Measurement of RON Requirements for Turbocharged SI Engines: One Step to the Octane on Demand Concept

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Abstract: Knock phenomena in Spark Ignition (SI) engines (especially for turbocharged engine) is limiting both for engine global efficiency at high load and maximum performance. Several parameters can change the occurrence of knock and might be classified into two different categories: common engine tuning parameters such as Spark Advance (SA), Variable Valve Timing (VVT) position, Start Of Injection (SOI), dilution of the fuel/air mixture if available on the one hand, and hard to change parameters such as compression ratio (CR), fuel octane number (RON: Research Octane Number), etc. on the other hand.

The aim of the current research program is to use the octane number as a tuning parameter and to improve the engine efficiency and its CO_2 emissions. The idea is to keep the engine operating on the entire map without occurrence of knock by adapting its RON feed in order to preserve its cycle efficiency (optimum Spark Advance). One major step in reaching this goal is to first quantify the octane quality needed to keep the best efficiency (optimal spark advance (SA) without engine knock) for each operating point (OP) of the entire engine map.

On an up-to-date turbocharged SI engine (1.6L Gasoline Direct Injection (GDI)), tests have been performed at test bench. RON was widely varied from 71 to 111, using surrogate fuels (TRF: Toluene Reference Fuels which are mixtures of n-heptane and toluene in varying proportions). This supplementary degree of freedom (RON value of the fuel) provides further opportunity for a new compression ratio optimization. In this context, besides RON variation tests, a wide three-step variation of compression ratio (CR): 7.5:1, 10.5:1 (stock CR) and 12:1 has been performed. To be representative of the real engine behavior under real driving conditions, the major part of the engine map has been tested at the test bench: from very low load to full load and from 1000 rpm to 5000 rpm.

Stock compression ratio (10.5:1) results show the improvement of combustion phasing (less retarded) with RON increase. Lowering RON is also very interesting. The lowest RON value (71) may be used with the optimal combustion phasing on a significant part of the engine map for the three compression ratios. Obviously, at low CR this area is larger than at higher CR. In other words, low octane fuel (i.e. RON 71) can be suitable for some parts of driving cycles, even for high CR. In case of a dual fuel (Octane on Demand) engine, a significant fraction of such a low octane fuel can be anticipated.

Furthermore, this large RON variation (from 71 to 111), especially for CR 10.5:1 and 12:1, reveals the non-linearity of RON effect on combustion phasing (i.e. knock occurrence). In fact, for low octane values (<97) the anti-knock behavior is lower than at higher RON value.

The overall comparison of RON and CR variation results allows to clearly show the efficiency and CO_2 emissions benefits of the Octane on Demand concept.

Keywords: Octane on Demand, Research Octane Number, RON, Knock Management, Combustion Phasing, CA50, TRF, Compression Ratio

1. Introduction

The demand for transport fuels increases rapidly, mainly driven by the economic growth of the non-OECD countries. Most major energy players agree to the fact that the transport energy demand will increase by almost 40% until 2040 (e.g. in 2013 the US Energy Information Administration reference forecast featured an average 2010-2040 worldwide annual growth of 1.1% [1]). Even though alternatives to conventional fossil fuels exist today (e.g. biofuels, fuel cells, electric cars, etc.) and are likely to grow in the future, fossil energy is to remain the main powertrain enabler for the decades to come.

The projected growth in energy demand is however imbalanced throughout light, middle and heavy fuels [2, 3, 4, 5]. It is primarily dictated by the ever growing commercial activities and impacts directly the demand in middle and heavy distillates (kerosene, gasoil, and marine fuels). The projected demand of light fuel (gasoline) is expected to remain flat, since technological improvements (engine downsizing, hybridization, etc.) enable considerable fuel economies [3]. From the supply side, the global refining infrastructure, as of today, will find it increasingly difficult to meet the projected shift in demand (increasing demand in middle and heavy distillates) without large-scale investments in hydrocracking units that lead to a substantial increase in associated CO_2 emissions [6]. This imbalance urges for less CO_2-intensive solutions for passenger transportation sector i.e. for reducing CO_2 footprint from well-to-tank and tank-to-wheel perspectives.

Motivated by the existing energy landscape and outlooks, and with the initiative to promote a responsible use of petroleum products in the transportation sector, Aramco is pursuing collaborative research programs with IFP Energies nouvelles to develop and prove novel fuel/engine solutions, capable of challenging modern technological and environmental issues. One of the research initiatives uses naphtha-based fuels to power spark ignition (SI) engines, today operated on conventional gasoline. Naphtha is a generic term designating the fraction of crude oil boiling within the 30-180 °C range. It is composed of C5 to C11 hydrocarbons and has a low research octane number (RON) value, roughly within the 50-70 range. It is a refinery product that could potentially be beneficial for the automotive industry as an example of a less processed fuel emitting less CO_2 during the refining process. Moreover, thanks to its different proportion of hydrogen and carbon (higher hydrogen to carbon ratio than standard gasoline), burning naphtha in engines produces less CO_2 per unit of energy injected (same behaviour as combustion of Compressed Natural Gas (CNG)). The order of magnitude is between -4 to -7% lower CO_2 emissions for naphtha fuel compared to standard gasoline (depending on naphtha's composition and its RON value).

Octane quality (which can be described by RON) of the fuel is crucial for avoiding knock phenomena. Without knock, the combustion phasing of a SI engine could be tuned in the optimal way whatever the engine speed and load conditions are. This is all the more true in case of turbocharged SI engines, but a high RON value becomes less necessary when the engine operates at low load. Based on this, varying fuel RON quality and adjusting it as any other engine operating parameter leads to what is known as the Octane on Demand concept. It is a dual fuel concept in which the engine operates on a more or less low RON base fuel that is continuously boosted on as-needed basis through the addition of an external octane booster [6, 7].

One of the bases of the Octane on Demand concept is to understand antiknock properties, namely research octane number (RON). To this purpose, RON measurements were performed on a CFR engine for different variations of blends of refinery naphtha and commercial gasoline used as base fuels and enhanced with octane boosters [8]. In this study, a wide range of RON values (71 to 111) was obtained from CFR measurements.

On a conventional combustion engine, the change of fuel properties, especially the RON value, and its effects on engine response is being studied for several years [9, 10, 11, 12]. The increasing literature work indicates that this is becoming a great opportunity for car makers to further decrease average fleet consumption and tailpipe GHG (Greenhouse Gas) emission levels [6, 7, 13, 14]. Indeed, unlocking RON value is a key parameter for enabling novel engine design. In fact, if higher RON value is of interest, higher compression ratio can lead to better engine efficiency at low loads without any knock limitation at higher loads due to high RON value of the fuel. Besides, high RON streams (> 105) are commonly obtained with ethanol blends or from refinery products rich in aromatic molecules (reformate).

The present work is intended as one of the first blocks toward the Octane on Demand concept, aiming to understand the anti-knock (or RON) requirements of a state-of-the-art turbocharged SI engine. In other words, for a given CR, what is the RON value needed on the different operating points (OP) of the engine map to avoid knock phenomena and to keep the best efficiency (optimal spark advance)? Is the RON requirement linear considering engine load, engine speed and compression ratio? Experimental measurements have been conducted on an engine test bench for a wide range of RON. Literature shows the effect of RON variation on engine outputs within the widest range of 88 to 110 [13, 14]. In order to enlarge the understanding of the RON effect, a larger RON variation from 71 to 111 was performed using surrogate fuels (TRF: Toluene Reference Fuels which are mixtures of n-heptane and toluene in varying proportions). Targeting better engine efficiency and lower CO_2 emission levels, the RON variation enables to look for different compression ratios: a wide three-step variation of CR: 7.5:1, 10.5:1 (stock CR) and 12:1 has been performed.

2. Experimental apparatus

2.1 Engine configuration

This study is performed on a state-of-the-art turbocharged four cylinder, 1.6L displacement SI engine equipped with a direct injection system

(Gasoline Direct Injection (GDI)), and with an intake Variable Valve Timing (VVT) device. The cam profile remains unchanged (i.e. valve lift amplitude). The maximum dephasing amplitude for intake VVT is 70°CA. For the entire engine operating conditions (speed and load), the homogeneous combustion mode is used. Main characteristics of the engine are given in Table 1.

Table 1: Main characteristics of the engine

Engine type	L-4
Displaced volume	1598 cc
Bore	77.0 mm
Stroke	85.8 mm
Compression ratio	7.5:1, 10.5:1 and 12:1
Number of valves	16
Output power	115 kW or less depending on engine configuration
Exhaust Valve Opening @ 1mm	22° BTDC
Exhaust Valve Closing @ 1mm	-8° BTDC
Inlet Valve Opening @ 1mm	From -36° to 34° BTDC
Inlet Valve Closing @ 1mm	From 45 to -25° BTDC
Fuel pressure	From 50 to 120 bar depending on the operating point
Injector	BOSCH HDEV 5.1 Laterally mounted
Boosting system	Twin scroll
Engine condition	Warm (coolant & oil)

During this study, three different compression ratios (CR) were tested. The stock CR is 10.5:1. A significant variation of the CR was performed in order to obtain 7.5:1 and 12:1. New piston geometries were designed to adapt the corresponding combustion chamber volume. Figure 1 shows the main differences for the three piston geometries. The piston corresponding to CR 12:1 is designed with supplementary matter at the surrounding of the piston in order to keep the original central shape (for cold start injection strategy). For CR 7.5:1, the combustion chamber volume is increased by removing matter of the piston and reducing the connecting rod length.

Figure 1: Piston geometries to obtain the three different CRs (left: CR=7.5:1, middle: CR=10.5:1 (stock), right: CR=12:1)

2.2 Fuel matrix presentation

The considered engine is designed and tuned to be fed with standard EN 228 E5 gasoline (5%v. ethanol). This gasoline is used to make the reference results. However, in the study a large place is given to fuel properties in order to quantify the RON requirement of each OP. To do so, surrogate fuels are used: Toluene Reference Fuel (TRF, not compliant with EN 228). The varying proportion of n-heptane and toluene enables the wide variation of RON from 71 to 111, RON steps are given in Table 2. The linear by mole blending rule was used to calculate the proportion of n-heptane and toluene required to obtain the desired RON value [15]. Indeed, the molar proportion of toluene multiplied by its RON value of 118 gives the TRF RON value (RON value of n-heptane is 0).

Table 2: RON step variation for TRF fuel and molar proportion of n-heptane and toluene

TRF	RON [-]	Molar n-heptane/toluene proportion [%]
#1	71	39.8 / 60.2
#2	85	28.2 / 71.8
#3	91	23.3 / 76.7
#4	97.5 (idem as standard E5)	17.7 / 82.3
#5	105	11.3 / 88.7
#6	111	6.1 / 93.9

The lowest RON value (71) corresponds to the potential low RON base fuel (naphtha-based) used for the Octane on Demand concept and widens the scope of low octane effects on engine outputs compared to previous studies [13, 14].

Intermediate RON 85 is useful to quantify the reduction of antiknock properties for low octane fuel, and especially to answer the question whether antiknock property is linear or not for low RON values.

RON 91 TRF fuel corresponds to the RON value of a non-oxygenated gasoline that will be tested later on during the project. This is a base fuel which can be splash blended with 10% of ethanol to obtain an EN 228 E10.

In order to crosscheck the antiknock properties of our E5 fuel, a TRF blend with the same RON value (97.5) is used.

For RON superior to 97.5, the objective is to correlate the behaviour of knock occurrence when using octane boosters. RON 105 TFR fuel is an intermediate RON value which can roughly correlate with the use of octane booster such as diisobutylene (DIB, RON=104), Superbutol™[1] (RON=107) or ethanol (RON=108).

Finally, RON 111 TRF fuel is used to correlate the highest octane booster RON value, which corresponds to reformate. This very high RON value is obtained due to its high level of aromatic compounds.

Based on the linear by mole blending rule, the other TRF fuel properties are estimated such as lower heating value (LHV), density and mass percentage of carbon and hydrogen. These properties enable the calculation of engine efficiencies (from measured fuel consumption) and Fuel / Air Equivalence Ratios (FAER, from exhaust gas analysis).

Since only RON value (and not MON) was of interest, isooctane (the third compound of TRF fuels) has not been used. As a consequence, the RON – MON value also defined as the sensitivity varies for the six TRF blends between 7.9 and 12.4: sensitivity increases with RON increase. This 4.5 variation of sensitivity will be considered as a second order effect on knock limit results compared to the wide 40 points RON variation. Moreover, since the standard E5 fuel has a 0.5 point gap in sensitivity compared to the TRF blend (at constant RON value 97.5), the corresponding engine results will enable to crosscheck the TRF behavior to the standard E5 fuel.

2.3 Test bench configuration

The engine is equipped with four in-cylinder pressure sensors (one per cylinder), an exhaust gas analyser, and several pressure sensors and thermocouples to ensure a good engine monitoring and a stable and repeatable engine behaviour, as shown in Figure 2.

The original Engine Control Unit (ECU) is replaced by a rapid prototyping system, while stock engine settings are conserved (€5 compliant). In addition to the on-line adiabatic combustion analysis, the high frequency acquisition data are saved and used for an off-line combustion analysis which considers wall heat exchanges. This home-made tool provides Heat Release Rate (HRR), Burnt Mass Fraction (BMF) and gas temperature. Wall heat losses are estimated using a Woschni model.

In addition, the oil temperature depends on the OP, and the intake air temperature is also controlled by the efficiency of the intercooler to simulate realistic vehicle conditions.

[1] SuperButol™ booster is a mixture representative of the product obtained in a patented Saudi Arabian Oil Company process (mainly butanol isomers, with minor quantities of DIB).

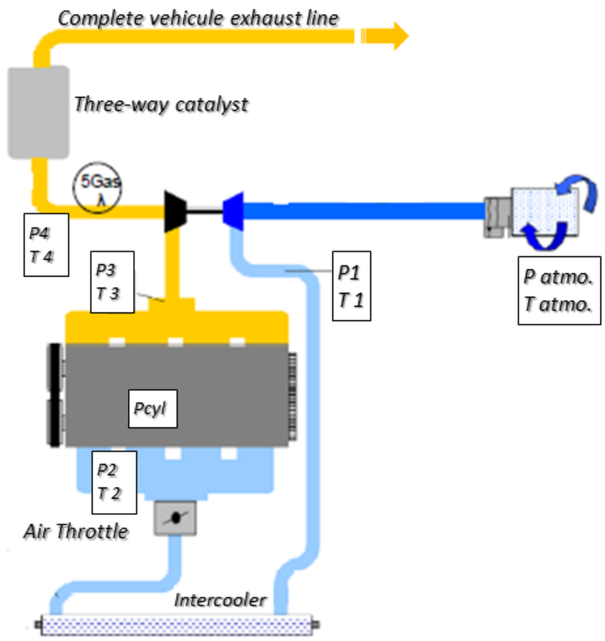

Figure 2: Equipped engine at test bench

2.4 Test methodology

The main goal of this study is to evaluate knock sensitivity for each configuration (RON, CR). To do so and in order to have a more repeatable behaviour of the engine, for each OP (speed and load), applied settings correspond to stock engine settings (€5 compliant) and are used for all configurations regardless of CR and RON values. This is especially the case for SOI, fuel pressure, inlet VVT position (IVO, IVC), intake temperature and oil temperature. FAER is set to 1 thanks to the use of exhaust gas analyser. All tests are performed under steady state operation with a warm engine at constant (and regulated) water (coolant) temperature 90°C, whereas the oil temperature is regulated between 90 and 115°C depending on engine speed. In other words, the engine settings are not optimum for each CR and RON configuration but are perfectly comparable, so that RON requirements can be deduced and compared between each engine configuration (CR, RON).

Spark Advance (SA) is controlled to phase the combustion such that 50% Burnt Mass Fraction (BMF) is at the optimum value 7°CA ATDC at low load or at the knock limit at higher loads.

For knock limit determination, in addition to the in-cylinder pressure signal visualization (to detect high frequencies), the test bench operator listens to the combustion noise thanks to a microphone placed close to the engine block.

For each combination of CR and RON values, acquisition is done for most of the engine speed and load area. Indeed, each 1000 rpm from 1000 to 5000 rpm, load increases are operated. Each 1 bar BMEP is acquired under 6 bar BMEP. At higher loads, up to full load, acquisition is done every 2 bar BMEP. Moreover, the knock limit is surrounded each 1 bar BMEP so that the knock occurrence accuracy is about 1 bar BMEP. Maximum tested engine torque output is determined by the stock engine full load settings even if in some CR-RON configurations the engine maximum output could be widely improved (especially for low CR and high RON values). In the worst cases in terms of knock occurrence (high CR and low RON values), the stock full load is not achievable and new (and lower) maximum performance is defined by using common engine outputs limits:

- Maximum CA50 is set to 30°CA;
- Maximum Fuel / Air Equivalence Ratio (FAER) is set to 1.3. Indeed the thermo-mechanical design of the engine limits the exhaust temperature (upstream turbine) to 920°C, which is regulated at high load thanks to fuel enrichment.

It is worth mentioning that due to the use of high RON fuel, before the occurrence of knock, the maximum in-cylinder pressure can reach the engine mechanical limit, set to 100 bar (mean value). In this case, full load performance is achieved by retarding CA50.

3. Results and discussion

More than 20 engine configurations (compression ratios and RON values of TRF fuels) were tested, each time producing whole engine map results. A methodic and synthesizing analysis of the results is crucial to extract the most relevant effects in accordance to knock occurrence and RON requirements.

3.1 RON effect on stock CR configuration

The first part of the analysis is done for the stock CR: 10.5:1. The main idea is to evaluate the RON effects on the knock limit, the occurrence of fuel enrichment limit and full load performances. Finally, the effect of RON (i.e. combustion phasing) on engine efficiency will be discussed.

3.1.1 RON effect on knock limit

The knock limit is defined as the last OP (at 1 bar) before the knock appears and makes it necessary to retard combustion.

First of all, Figure 3 illustrates the evolution of knock occurrence, expressed in relative torque (compared to the maximum engine torque), over the engine speed when RON varies. First, the occurrence of knock is consistent within 1 bar range for both TRF and E5 fuels at constant RON 97.5. Here, knock limit varies between 30% and 60% of maximum output torque, depending on the engine speed. This demonstrates that despite an important gap in fuel composition between TRF and standard E5 fuel (TRF is only composed of n-heptane and toluene), RON value is a good parameter to describe the occurrence of knock. Note that in the case of these two fuels, the sensitivity (RON-MON) gap is small: 0.5 pt. In other words, TRF RON variation is expected to well describe RON requirements of the engine.

For a given RON value (for example 97.5), Figure 3 presents the effect of engine speed on knock limit. As the engine speed increases up to 3000 rpm, the knock limit becomes higher. This is due to the fact that, for a given auto-ignition delay defined by thermodynamic conditions, the probability of having knock is reduced when the engine speed increases. For engine speeds higher than 3000 rpm, two tendencies can be distinguished:

- at RON lower than 91, the knock limit becomes higher than at lower engine speed. This has again the same explanation: less time for end gas to auto-ignite at higher engine speed;

- at RON higher than 97.5, the knock sensitivity increases after 3000 rpm. This is in fact due to the turbocharging mode (intake pressure greater than 1 bar) which increases exhaust back-pressure and so the hot internal residual gas (IGR) which increases knock sensitivity. This is partially linked to the experimental methodology: no optimisation of the engine settings has been performed (except spark advance).

For the highest RON values (111), knock does not appear until stock full load curve. That is why the corresponding dots do not appear in Figure 3. For the stock CR (10.5) configuration the maximum RON requirement for the entire engine operating map is lower than RON 111. Nevertheless, the optimal combustion phasing at high load reaches the maximum in-cylinder pressure limit (100 bar), so that CA50 was retarded to avoid any mechanical issues (but not due to knock) near the stock full load curve from 2000 to 4000 rpm.

Then, for the lowest RON value (71), the knock limit is around 3 to 5 bar BMEP (16 to 26% of maximum output torque). On the one hand, this can be considered as a very early knock occurrence. But on the other hand, considering the very large RON gap compared to standard E5 (RON 97.5) of more than 25 RON points, the knock limit with RON 71 is rather high. Indeed, it is high enough to allow for a conventional passenger car to use very low octane fuel on a significant part of various "real-life" driving cycles[2].

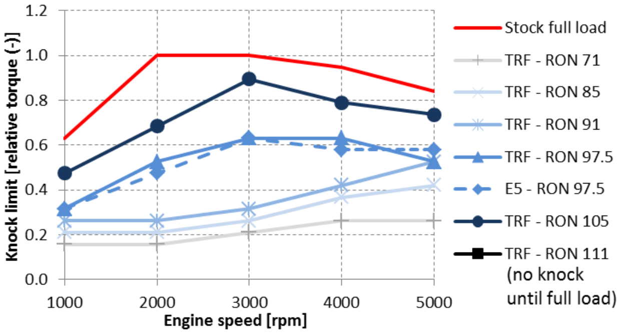

Figure 3: Knock limit for different RON at CR 10.5:1

Finally, Figure 3 also shows the non-linear variation of knock limit when considering RON and engine speed variations:

- At engine speeds lower than 3000 rpm and for RON lower than 97.5, the knock limit almost does not vary when RON increases: between RON 71 and 91 at 3000 rpm, knock limit barely increases by 2 bar BMEP which corresponds to an average increase of knock limit of 0.5 bar BMEP per 5 RON points increase;
- For RON lower than 97.5 at speeds higher than 3000 rpm and for RON higher than 97.5 whatever the engine speed, the increase of knock limit is more significant. For example, between RON 97.5 and 105 at 3000 rpm, the knock limit is increased of 3.3 bar BMEP per 5 RON points increase.

This non-linear occurrence of knock considering RON and engine speed is both linked to the RON effect of the corresponding fuels and to the experimental methodology: no optimization of engine settings (except spark advance).

For the lowest RON values, the low sensitivity of knock limit to RON variation is important because it opens the way to the use of very low octane fuel (RON 71, naphtha), thus improving CO_2 footprint (favourable hydrogen to carbon ratio and less processed fuel at the refinery stage). For RON values higher than 91, the high sensitivity of knock limit to RON variation is important because it enables to perform stock full load curve at optimal combustion phasing (thus improving engine efficiency) and probably to increase the engine's full load capacity (not shown here) with alternative streams with high RON of 111.

3.1.2 RON effect on fuel enrichment limit

Keeping engine settings unchanged (except spark advance) for different TRF fuels (with different RON values), the subject of the current paragraph is to define whether RON influences the fuel enrichment needed at high engine speeds and loads to regulate exhaust temperature as mentioned in paragraph 2.4. In order to synthesize the results, the comparison is not based on the enrichment level for each OP but is based on the comparison of the enrichment limit which is defined as the first OP which needs a FAER superior to 1 for a given engine speed.

For lower RON TRF fuels (lower than RON 97.5), the enrichment limit is reached at the lowest loads, see Figure 4. As RON value increases, the enrichment limit is reached at higher torque. In this case, the enrichment limit is mainly driven by the combustion phasing: more retard gives higher exhaust temperature.

As the RON value increases, the effect of RON on enrichment limit decreases especially at the highest engine speed tested (5000 rpm). Indeed, this is due to the fact that combustion phasing reaches its optimal value, so the RON increase does not change the exhaust temperature anymore. It is worth mentioning that the highest RON value (111) almost suppresses the fuel enrichment up to the stock full load curve at 4000 rpm, leading to additional efficiency gains.

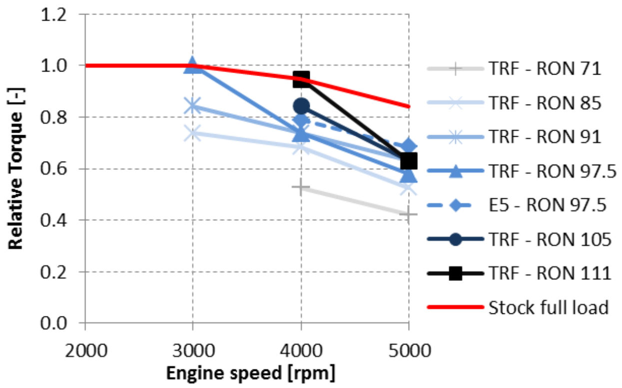

Figure 4: Fuel enrichment limit (FAER > 1) for different RON at CR 10.5:1

3.1.3 RON effect on full load performance

RON value of the TRF fuels changes the global engine behaviour (settings are kept unchanged, except spark advance) not only on knock and enrichment limits but also on full load performances. Here, the objective is not to quantify the full load performance gains thanks to the use of higher than standard gasoline RON values, but rather to assess the loss of performance when decreasing RON value. As mentioned in paragraph 2.4, full load

[2] The estimation of very low octane fuel (as well as octane booster) consumption for different driving cycles for a C-segment car will be the subject of a separate paper.

performance is set either when FAER reaches 1.3 or when CA50 reaches 30°CA ATDC. Figure 5 confirms that full load performance decreases when RON decreases. At low engine speed (≤ 3000 rpm), full load performance is limited by knock level which implies important combustion phasing retard. This combustion retard is all the more important than the RON value is low. For the higher engine speeds (≥ 4000 rpm), the full load performance is limited by the maximum FAER (1.3). As mentioned in paragraph 3.1.2, fuel enrichment limit appears earlier with lower RON values.

Figure 5 and Figure 6 show important loss on full load performance for the lowest RON value (RON 71) especially at 1000 and 2000 rpm. However, when increasing the speed, the corresponding power at 5000 rpm is "only" 25% lower. If RON 71 were used in a car as the sole fuel, the corresponding drivability performances and more largely the efficiency would be quite poor. However, the fact that RON 71 fuel could be used in a car without any engine setting optimization (except spark advance) is already an important outcome of this work.

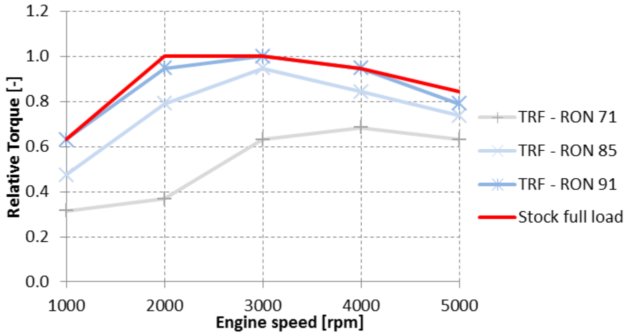

Figure 5: Full load curve for different RON at CR 10.5:1 (limits: CA50 = 30°CA or FAER = 1.3)

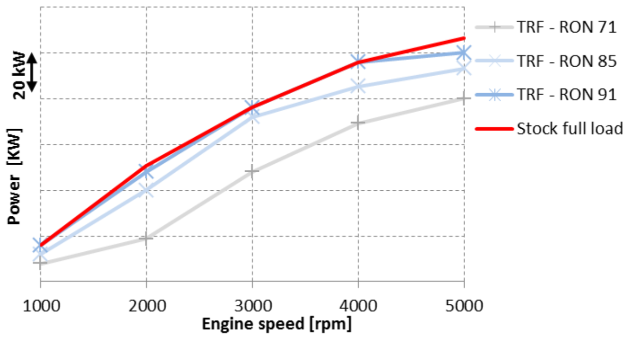

Figure 6: Full load curve for different RON at CR 10.5:1 expressed in effective power (limits: CA50 = 30°CA or FAER = 1.3)

3.1.4 RON requirement at CR 10.5:1

The engine tests performed with stock engine settings for the six TRF fuels with RON values between 71 and 111 enable to define the RON requirement of the engine (in CR 10.5 configuration, with stock engine settings, except spark advance). This full engine map is drawn up based on the knock limit occurrence of different tested fuels (Figure 3). As a matter of fact, RON requirement is defined as the minimum RON value that prevents knock occurrence on a given engine speed and load. To be more explicit, the RON requirement is displayed in Figure 7. As mentioned previously, this knock-free engine map (thanks to variable RON values of fuel) is nevertheless not fuel enrichment-free (cf. Figure 4).

Figure 7 clearly shows that RON 97.5 (RON value of standard gasoline) is not needed in terms of knock occurrence and combustion phasing until average mid-load for this engine with its stock €5 compliant engine settings. However, this waste of octane of standard fuel is now imposed by EN 228 (minimum RON is 95). Nevertheless, this RON level enables to reach the targeted automaker's full load performance.

Figure 7 also shows different knock sensitivities between low and high octane fuels. Indeed, at low RON values, the need for higher RON appears rapidly (in terms of torque): the knock sensitivity to RON variation is low (i.e. higher RON does not allow much higher torque without knock). For higher RON values, this is the opposite: the knock sensitivity to RON variation is higher.

Considering a normalized driving cycle (for example NEDC), based on this RON requirement map (Figure 7), in case of a C-segment car, the lowest RON value fuel (RON 71) could be approximately used up to stabilized 70 km/h. For a whole driving cycle, significant proportion of very low RON fuel consumption can be inferred.

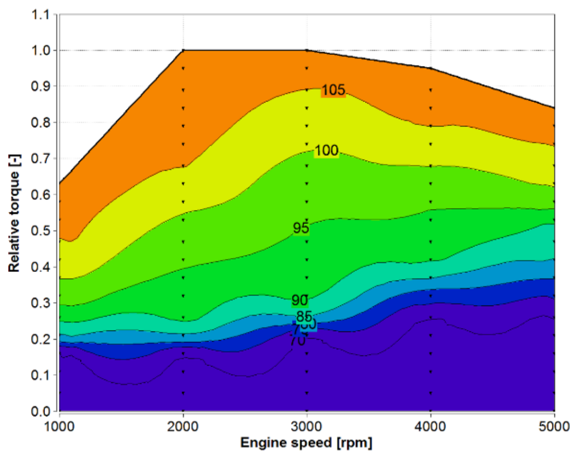

Figure 7: RON requirement at CR 10.5:1 (stock configuration)

3.1.5 Efficiency improvement

The basis of the Octane on Demand concept is the engine efficiency improvement thanks to the suppression of knock occurrence and partially to the improvement of fuel enrichment (as seen in paragraph 3.1.2). To confirm this improvement, Figure 8 shows the efficiency gap between tests performed with TRF fuels at the same RON value as E5 (RON 97.5) and with TRF RON 111. This enables to quantify the engine efficiency improvement linked to the RON increase. Dashed line denotes the knock limit at RON 97.5. First, the efficiency improvement remains lower than 1% on few OP at higher loads than the knock limit. Near the optimal CA50 value, a small combustion phasing variation (within a few degrees CA) does not change significantly the engine efficiency. Second, the improvement with the highest RON value reaches up to 7% at 3000 and 4000 rpm full load. On these OP, both combustion phasing and fuel enrichment levels improve the engine efficiency. The efficiency improvement at 5000 rpm near full load is lower than at 4000 rpm. This is due to the lower RON effect on enrichment limit at 5000 rpm compared to 4000 rpm as already seen in paragraph 3.1.2 and Figure 4. Finally, quite low efficiency improvement at 1000 rpm is linked to the relatively low engine torque at stock full load, which does not require a significantly retarded combustion phasing. At this low engine speed near full load, scavenging helps to maintain a good combustion phasing. At 1000 rpm stock full load, combustion phasing is about 16°CA ATDC with TRF RON 97.5, whereas it is about 22°CA ATDC at 2000 rpm stock full load.

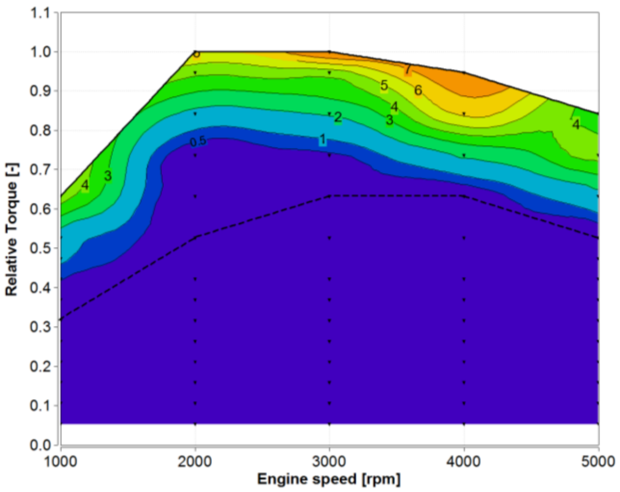

Figure 8: Efficiency gap (%) between TRF RON 97.5 and TRF RON 111 fuels (dashed line denotes the knock limit at RON 97.5)

3.2 CR ratio variation on RON effect

The Octane on Demand concept enables to seek for wider engine optimization. Varying the compression ratio (CR) is a relatively simple way to affect the global engine efficiency but has an important effect on knock sensitivity. The wide CR variation enables to evaluate a 7.5:1 and a 12:1 engine configuration. The decrease of CR (compared to stock CR: 10.5:1) is higher than the increase (3 points decrease vs. 1.5 increase).

The aim is not to present all the results of the two additional CRs, but mainly the main effect of the CR variation that can be drawn up and finally the RON requirement for each CR.

3.2.1 Knock limit similarities and differences for the two extreme CRs

Figure 9 to Figure 11 show, as already seen in previous work [7, 13, 14], that the higher the CR, the lower the knock limit (appears at lower BMEP). But the knock limit between CR 10.5 and 12 is relatively close. On the contrary, for the lowest CR (7.5), the decrease of knock sensitivity is so important that knock is suppressed for all engine speeds and loads with a RON 97.5 TRF fuel (up to stock full load curve, except at 5000 rpm). The main conclusions of Figure 10 are that RON 71 fuel can also be used without knock with CR 12 configuration even though the area becomes very restricted, and that at CR 7.5 RON 71 can be used without knock on about half the engine map (speed and load).

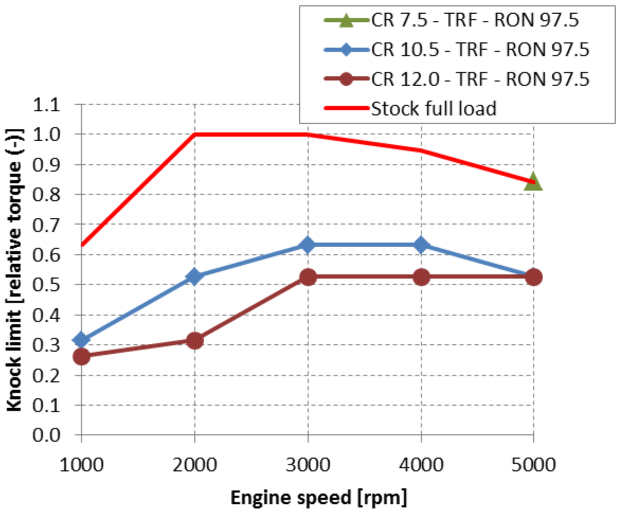

Figure 9: Knock limit at RON 97.5 for CR 7.5:1 (green), 10.5:1 (blue) and 12:1 (red)

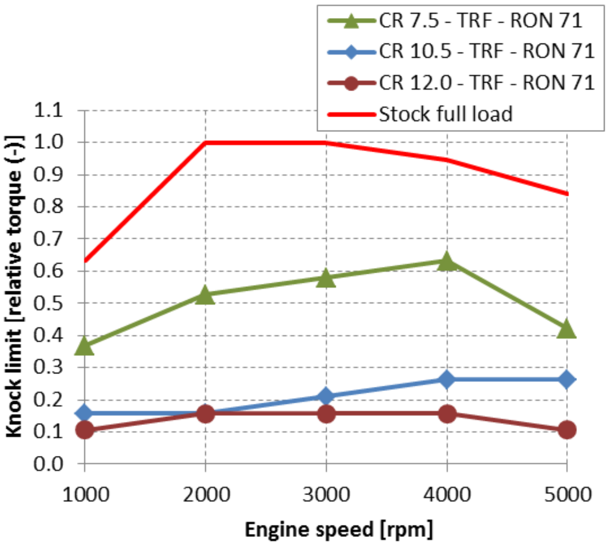

Figure 10: Knock limit at RON 71 for CR 7.5:1 (green), 10.5:1 (blue) and 12:1 (red)

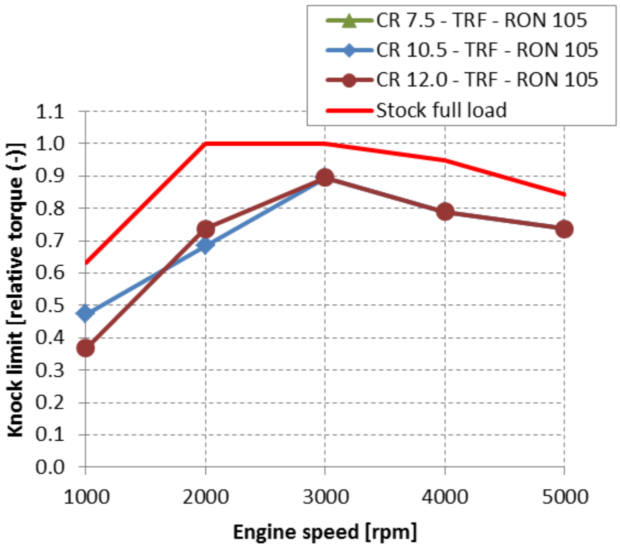

Figure 11: Knock limit at RON 105 for CR 7.5:1 (green), 10.5:1 (blue) and 12:1 (red)

3.2.2 Fuel enrichment limit similarities and differences for the two extreme CRs

As seen in paragraph 3.1.2, the fuel enrichment limit is influenced by the RON, especially for RON values lower than 97.5 (effect on exhaust temperature due to combustion phasing). Now, the comparison of different RON values for different CRs shows that expansion ratio and combustion phasing are the two main levers which draw up the enrichment limit. Figure 12 shows that the expansion ratio is the main lever at RON values higher or equal to 85. The increase of compression ratio mechanically implies an increase of expansion ratio which decreases the exhaust temperature and therefore the fuel enrichment limit.

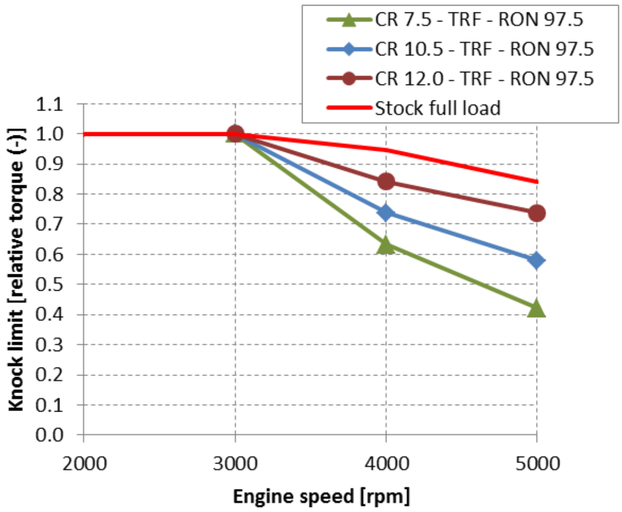

Figure 12: Fuel enrichment limit at RON 97.5 CR 7.5:1 (green), 10.5:1 (blue) and 12:1 (red)

On the contrary, Figure 13 shows that for the lowest RON value (71), the main lever of fuel enrichment limit becomes combustion phasing. For this very knock sensible TRF fuel, on the same OP, the CA50 gap can reach 20°CA for the two extreme CRs. Moreover, at 5000 rpm the enrichment limit is approximatly the same so the exhaust temperatures are the same for the three CRs. Then, the 15°CA CA50 retard gap seems to be equivalent to a 4.5 pt CR gap at constant other engine settings and RON value.

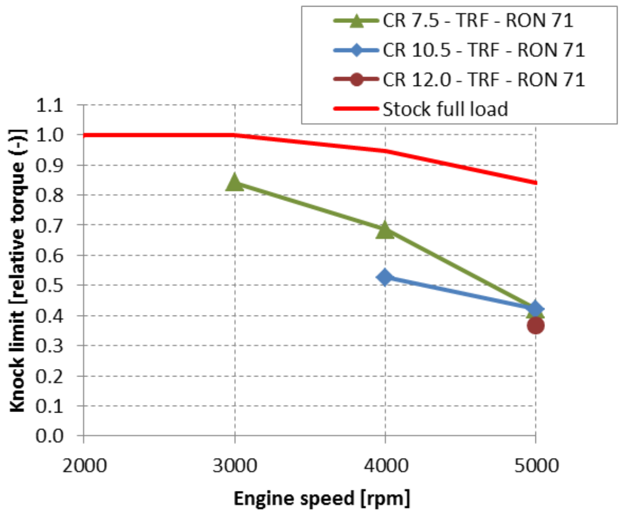

Figure 13: Fuel enrichment limit at RON 71 for CR 7.5:1 (green), 10.5:1 (blue) and 12:1 (red)

3.2.3 Full load curve similarities and differences for the two extreme CRs

The full load curve is defined by the maximum engine outputs when considering the engine limits (CA50 equals to 30°CA or FAER equals to 1.3) with stock engine settings (except spark advance). Figure 14 shows the evolution for the lowest RON value

(71) for the three CRs tested as a function of engine speed. For all engine speeds, the full load curve is higher with the lowest CR. This is the first order effect of lower knock sensitivity when CR decreases. Combustion phasing is the limiting parameter at low engine speeds, whereas the FAER becomes the limiting parameter for engine speeds higher than 4000 rpm.

In the case of the highest CR and the lowest RON value, IMEP stability also appears as a limiting parameter as well as combustion phasing. IMEP stability reaches 4%, which is the consequence of both combustion phasing and surely high IGR rates, because for this fuel, the full load curve appears in the area where the engine volumetric efficiency is voluntarily decreased (valves overlapped).

The main difference between the two extreme CRs (7.5 and 12) is the behaviour trend when engine speed increases. Indeed, at CR 7.5 the full load performance decreases because high FAER is needed due to the low expansion ratio (as mentioned in paragraph 3.2.2). Whereas for CR 12, when engine speed increases, full load limit increases due to the lower knock occurrence (because engine speed increases), even though the limiting parameter at 5000 rpm still remains the FAER of 1.3.

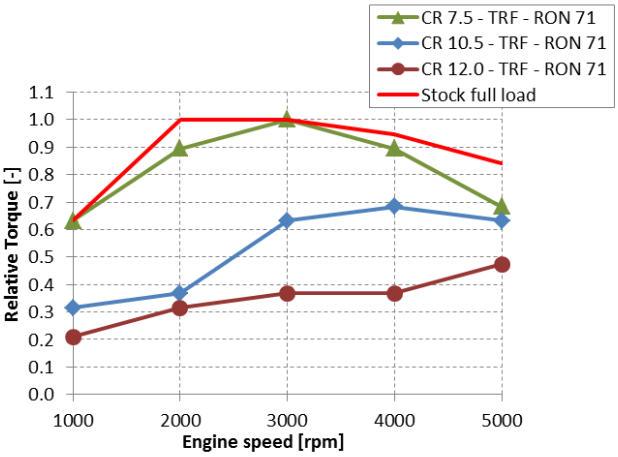

Figure 14: Full load curve at RON 71 CR 7.5:1 (green), 10.5:1 (blue) and 12:1 (red) (limits: CA50 = 30°CA or FAER = 1.3)

Another difference in full load behaviour is the occurrence of maximum in-cylinder pressure limit (mean pressure 100 bar). Once this limit is reached, the combustion is retarded to be able to perform higher load (even if no knock appears). The in-cylinder pressure limit only occurs for TRF fuels with RON superior or equal to 105 and only for CRs 10.5 and 12. As a consequence, engine efficiency is decreased. But considering the imposed RON value of 105 or 111, the occurrence of maximum in-cylinder pressure limit also appears as a waste of RON quality. In future work, final Octane on Demand concept, this will not be the case because for each OP, the RON will be adapted as-needed, just sufficient to avoid knock..

3.2.4 RON requirement at CR 7.5:1

The corresponding RON requirement for the low CR (7.5:1) is displayed in Figure 15. Main difference of RON requirement at CR 7.5:1 compared to 10.5:1 (cf. Figure 7) is the much higher loads reachable without knock at RON 71 (for CR 7.5:1). The knock limit at RON 71 for the CR 7.5 is almost equivalent to the knock limit at RON 95 for the CR 10.5:1. Moreover, the RON requirement gap between CR 7.5:1 and 10.5:1 reaches 25 points RON in the intermediate load area (between 30 and 60% of maximum torque).

Finally, the maximum requirement at CR 7.5:1 is slightly higher than RON 95. So, with standard gasoline (RON 97.5), knock is completely suppressed (until stock full load) with the CR 7.5:1 (3 points lower than the stock CR).

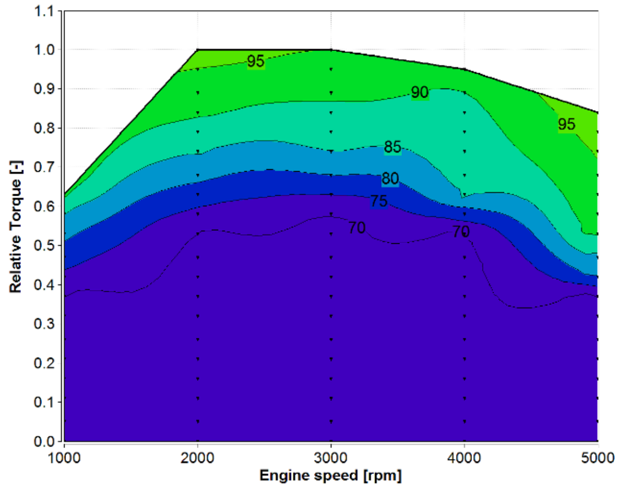

Figure 15: RON requirement at CR 7.5:1

3.2.5 RON requirement at CR 12:1

The corresponding RON requirement for the increased CR (12:1) is displayed in Figure 16. The global trend is as seen previously in paragraph 3.1.4 relatively similar to the RON requirement at CR 10.5:1 (cf. Figure 7).

The main difference between CR 10.5:1 and CR 12:1 appears at low loads for the lowest RON requirement and especially for engine speeds higher than 4000 rpm. The higher knock sensitivity at CR 12:1 is accentuated by the stock engine settings which consist in relatively high IGR rates which increase the knock sensitivity.

As for the CR 10.5:1 configuration, RON higher than 110 is not needed for CR 12. Indeed, max in-cylinder pressure delays the combustion phasing, thus decreasing the RON requirement.

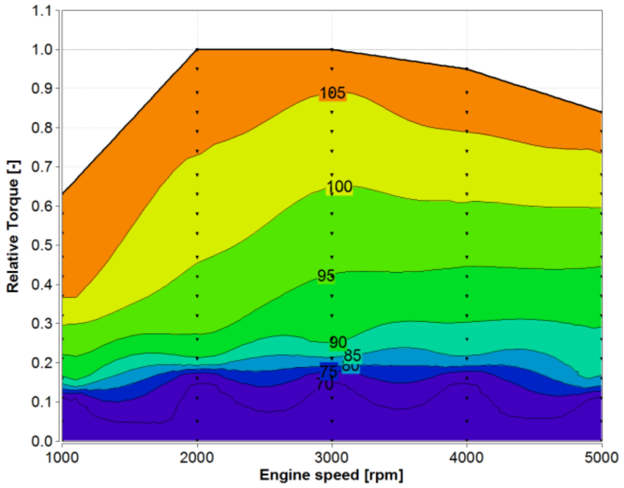

Figure 16: RON requirement at CR 12:1

3.2.6 Efficiency comparisons for the different CRs

The main target of this paragraph is to compare the engine efficiency for the three different tested CRs with the knock free corresponding engine maps. This will give the full engine efficiency potential of each CR configuration in the Octane on Demand concept. However, this does not give the effect of combustion phasing on consumption for the three different CRs. In paragraph 3.1.5, the RON effect (i.e. combustion phasing) is already displayed for CR 10.5. Moreover, the current efficiency comparison is not a detailed comparison but one mainly driven by the first order effects that impact the energy balance of the corresponding configuration: combustion efficiency, LP IMEP, heat transfer, etc.

Figure 17 shows the BSFC (Brake Specific Fuel Consumption) for the stock configuration (CR 10.5) in the case of Octane on Demand concept, so that no knock appears on the whole engine map. This is the corresponding engine efficiency based on the OP displayed in the RON requirement maps (Figure 7). As this is a concatenation of results obtained with different fuels, the BSFC is expressed as BSFC equivalent of E5. Indeed, lower heating value of each TRF and RON values are different due to the different proportion of n-heptane and toluene. Generally, for standard SI engine efficiency (with constant RON value), the minimum BSFC (highest engine efficiency) is reached around 3000 rpm and 2/3 of full load torque. Thanks to the Octane on Demand concept, since there is no combustion retard, the minimum BSFC is reached at full load performance between 2000 and 3000 rpm 230 g/kW.h which corresponds to an effective engine efficiency of 37.1% (a result that may look similar to CNG engines, which also benefit from very high RON values [16]).

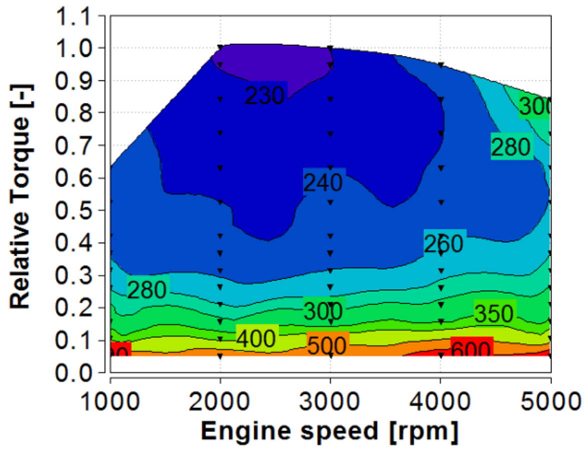

Figure 17: BSFC for CR 10.5 configuration in case of no knock limitation (blue colors indicate the best efficiency zone; as a contrary red indicates the worst)

Figure 18 shows the BSFC gap between the CR 10.5 and CR 7.5 configurations. Both BSFC maps are based on the OP displayed in the RON requirement maps (Figure 7 and Figure 15). The consumption gap is about 4 to 10% lower with the CR 10.5 configuration. Due to the enrichment gap between the two configurations, the maximum BSFC gap reaches about 20%.

The following levers are in favour of better BSFC at CR 10.5 than at 7.5:

- Better theoretical efficiency (Beau de Rochas cycle: CR effect);
- Better pumping losses on half the engine map (at low speeds, high loads only; high speeds from medium loads to full load);
- Better combustion durations (between 0 and 10°CA faster);
- Lower exhaust heat losses;
- Lower wall heat transfers (lower combustion chamber surface in case of CR 10.5).

The only two levers that partially counterbalance the better efficiency at 10.5 than 7.5 are:

- Better combustion efficiency (higher exhaust gas oxidation due to higher exhaust temperature (lower expansion ratio), and lower HC trapped);

- Better pumping losses on the lower half of the engine map (at low speeds until high loads, high speeds only low loads), due to lower engine efficiency and therefore higher mass air flow.

The three points decrease of CR lowers the engine efficiency by 4 to 20%. At CR 7.5, the maximum effective efficiency is obtained for the same operating point as CR 10.5. BSFC is 248 g/kW.h which corresponds to the efficiency of 34.5%. This represents a decrease in efficiency of 8% compared to CR 10.5 best efficiency.

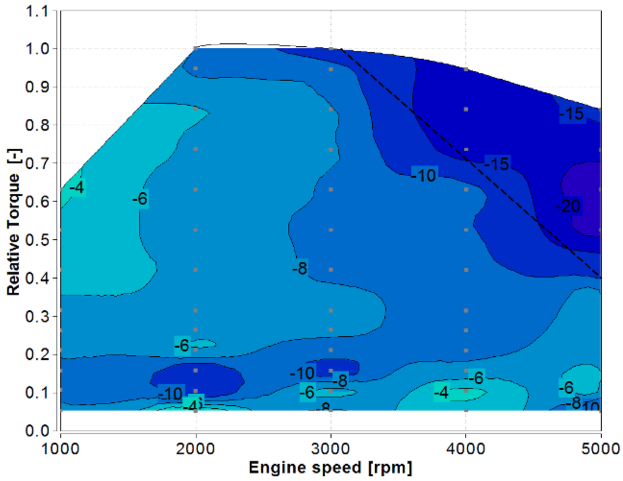

Figure 18: BSFC gap between CR 7.5 and CR 10.5 (blue <=> BSFC 10.5 < BSFC 7.5, dashed line denotes the enrichment limit at CR 7.5)

Figure 19 shows the same BSFC gap as Figure 18, but this time to compare the CR 12 and CR 10.5. The consumption gap is separated into two areas. The major part of the engine map has better engine efficiency with the CR 12: between 0 to 15% lower BSFC. Three levers drive the better BSFC at CR 12 than 10.5:

- Better theoretical efficiency (Beau de Rochas cycle: CR effect);
- Better pumping losses except at low engine speeds and high loads;
- Lower exhaust heat losses.

For loads lower than 20% of maximum torque the best efficiency is obtained with the CR 10.5: between 0 to 4% lower BSFC. The following levers are in favour of better BSFC at CR 10.5 than at 12:

- Better pumping losses only at low engine speed and high load (scavenging zone: intake pressure superior to exhaust pressure);
- Better combustion duration (between 0 and 10°CA faster), due to better combustion chamber shape*;*
- Better combustion efficiency, due to the non-optimal combustion shape at CR 12, higher exhaust gas oxidation due to higher exhaust temperature at CR 10.5;
- Lower wall heat transfer (lower combustion durations).

The 1.5 pt increase of CR, enables to improve the engine efficiency by 0 to 4% for the major part of the engine map and up to 15% in the case of fuel enrichment zone. At CR 12, the maximum efficiency is obtained for the same OP as CR 10.5: BSFC is 220 g/kW.h - efficiency 38.7%. This corresponds to a 4% efficiency improvement compared to CR 10.5 best efficiency.

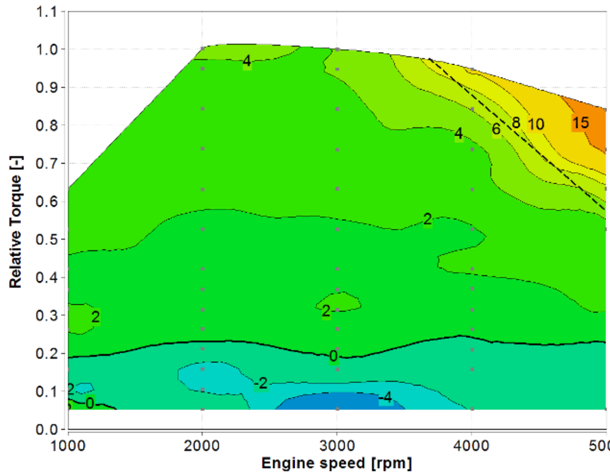

Figure 19: BSFC gap between CR 10.5 and CR 12 (from green to orange <=> BSFC 12 < BSFC 10.5, dashed line denotes the fuel enrichment limit at CR 10.5)

4. Conclusion

The adaptation of RON value for every operating point of the engine map to prevent knock occurrence is an appreciable degree of freedom which is the core of the Octane on Demand concept: higher engine efficiency and possible compression ratio (CR) optimization. The present work enables to establish the occurrence of knock (in terms of engine speed and load) for different surrogate fuels (TRF) with a large RON value variation (between 71 and 111) and for three different compression ratios (7.5:1, 10.5:1 (stock), 12:1) on a modern turbocharged GDI engine.

The RON requirement of the engine shows that very low RON fuel (71) can be used in an up to date SI engine without any settings re-optimization (except spark advance). Indeed, knock does not appear before 2 bar BMEP even with the CR 12:1 configuration, up to 5 bar BMEP at stock CR (10.5:1). This is due to the benefit of a non-linearity in the occurrence of knock for RON lower than 91. This work demonstrates the feasibility of using RON lower than 91 for low load operations. It can be inferred that very low octane fuel (i.e. 71) can be used in significant proportion during different "real-life" driving cycles. This proportion becomes more significant for lower CR. The main advantages of low RON base fuel (naphtha-based fuel) are the lower well-to-tank CO_2 intensity (potential lower CO_2 emissions at the refinery stage) and higher tank-to-wheel "carbon-efficiency" (lower CO_2 emissions due to higher hydrogen to carbon ratio). Furthermore, at high loads, thanks to high RON values (mainly better combustion phasing), the engine efficiency is improved by up to 7%, in case of stock compression configuration: 10.5:1. The increased CR (12:1) enables to reach a maximum efficiency of 38.7%. Moreover, RON requirements enable to account for what could be considered as octane waste for loads lower than the knock limit (obtained with a standard gasoline). This shows the benefits of using a low octane fuel for an Octane on Demand engine.

RON value of the different tested TRF fuels has not only an effect on knock limit but also on fuel enrichment limit and on full load curve (loads higher than stock full load were not investigated). About the full load, stock full load performances are reachable at CR 7.5:1 with RON 91. In case of CR 10.5:1, RON 97.5 needs to be used, and for the CR 12:1, the stock full load is again obtained with RON 97.5. Concerning the fuel enrichment limit, the RON increase allows better combustion phasing which decreases the exhaust temperature and therefore the fuel enrichment limit. But when the combustion phasing is optimum, the effect of RON on enrichment limit becomes negligible.

The next experimental step will be to cross check these RON requirements (obtained with TRF fuels) with RON requirements of real fuels: both for base fuel (low RON: naphtha-based) and for the octane boosters (reformate, ethanol, Superbutol^{TM} etc.). Then a dual fuel system will be designed to feed the engine with both GDI and PFI injections. At test bench, one injection system will be dedicated to base fuel injection whereas the second one will be for octane booster fuel injection. Complete engine calibration will be performed so that the final experimental step will be the implementation of the Octane on Demand concept with dual fuel injection in a demo car.

Moreover, further analysis work will be done to find the best engine configuration i.e. compression ratio and fuels which lead to the best compromise between well to wheel greenhouse gas emissions (CO_2) and fuel consumption (base fuel & octane booster). To do so, driving cycle simulations will be performed for the different tested CRs, with different low octane base fuels and octane boosters for different driving cycles (NEDC, WLTC and "real-life" cycles).

This leads to a global and optimal vision of the energy demand from well-to-wheel, fulfilling the environmental and performance requirements for both automakers and the refining industry.

5. Acknowledgement

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7. Glossary

BMF	Burnt Mass Fraction
BSFC	Brake Specific Fuel Consumption
BTDC	Before Top Dead Center
CA	Crank Angle
CAxx	Crank Angle of xx% burnt mass fraction
CNG	Compressed Natural Gas
CR	Compression Ratio
DIB	Diisobutylene
DISI	Direct Injection Spark Ignition
ECU	Engine Control Unit
EVO	Exhaust Valve Opening
EVC	Exhaust Valve Closing
FAER	Fuel / Air Equivalence Ratio
FCC	Fluidized Catalytic Cracker
GDI	Gasoline Direct Injection
HRR	Heat Released Rate
IGR	Internal Residual Gas
IVO	Intake Valve Opening
IVC	Intake Valve Closing
MON	Motor Octane Number
OECD	Organisation for Economic Co-operation and Development
OP	Operating Point (speed and load)
RON	Research Octane Number
RPM	Rounds Per Minute
SA	Spark Advance (°CA)
SI	Spark Ignition (engine)
SOI	Start Of Injection
TDC	Top Dead Center
TRF	Toluene Reference Fuel
US	United States
VVT	Variable Valve Timing