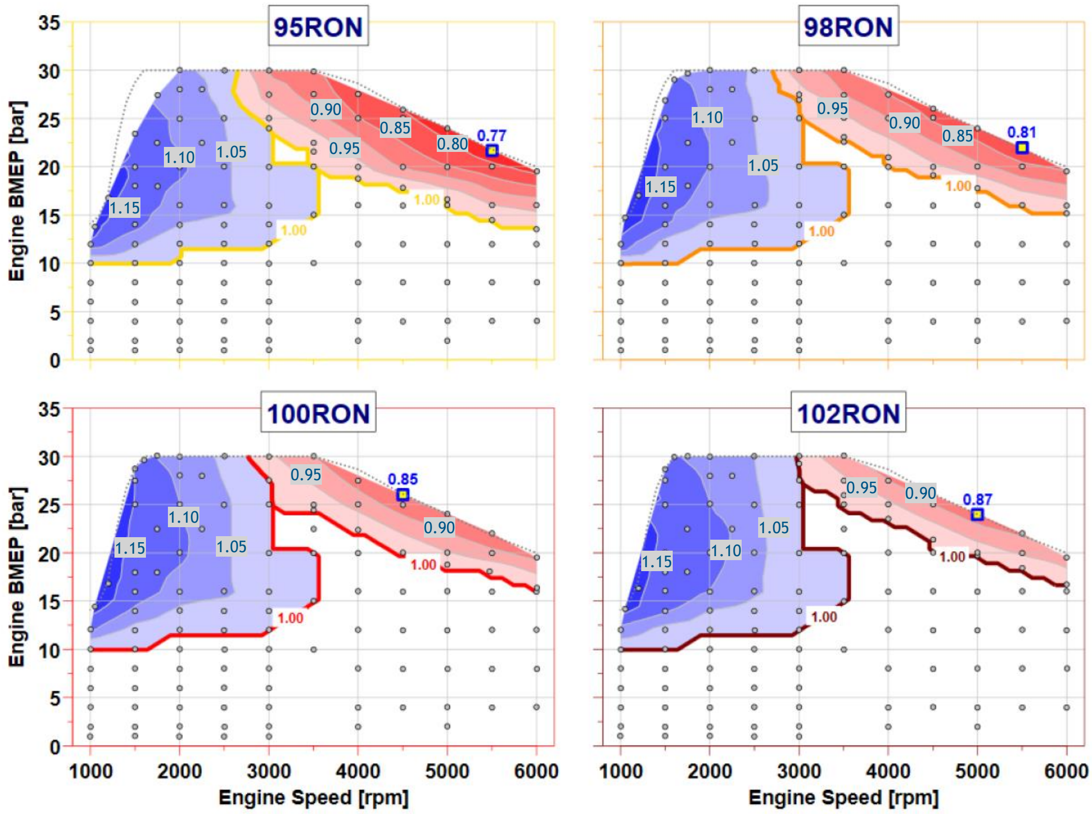


Figure 12. Contour plots for over-fuelling and under-fuelling

4.3. COMBUSTION STABILITY AND KNOCK LIMIT

Combustion stability is measured by calculating the covariance of the Net Mean Effective Pressure (NMEP) expressed as a percentage. The stability decreases (i.e. NMEP covariance increases) when going to low loads as the lower air flow leads to increased rate of residual burnt gases, which is detrimental to combustion propagation. The stability improves with load for the opposite reason than above. However, once the combustion phasing is knock limited, the spark retardation leads to reduced stability, due to the combustion happening later in the cycle in less favourable pressure and temperature conditions, and the combustion chamber volume varying faster than when the piston is closer to the top dead center. Over-fuelling shifts the combustion mixture away from the target stoichiometric air-fuel ratio. As figure 13 shows, due to the last two points, as the RON increased, the size of the area of combustion stability increases (pale blue area). The knock limit is also shown on the diagram (yellow, orange, red and brown lines) and increases as RON increases from 95 to 102.

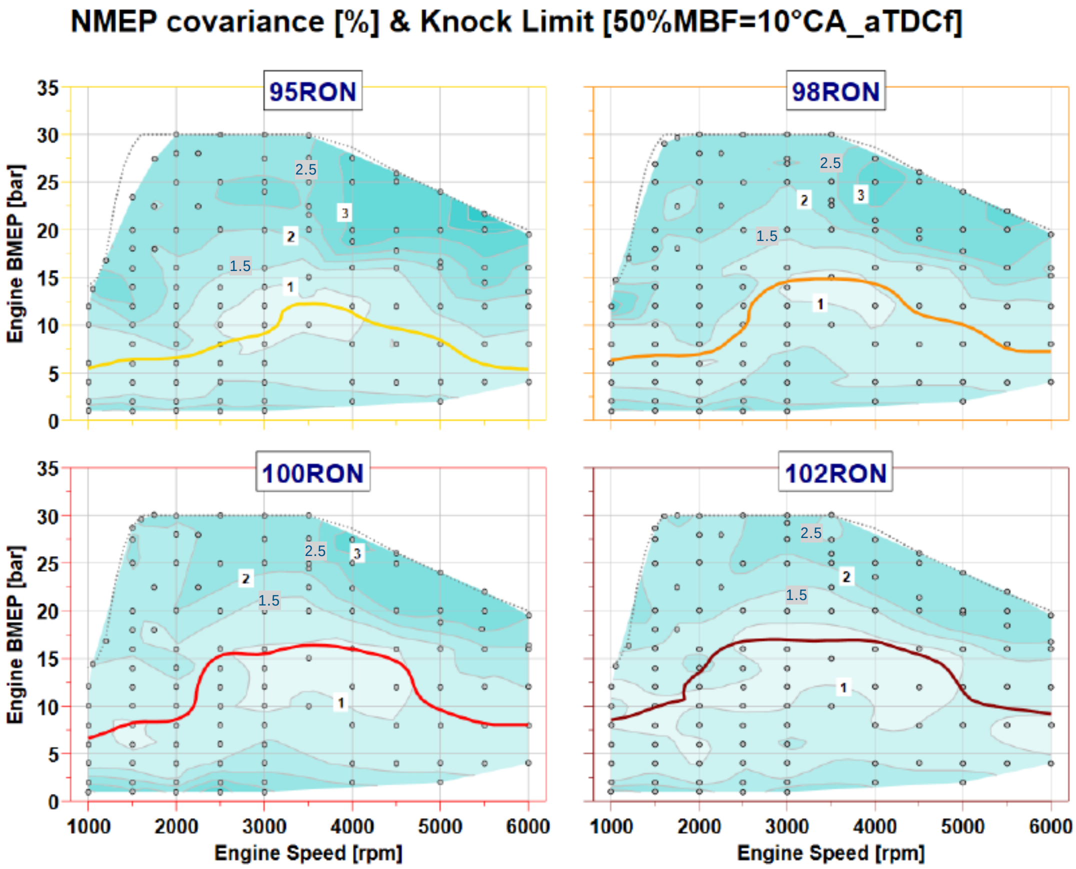


Figure 13. Contour plots for NMEP covariance with knock limit superimposed

4.4. VEHICLE MODELLING RESULTS

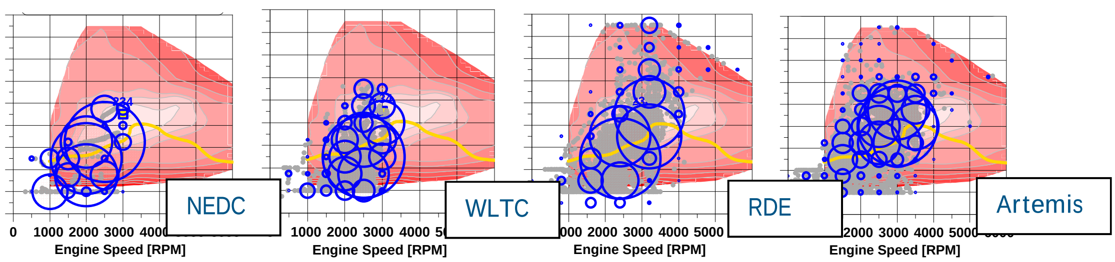


Figure 14. Fuel weighted residency maps for each drive cycle, 95RON knock-limit displayed

The fuel-weighted speed-load residency plots in Figure 14 further demonstrate the potential benefit that can be achieved through the use of higher octane fuels. The yellow line plotted on each chart describes the knock limit of the engine. The size and number of blue circles plotted above that 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. The plots are superimposed on the 95 RON BSFC contour plot and it can be seen that the RDE and Artemis cycles cover a greater percentage of the map particularly at the high speed high load areas. Other plots for NEDC, WLTC and Artemis test cycles are included in Appendix 1 which represent the following:

a) Time weighted no stop-start
b) Fuel weighted no stop-start
c) Time weighted stop-start
d) Fuel weighted stop-start

The benefits from the conditions above translate to the drive-cycle fuel efficiency for each fuel and cycle combination presented in Table 3 below.

	95 RON	98 RON	100 RON	102 RON		95 RON	98 RON	100 RON	102 RON
Drive Cycle	**L/100km**					**% 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

Table 1. Simulated fuel consumption

Fuel economy benefits associated with an increase of RON from 95 to 102 of between 1.75% and 3.72% were observed in the simulations, 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 WLTP cycle is operated at slightly higher loads, although the majority 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. As a result the Artemis and RDE cycles showed fuel economy improvement from higher RON fuels due to reduced over-fuelling requirements versus 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 between RON 95 and RON 102, meaning that each step increase in RON between these two values is beneficial to fuel consumption for this high compression ratio engine. While the engine's compression ratio was not varied in the this work, we may use data from the literature [18] to evaluate how much its increase from 10.2:1 to 12.2:1 would additionally contribute to fuel consumption benefits. As far as the real driving conditions are concerned, a gain of 1.3% can be added due to this compression ratio increase as demonstrated in BP's work [18], leading to a ~5% (= 3.7% + 1.3%) fuel consumption benefit, which is once again consistent with BP's results.

For the NEDC, WLTC and Artemis cycles, the results were also modelled with and without stop-start. The results with stop-start are shown with the benefit from using stop-start ranging from 1% for the Artemis to around 4.7% for the NEDC due to the high idle content of the latter cycle.

- Shift strategy

The modelling for the RDE testing was carried out using two shift strategies: one which assumes a driver who drives more normally and moderately (ECO strategy); and another assuming more aggressive driving, where the driver revs the engine higher than under moderate conditions (SPORT strategy). Figure 15 shows an example of the speed – load diagram superimposed on the BSFC map for the 102 RON fuel, and the different shift points for gear changes from first to second. Economical driving requires down-speeding and guiding the engine operating points into the economical part of the map. More aggressive driving, reflected by the SPORT strategy, involves higher upshift speed and down shift moving into a higher speed. The same tendencies are also reflected in other shifts.

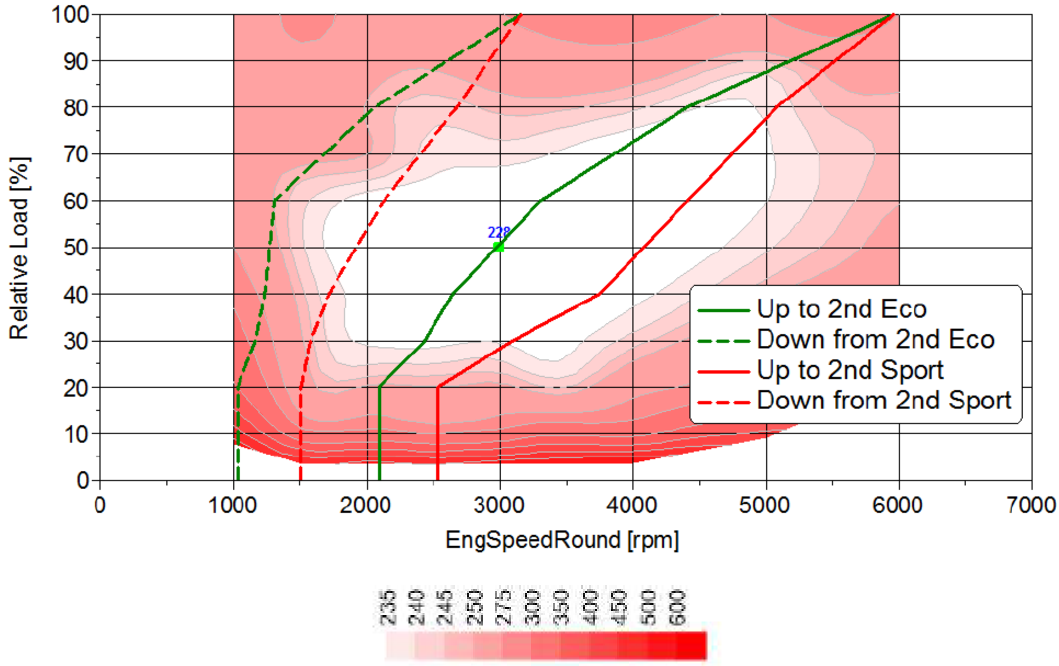


Figure 15. Speed-load diagram superimposed on the 102 RON BSFC chart

The RDE results reported in table 3 are shown for a shift strategy run in ECO shift mode. The SPORT shift mode was also run and for the chosen cycle there was a penalty of around 3% for all fuels. The RDE residency plots in the appendix 3 represent the time-weighted and fuel-weighted cycles as above but with ECO and SPORT shift modes respectively.

4.5. VEHICLE TESTING RESULTS

Figure 16 shows the results for CO_2 and fuel consumption for the measured test cycles. Each of the results was the average of three repeats. The bars in the figure show the range of data around the average points. Both the WLTC and the RDE showed trends of CO_2 and fuel consumption falling as RON increased, with no overlap between the results from the 102 RON fuel and the other fuels. The NEDC results were less clear and in line with the residency maps including the amount of time spent in low load versus high load conditions. Interestingly, the WLTC CO_2 results were lower in absolute terms than the NEDC and the RDE. The average measured improvement when going from 95 to 102 RON in the RDE test cycle is around 3.9% which is consistent with the modelled value of around 3.7%. This CO2 data and other modelled fuel consumption results are superimposed on the charts in figure 17, and it can be seen that the modelled results for the NEDC appears to follow the same trend as the other test cycle. In general, the difference between the modelled and measured results was around 1.5% or less, with the smallest difference in the RDE results, and the largest difference in the WLTC. For all the cycle simulations, particular attention was paid to idle speed, road load, catalyst heating, alternating lambda and fuelling during gearshifts. In sensitivity analyses, the latter three items in particular were identified as being the key drivers of the difference between the modelled and measured results. It is expected that differences between these parameters would account for the differences between the measured and modelled results for each cycle.

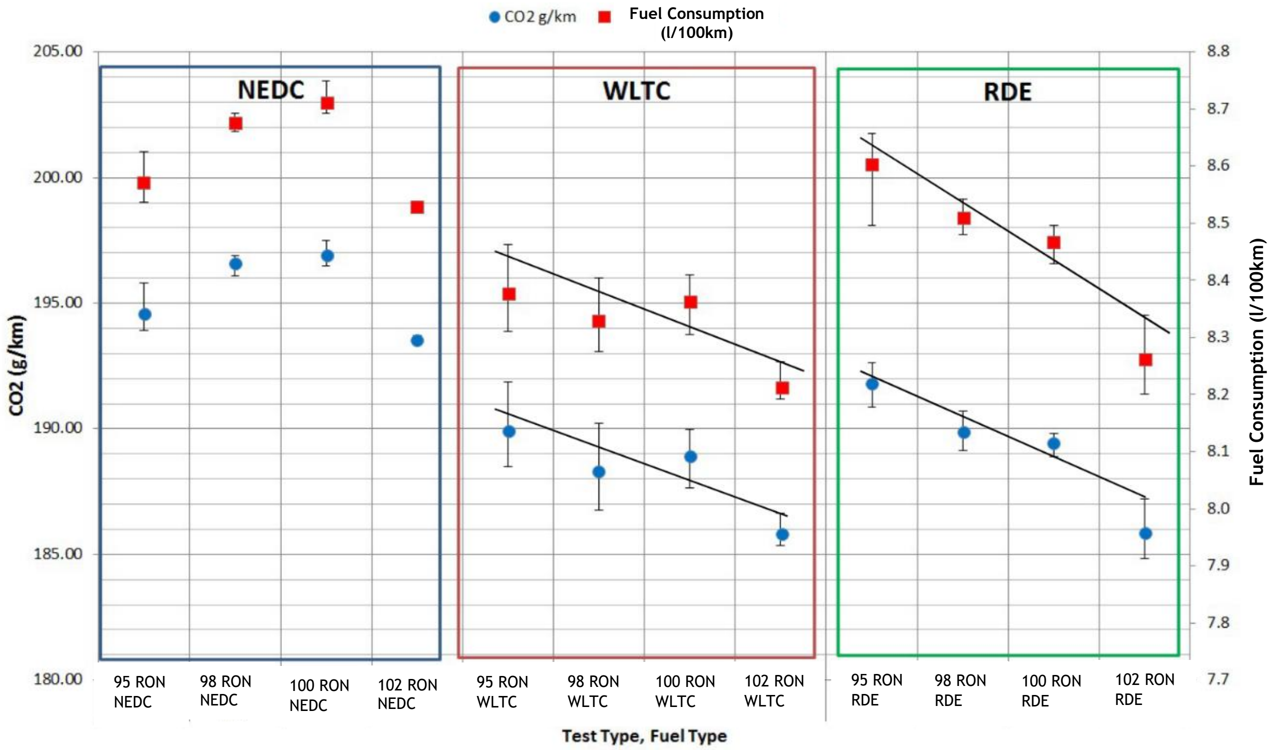


Figure 16. Averaged CO_2 and Fuel Consumption results for measured test cycles

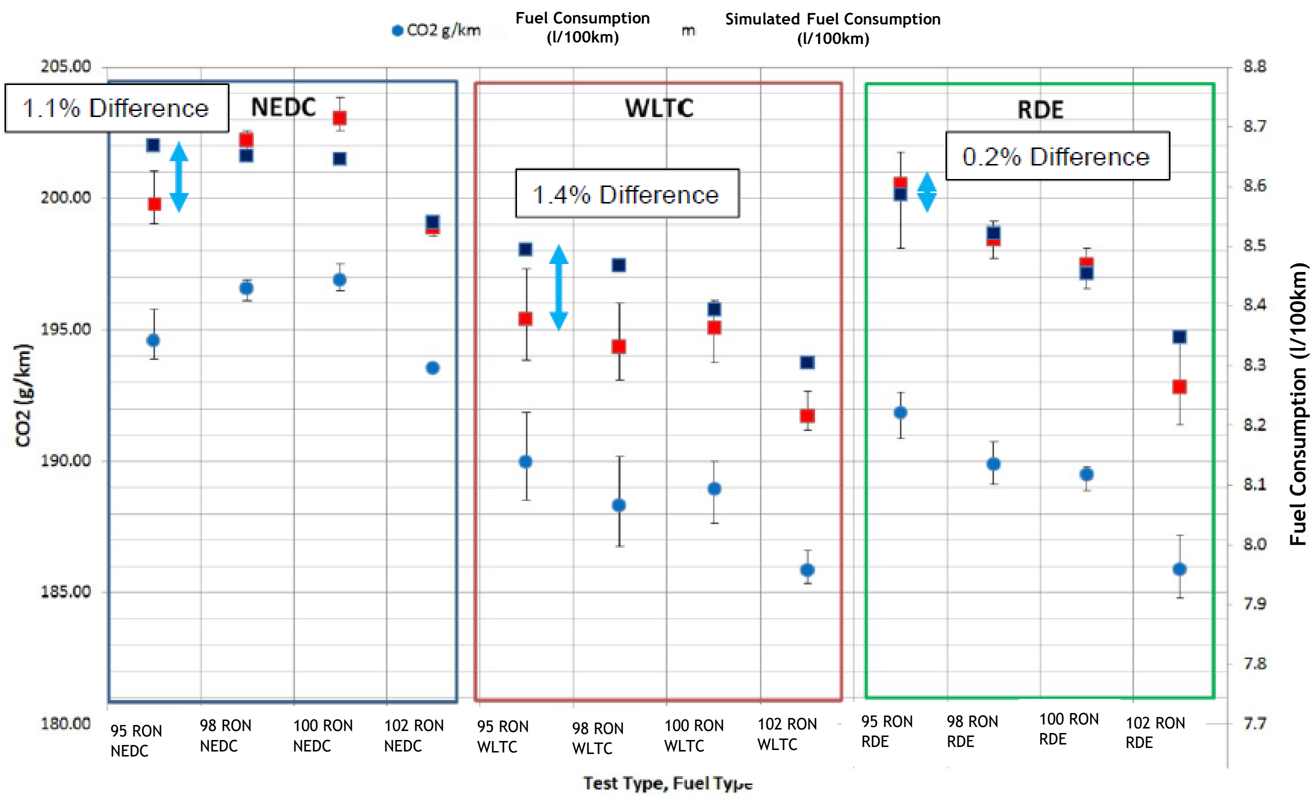


Figure 17. CO_2 and fuel consumption results including modelled fuel consumption results

5. CONCLUSIONS

Tests and simulation based on a downsized, high compression, turbocharged spark-ignition engine have been conducted on an engine dyno bench and in a vehicle. These engine attributes are not typical of current vehicles, but are widely accepted as having potential to give efficiency and therefore CO_2 benefits, especially if used in conjunction with high octane fuels.

When optimised to take advantage of higher RON fuels, an engine can demonstrate significant improvements in efficiency and CO_2 emissions, particularly when operating under high load conditions.

The engine modelling predicted a maximum of around 3.7% fuel consumption benefit, in the RDE cycle as octane was increased from 95 to 102. The simulations demonstrated a linear improvement in the fuel consumption benefit between RON 95 and RON 102, meaning that each RON increase between these two values is beneficial to fuel consumption. Vehicle testing aligned with the simulated results for all test cycles, although the RON benefits were more evident in the more transient driving cycles, including the real driving emissions where the benefits were around 3.9%. Adding the benefit of the compression ratio increase from 10.2:1 to 12.2:1 allowed by the fuel's antiknock behaviour (the latter being not demonstrated in this study, was sourced from the literature [18]), the fuel consumption benefit reaches up to ~5%.

During lower engine speed operation, the majority of the efficiency benefit associated with higher RON fuels can be directly attributed to the improved thermodynamic efficiency from earlier ignition timing. At higher engine speed, the ability to maintain advanced ignition timing also reduces the necessity to use over-fuelling as a means to protect exhaust system components from excessive gas temperature, thus providing a significant further benefit for higher RON fuels, this is more noticeable during real driving conditions.

To understand the societal impact of the future use of higher RON fuels in terms of well-to-wheels CO_2, the impact that the production of higher RON fuels has upon refinery efficiency must be understood. This topic has been studied by Concawe and will be the subject of a future publication.

6. GLOSSARY

A/F	Air / Fuel
AFR	Air-Fuel Ratio
BDC	Bottom Dead Centre
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
CFR	Cooperative Fuel Research Engine - used in the standard RON and MON tests
CA50	Crank angle position where 50% of the heat is released
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
CRC	Co-operative Research Council
E20	Gasoline containing 20% ethanol
E25	Gasoline containing 25% ethanol
ECE	City cycle, First part of the NEDC
ECU	Electronic Control Unit, a component of the EMS
EMS	Engine Management System
ETBE	Ethyl Tertiary Butyl Ether
EtOH	Ethanol
EUDC	Extra-Urban Driving Cycle. Second part of the NEDC
GDI	Gasoline Direct Injection
HC	Hydrocarbon
lambda	Normalised AFR (relative to stoichiometric AFR)
LCV	Lower Calorific Value (same as LHV)
LHV	Lower Heating Value (same as LCV)
LP	Line planning

MJ	Mega joule
NEDC	New European Driving Cycle
NMHC	Non-Methane Hydrocarbon
MON	Motor Octane Number
NEDC	New Emissions Driving Cycle, the legislative test cycle for emissions and fuel consumption measurement in Europe
NMEP	Net Mean Effective Pressure
NOx	Oxides of Nitrogen
PRF	Primary Reference Fuels used in RON/MON determination.
RDE	Real driving emissions test cycle
RON	Research Octane Number
S	Fuel Sensitivity, defined as RON-MON
TDC	Top Dead Centre
UEGO	Universal Exhaust Gas Oxygen sensor. Measures AFR or lambda.
US06	US transient test cycle
VCR	Variable Compression Ratio
WLTC	Worldwide harmonized Light duty Test Cycle

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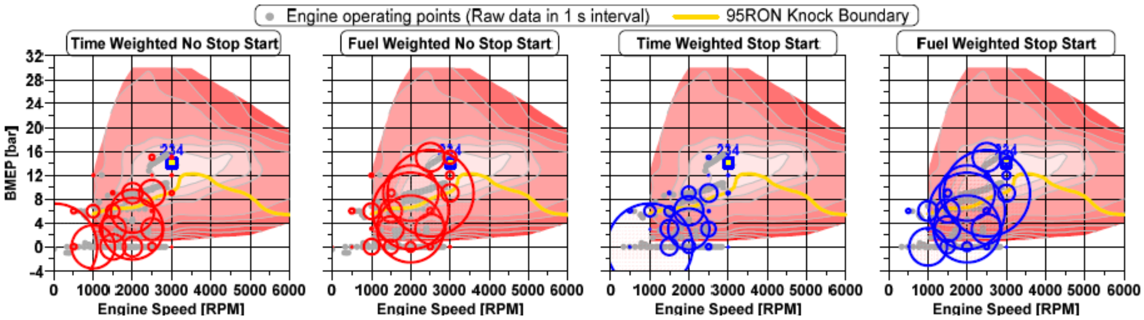
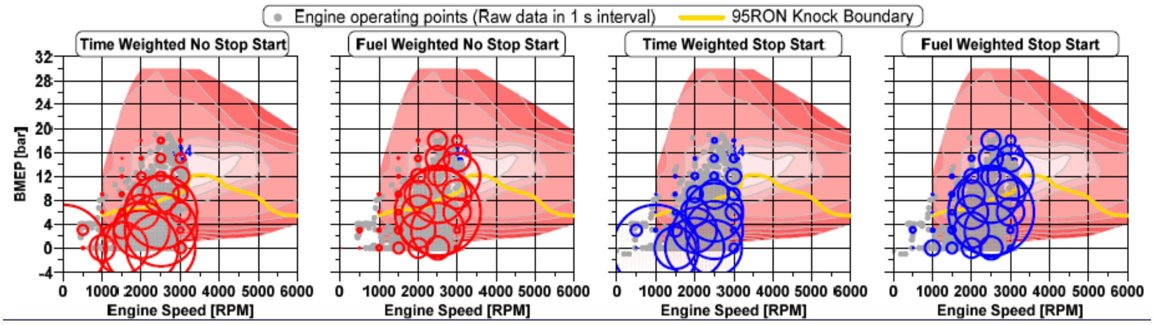
APPENDIX - TIME AND FUEL WEIGHTED RESIDENCY MAPS FOR TEST CYCLES

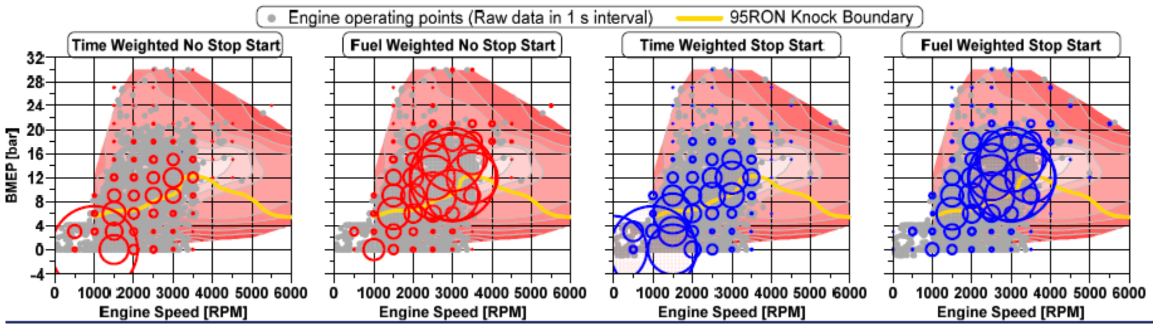
NEDC



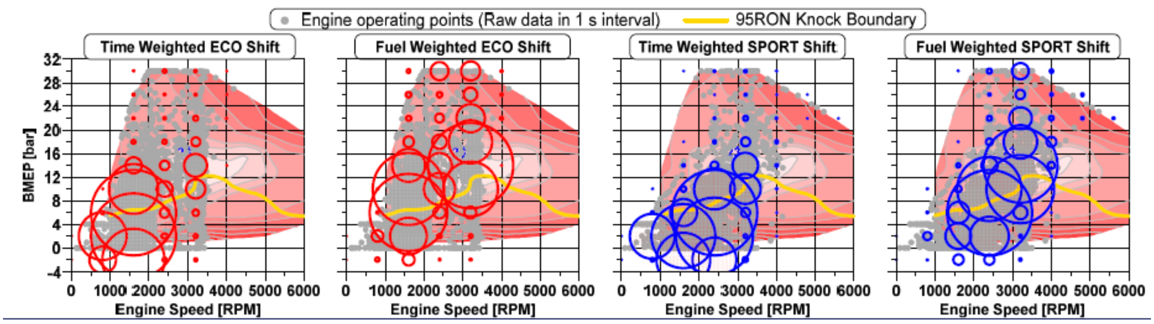
WLTC



Artemis



RDE



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