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TURBOCHARGING TO EXTEND THE CONTROLLED AUTO-IGNITION COMBUSTION RANGE OF A GASOLINE ENGINE

Mario Martins, mario.martins@smail.ufsm.br[1]
Hua Zhao, hua.zhao@brunel.ac.uk[2]

[1]Universidade Federal de Santa Maria, Av. Roraima, 1000 – Centro de Tecnologia, Departamento de Engenharia Mecânica , CEP: 97105-900. Santa Maria – RS- Brazil
[2]Brunel University, School of Engineering and Design, Uxbridge, Middlesex, UB8 3PH, United Kingdom

Resumo: Controlled Auto-Ignition (CAI), also known as HCCI (homogeneous Charge Compression Ignition), is increasingly seen as a very effective way to reduce both fuel consumption and emissions and it`s seen as a potential way to meet future engine emissions legislation. This combustion concept was achieved in a production type, port-injected, 4 cylinder gasoline engine with no modifications to the original configuration other than just the addition of a new set of custom made camshafts and an industry-standard turbocharger. After previous studies with naturally aspirated operation, it was decided to investigate the capability of turbocharging for extended CAI operation.The results show that the CAI range can be greatly improved by the use of a turbocharger. Fuel consumption, however, has increased due to excessive pump losses whereas emissions have been reduced substantially in comparison to the original engine. To better understand the results and to find ways to improve the current set-up, detailed analysis of engine performance and emissions was performed.

Keywords: *cai; hcci; auto-ignition; combustion; engines*

1. INTRODUCTION

One of the most promising technologies aiming to reduce both fuel consumption and emissions from internal combustion engines is CAI/HCCI combustion which has been under intense investigation over the last decade. This technology shows a great potential in reducing fuel consumption and emissions levels, while still retaining a substantially standard engine concept. In addition, by providing very low emissions levels, it does not need expensive and complicated exhaust after-treatment systems.

CAI combustion is a process that combines characteristics of both SI and CI engines. It relies on the compression and charge heating to promote auto-ignition of a premixed combustible charge and its subsequent combustion. Controlling temperature and composition of the charge enables the auto-ignition of very lean or highly diluted mixtures and combustion at low temperatures, substantially reducing NOx emissions. Since the engine operates at WOT, no throttling losses are present., resulting in significant improvement in the part-load fuel economy of a gasoline engine.

The CAI combustion method was first studied in the late 1970s by Onishi et al.(1979) (the ATAC paper) and Nogushi et al. (1979) working on conventional 2-stroke gasoline engines. The first experiment on a 4-stroke gasoline engine was achieved by intake charge heating as reported by Najt et al. (1983). The effects of A/F ratio, exhaust recirculation (EGR), fuel type, and compression ratio on emissions and the attainable HCCI range were studied by Thring et al. (1989). Christensen et al. (1999) tested various fuels with different compression ratios and intake temperatures. Lavy et al. (2000) presented results about the first 4-stroke engine that was able to achieve CAI over a limited load and speed range by means of exhaust gas trapping using bespoke camshafts for negative valve overlapping.

Law et al. (2000) and Milovanovic (2005) demonstrated the use of a fully variable valve train (FVVT) in a single cylinder engine for CAI combustion. They studied the influence of valve timing events on controlling CAI combustion.

The main strategies for achieving CAI combustion in a 4-stroke gasoline engine can be summarized as:

1. Intake charge heating
2. Higher compression ratio
3. More auto-ignitable fuel
4. Recycling of burnt gases

Recycling of burnt gases appears to be the most practical way for obtaining CAI combustion in a gasoline engine, especially if it is done by means of trapping exhaust residuals using the negative valve overlap (NVO) approach (Zhao, 2007).

One of the disadvantages of CAI combustion is its limited range of operation. Measures tackle this problem are therefore very necessary. At the boundaries of the CAI range, cycle-by-cycle variations tend to increase substantially, eventually leading the engine to misfire. In such a critical situation, it has been shown that spark assistance could help trigger CAI (Wang et al 2006).

A good way to tackle the low volumetric efficiency (low power density) problem associated with residual gas trapping by NVO and, therefore, to expand the CAI range could be the use of forced induction. Indeed, boosting is regarded as an effective way to increase the engine's load range while on CAI operation.

Stanglmaier et al. (1999) researching with Diesel engines stated that highly boosted, fuel-lean HCCI engines appear to be a promising option for producing full power output in stationary and marine applications.

Christensen et al. (1998) showed that supercharging can dramatically increase the attainable IMEP for HCCI/CAI operation. The maximum IMEP achieved was 14bar with natural gas as the fuel. HC emissions tended to decrease with an increase in boost pressure and load. CO emissions showed to be very dependent on AFR and pre-heating. If operated near the rich limit, but with hot inlet air, CO emission was negligible. NO_x emissions were overall extremely low.

Christensen et al. (2000) also studied supercharged HCCI in a single cylinder engine with variable compression ratio (VCR), modified from a truck engine. The engine was fuelled with natural gas and had pilot injection of iso-octane to improve ignition properties of the mixture at high loads. This setup also had cooled external EGR. It was found that supercharging in combination with cooled EGR extends the load limit while keeping maximum cylinder pressures at the same level as the original diesel engine. Substantial reductions of NO_x were achieved at a gross IMEP of 16bar.

Olson et al. (2001, 2003, 2004) investigated CAI/HCCI combustion in several supercharged and turbocharged engines, demonstrating much increased CAI ranges. Several fuels were tested together with different alternatives of EGR, demonstrating the benefits and challenges of this technology. It was found that the best solution for boosting depends very much on the particular application. In addition, it was concluded that turbocharger matching is a key issue for achieving high-load operation combined with high efficiency.

Yap, et al. (2005a, 2005b) investigated the effects of boost on a gasoline engine with residual gas trapping. Boost was supplied from an external air compressor. A substantial increase in the upper limit of load range could be achieved without auxiliary intake heating, while NO_x emissions were characteristically low.

Wilhelmsson, et al. (2007) studied an operational strategy suitable for HCCI operation in a heavy duty turbocharged duel fuelled port injected engine. N-heptane and natural gas were used and the engine was under closed loop combustion control during the experiments. It is stated that the low exhaust temperature of HCCI engines limits the benefits of turbocharging by causing pumping losses, indicating that maximum boost does not necessarily mean maximum efficiency in HCCI engines.

More recently, it has been demonstrated that the range of CAI operation can also be increased by means of exhaust boosting due to exhaust gas dynamics in a 4-cylinder engine through the use of an camless system (Hatamura, 2007).

With all the above, it is proved that there is a potential for pressure charging to be used to extend the CAI/HCCI load and speed range. There are still many drawbacks and pitfalls to overcome, and therefore, further research and development is needed.

This paper reports the modification of a production-type port fuel injection (PFI) gasoline engine to achieve CAI combustion operation under forced induction by means of a turbocharger. The experimental results on turbocharged CAI operation are presented and analyzed. Engine performance and emission parameters are assessed and analyses are carried out.

2. EXPERIMENTAL PROCEDURE

2.1. Engine Set-Up

This research was carried out on a 1.6 litre gasoline engine equipped with Ti-VCT (Twin Independent Variable Cam Timing). The maximum shifting range for the VCT units is 47°CA for the exhaust and 52°CA for the intake. An aftermarket engine management system and an in-house built wiring loom were used to control the spark timing, and air/fuel ratio through a lambda sensor. This set-up had been used for previous experiments with NA CAI combustion (Martins, 2007).

The only substantial modifications on the engine were the replacement of the original camshaft by a new set of bespoke low lift/small duration camshafts, the installation of a turbocharger and new exhaust manifold and the reduction of the compression ratio by means of a spacer plate.

Due to the nature of CAI combustion and its low levels of energy available in the exhaust, it was very difficult to find a turbocharger that could properly match the engine. The best choice commercially available was indicated by the manufacturer to be used with a 500cc displacement four-stroke gasoline engine. The lack of information about this unit was also a difficulty encountered.

The fuel used was standard unleaded gasoline of 95 RON available in UK. The engine was coupled to a 230KW AC dynamic dynamometer for speed and load control. Exhaust measurements were carried out using a Horiba 7100-DEGR exhaust gas analysis equipment. Emissions of Carbon Monoxide (CO), Carbon Dioxide (CO_2), Oxygen (O_2), Unburned Hydrocarbons (uHC) and Oxides of Nitrogen (NO_x) could be measured. The heat release analysis was based on in-cylinder pressure measurements using a Kistler 6121 piezoelectric transducer installed in the number 4 cylinder. Exhaust temperatures were measured via standard thermocouples placed in the exhaust ports. All other temperature measurements were also done using standard thermocouples. It should be noted that all the values for pressure in this paper are given as gauge. Table 1 summarizes the engine specifications and test conditions.

2.2.The CAI Engine Operation

The method for obtaining CAI is similar to the one used in previous experiments [22], with the particularity of having a turbocharger installed. Together with intake boosting, the NVO approach was used and the amount of residuals was directly affected by boost pressure as well as valve timing.

The NVO strategy can be achieved by early exhaust closure and late inlet opening. However, in the case of mechanical camshafts, the change in EVC would also affect EVO. Early EVC would result in advanced EVO, impairing the expansion stroke. This means that for running with CAI, a camshaft with smaller duration was needed. This, in turn, would result in the same cam having a smaller lift in order to keep it inside reasonable acceleration limits. The same applies for the intake cam.

The camshaft profiles initially used were the same low lift/duration as those used in the previous experiments with NA CAI combustion [22]. However, with such low lifts it was impossible to generate enough exhaust flow to drive the turbocharger. As a result, it was decided to use a new intake camshaft, with higher lift and longer duration. The profile for the new intake camshaft is shown in Figure 1, which also shows the valve timing used. EVC was chosen to have a range from 44 to 64°CA BTDC and IVO had a range from 25 to 75°CA ATDC.

With the use of the higher lift intake cam (4mm), it was possible to produce substantially higher boost levels, which would put the engine straight into the knocking zone. Even with increased residuals, knock would still take place, narrowing the available operating range. In order to reduce the engine's knock sensitivity, it was decided to reduce its compression ratio.

Table 1 Ford Duratec 1.6L Ti-VCT Engine Specifications and operating conditions

Engine Type	Inline 4-cylinder
Bore (mm)	79
Stroke (mm)	81.4
Displacement (cm3)	1596
Fuel Supply	Port Injection
Original Compression Ratio	11:1
Modified Compression Ratio	8.8:1
Fuel	Gasoline 95 RON
Coolant temperature	90°C

Fuel line pressure	3.5 bar
IVO	25^o-75^o ATDC
EVC	44^o-64^o BTDC
Boost Pressure (gauge)	0.14 - 0.64bar
Engine Speed	1250-4500rpm
Throttle Opening	100%

After having the compression ratio reduced from 11:1 to 8.8:1 via a custom made cylinder head spacer, testing could actually start. With the reduced compression ratio, the engine operating range was largely improved so that comprehensive experiments could be carried out.

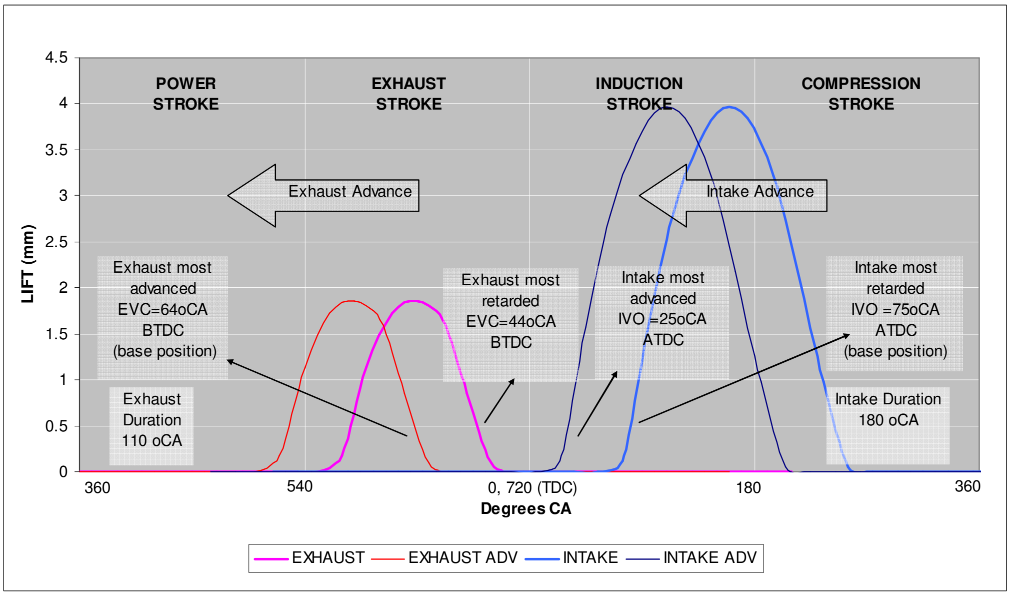

Figure 1 Intake and Exhaust cam profiles and VCT range for the turbocharged operation

2.3. Turbocharged engine operation and test procedure

For the current experiment, the engine was kept at WOT and the air flow was varied by changing the valve timing. The engine was started in SI mode and 50% throttle and left to warm up. When the coolant temperature reached 60oC the valve timing could be changed and the throttle fully opened to allow for CAI operation, which would become more stable as the temperature continued to rise. The engine was kept, therefore, around 90oC coolant temperature to ensure maximum stability for the whole operational range. When running on CAI, the spark could be turned off. However, it was always left on to avoid premature misfiring when the engine was running at highly diluted conditions. The presence of spark ignition was found to increase slightly the CAI range.

3. RESULTS AND DISCUSSION

3.1 Range of the turbocharged engine operation with negative valve overlap

The engine experiments were conducted at 1250rpm, 1500rpm and every 500rpm from 2000rpm to 4500rpm. For every speed, the load range was examined in increments of 0.5 bar BMEP from minimum to maximum load, and, at every step, the combination of IVO, EVC, λ and spark timing that would yield the lowest BSFC value was selected. This was also done in order to minimize data points and to get more comprehensible plots. The achievable range of engine operation with the turbocharger and low lift camshafts is shown in Figure 2 where it can be seen that the engine operated in the SI combustion mode at low speeds and progressively changed to CAI combustion from 2500rpm onwards, when enough hot exhaust residuals could be trapped inside the cylinder.

The higher load range in the SI mode (below 2500rpm) was limited by knocking combustion. Between 3000rpm and 4500rpm, the engine operated in the CAI combustion mode and the upper limits were imposed by the restricted gas exchange process using the low lift cams, or the increased combustion noise. Speeds above 4500rpm could not be achieved, since there was not enough fresh charge been drawn into the cylinder anymore. The lower load range was limited by misfire for all the speeds.

At every speed, the engine's output was primarily controlled by the exhaust valve closure (EVC) timing. As EVC was advanced, load decreased and reached the misfire limit, determined primarily by the amount of trapped residuals, calculated by means of s single-zone model (Fig.4). The misfire limit happened at a near to stoichiometric mixture. However, the lower load limit at each engine speed could be further extended by increasing the air/fuel ratio up to the lean limit and by moving ignition timing away from MBT during SI or spark assisted CAI combustion operations. During full CAI operation (above 3000rpm), changes on ignition timing would have no effect anymore.

A region of strong instability was found at 2500rpm, narrowing the operating range at this condition. However, as soon as the engine passed this point, combustion became more stable and the operating region widened once again.

As it can be noticed from Figure 2, CAI combustion could be obtained at much higher load with the turbocharged operation than the NA operation. The lower load limit, in its majority, tends to be higher than the higher load limit obtained in the NA CAI operation, despite of having higher exhaust temperatures (~600^{o}C), which improve auto-ignition. As it will be discussed later, this is due to the increased pumping losses associated with turbocharging in this particular set-up.

3.2 Turbocharged CAI engine: performance and emissions overview

In the current turbocharged NVO engine setup, boost pressure and trapped residuals were highly inter-dependent variables that directly affected load. Hence, these two quantities could not be analyzed separately, as it will become evident in this section.

The turbocharger chosen for the turbocharged CAI engine set-up was the best match available at the time. However, it is still oversized for the current CAI set-up. Thus, in order to have good levels of boost throughout the whole operational range, the waste-gate was always kept closed, and the turbine received all the exhaust gases produced by the engine. There was no direct boost control and the turbine speed was, therefore, solely dependent on the enthalpy of the exhaust gases produced by the engine.

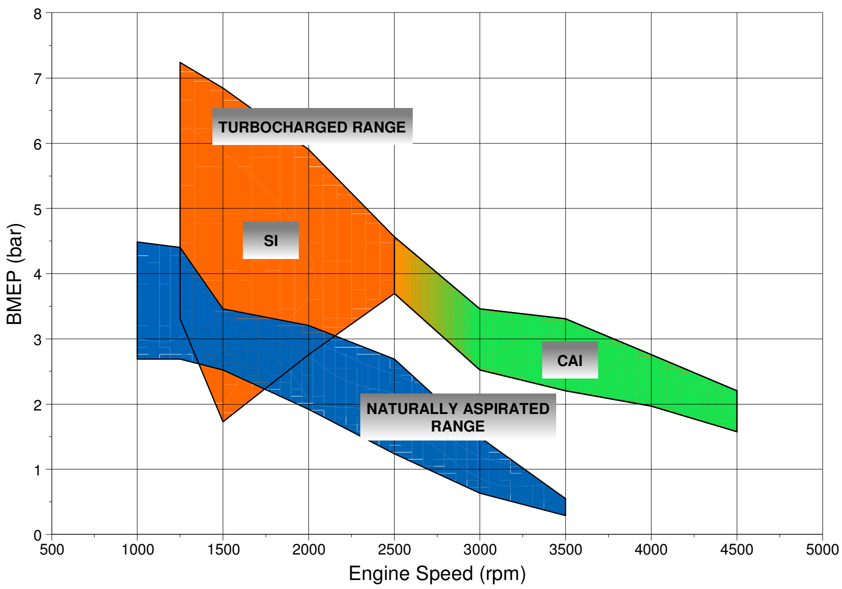

Figure 2 Comparison between NAand Turbocharged CAI ranges

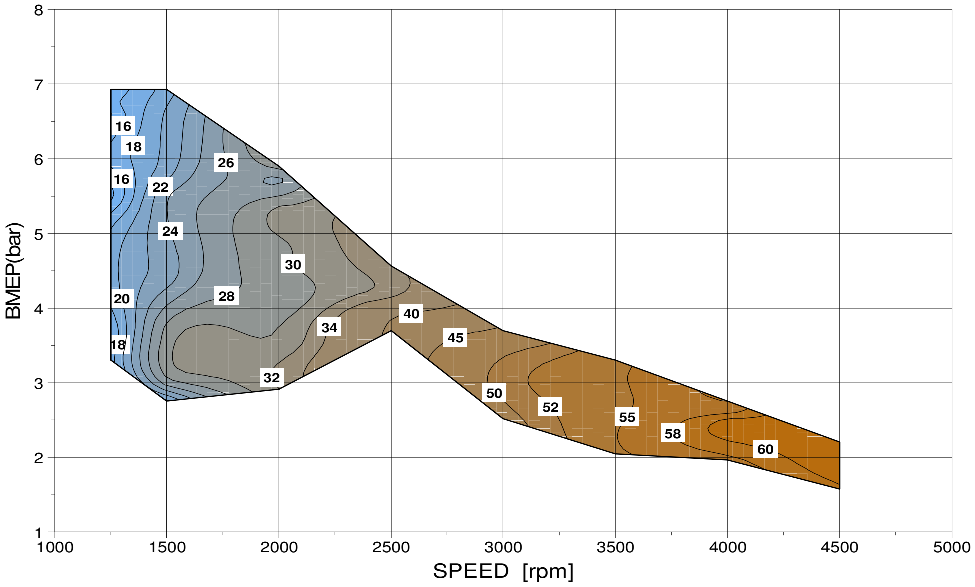

Figure 3 Exhaust residual concentration as a function of speed and load (%)

By changing EVC, the exhaust flow rate could be changed, causing the speed of the turbine and, consequently, the boost pressure to change. With early EVC timings, less exhaust gases were delivered to the turbine and hence lower boost was produced. Conversely, for late EVC timings, higher levels of exhaust were delivered and higher levels of boost were generated. Intake manifold pressure (boost pressure), therefore, had a direct correlation with exhaust residuals, which in turn, affected directly the engine output. The higher the amount of exhaust residuals, the lower was boost and load. Nevertheless, boost levels still showed acceptable values, ranging from 0.20bar at 1250rpm to 0.64bar at 4500rpm.Since the engine had no direct, independent boost control, intake manifold pressure was always determined and inversely proportional to the exhaust residuals rate.

As stated previously, for every speed, the load range was examined in increments of 0.5 bar BMEP from minimum to maximum load, and, at every step, the combination of IVO, EVC, λ and spark timing (in the SI and spark-assisted CAI range) that would yield the lowest BSFC value was selected. It is noticeable that the minimum BSFC region was obtained around symmetrical EVC/IVO timings, which prevent intake backflow to happen and avoid wasting the energy accumulated during the recompression stroke (NVO).

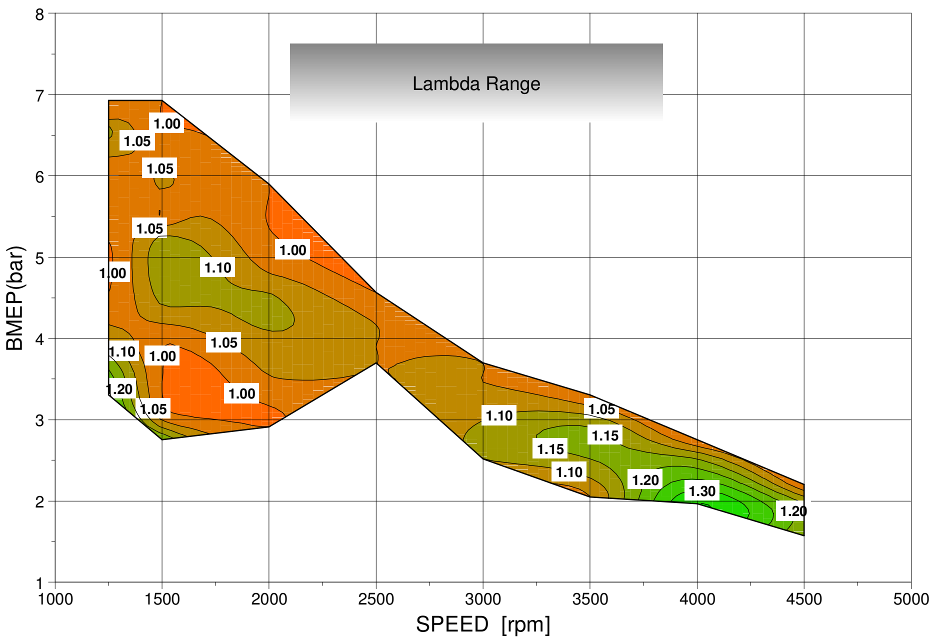

Figure 4 Lambda range for the turbocharged operation for minimum BSFC

Figure 4 shows the λ range for minimum BSFC. It is noted that leaner mixtures were required and that the leanest mixture occurred at high speed when the residual gas temperature reached its highest value, a fact that improves autoignition.

3.3 Turbocharged CAI vs. NA CAI engine: performance and emissions comparison

A comparison of changes in CO emissions of the NA and the Turbocharged CAI engine over the standard SI engine shows an overall reduction reaching up to 80% less CO emissions near the full load curve. This is an indication of a more efficient combustion. In the specific case of the Turbocharged CAI engine, this is mainly due to the lean mixtures used (Figure 4). In the case of CAI combustion, CO emissions are not a real concern. HC and specially NOx emissions are far more important and this paper will therefore focus on them.

Figure 5 shows the HC emissions changes in comparison to the standard SI engine. It can be noticed that HC emissions from both CAI engines are much higher than from the standard SI counterpart. This can be attributed to the fact the highly diluted CAI combustion leads to reduced in-cylinder temperatures, allowing flame quenching at the walls. The Turbocharged CAI engine, however, in comparison to the NA CAI engine, produces much less HC emissions. This can be explained by the fact that in-cylinder temperatures are higher in the turbocharged operation and that due to increased exhaust temperatures and leaner mixtures, some uHC that leave the cylinder can still be oxidized in the exhaust manifold and turbine.

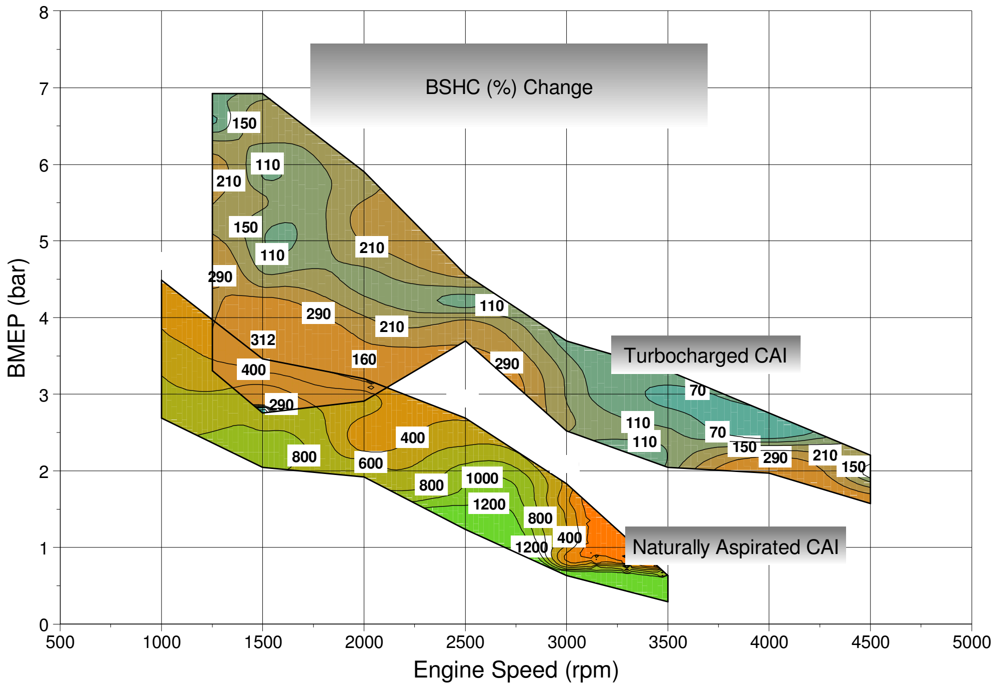

Figure 5 Change in BSHC (%) of the NA and the Turbocharged CAI engine over a standard SI engine

Figure 6 shows that NO_x emissions for both CAI engines are much lower than for the standard SI engine. The NA CAI engine yields ultra-low values (due to its higher charge dilution) while the Turbocharged CAI engine shows some increased results, but still very low in comparison to the standard SI engine. As expected, when the turbocharged engine reaches the CAI range, i.e., above 3000rpm, the reduction in NOx emissions becomes more significant. Again, this is caused mainly by the high residuals rate existent in the CAI range.

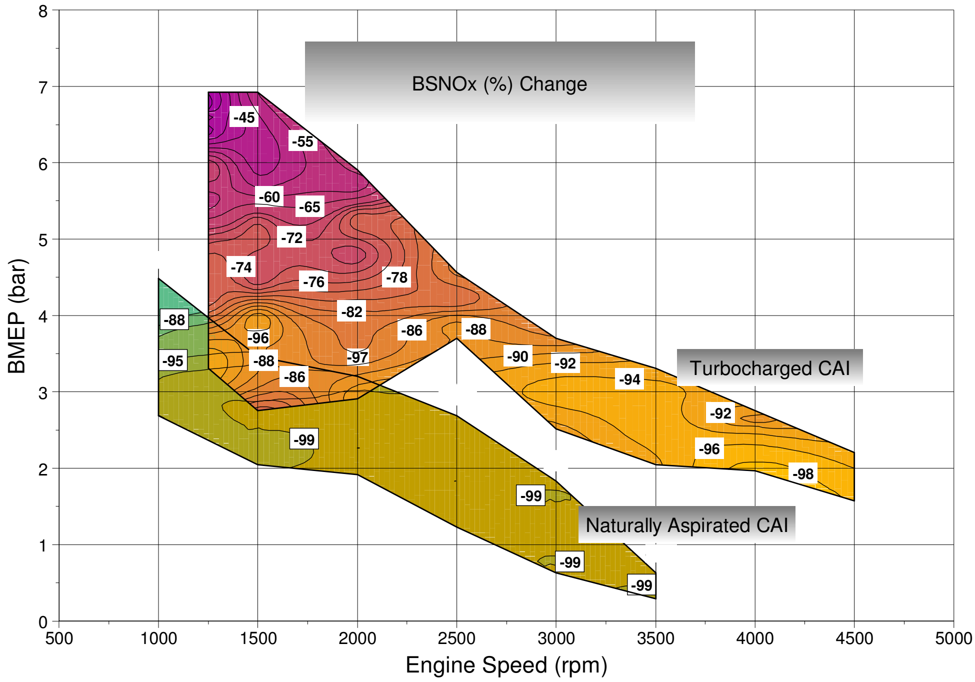

Figure 6 Change in BSNOx (%) of the NA and the Turbocharged CAI engine over a standard SI engine

Figure 7 shows the changes in BSFC of the NA and the Turbocharged CAI engines in comparison to the SI standard engine. With turbocharged operation, BSFC is higher over the whole range by an average of 20%. The main reason for that, as it will be shown later, is the increase in pumping losses caused by the turbocharger, its manifold and the very restrictive camshaft profiles. It can be noticed, however, that the difference becomes smaller at the lowest load points, at high engine speeds, where the standard SI engine operates with more throttling and becomes less efficient. The NA CAI engine, conversely, shows a reduction in BSFC over the whole operational range.

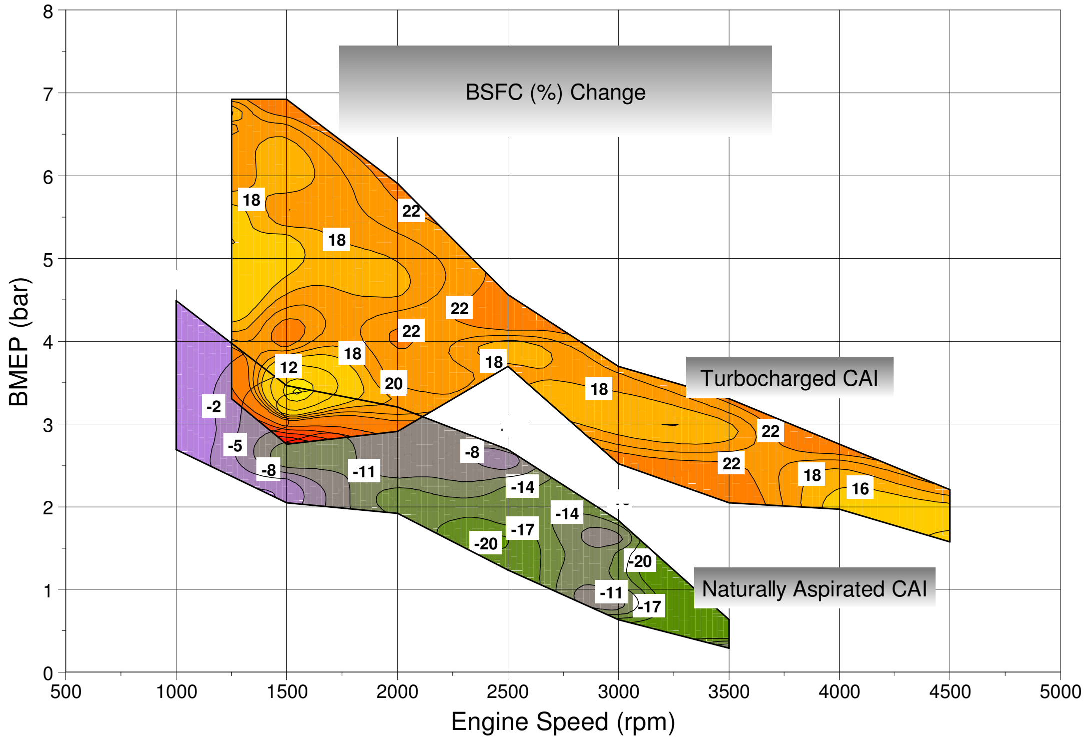

Figure 7 Change in BSFC (%) of the NA and Turbocharger CAI engine over a standard SI engine

Friction tends to be more dependent on speed than load. This fact could be confirmed by the small difference between values obtained with both engines. The NA CAI engine showed an average of 1.5bar FMEP at its highest speed while the Turbocharged CAI showed an average of 1.8bar FMEP at 4500rpm. Since friction values for both engines were roughly similar, it becomes clear that the main reason for the increased fuel consumption of the Turbocharged CAI engine was the excess of pump losses.

An interesting theoretical exercise can be done to assess the improvement that could be achieved in the engine by reducing pump losses. Table 2 shows some performance values for the Turbocharged CAI engine, at 3000rpm and 3.46bar BMEP. At this condition, the engine has its GIMEP reduced by 1.26bar due to pump losses. Normal turbocharged engines with a properly matched turbocharged will have the intake pressure higher than the exhaust, leading to a negative pump work that increases the engines IMEP.

If one keeps the same GIMEP value as before and reduces the PMEP to a (conservative) value of -0.5bar, the engine's brake efficiency increases from about 22% up to 30%, and the engine reaches higher load. Thus, it becomes evident that reducing pump losses in the turbocharged CAI engine will not only increase its efficiency but also increase the load range of achievable CAI combustion, while probably still keeping the benefits of reduced NOx emissions.

Table 2 Efficiency increase by reducing pumping losses

		MEAN EFFECTIVE PRESSURE						
	SPEED	NIMEP	GIMEP	BMEP	PMEP	FMEP	BSFC	BEff
	RPM	bar	bar	bar	bar	bar	g/kWh	%
ACTUAL CAI TURBO ENGINE	3000	4.78	6.04	3.46	1.26	1.31	373.91	21.88
OPTIMIZED THEORETICAL CAI TURBO ENGINE	3000	6.54	6.04	5.73	-0.5	1.31	273.29	29.93

4. CONCLUSIONS

Boosting via turbocharging, in conjunction with residual gas trapping, has been shown to be an effective way to raise the CAI/HCCI load range. It was possible to achieve much higher loads and increase the attainable speed.

Turbocharged CAI operation is still advantageous from the emissions point of view. In comparison to the original SI engine, CO and NO_x emissions show very low figures. HC emissions, despite of being still higher than the original SI engine, are much lower than with the NA CAI engine. In addition, HC emissions can be effectively treated by a standard 3-way catalyst if stoichiometric operation is made constant.

Compared to the standard SI engine, BSFC was 20% higher with the Turbocharged CAI operation. This is mainly due to the increased pumping losses caused by the turbocharger, which affected engine efficiency. The results suggest that a better matched turbocharger would help decrease pumping losses and hence fuel consumption. Moreover, it would enable an increase in load, which, as the results show, would lead to zones of higher efficiency on the engine operating map. With turbocharged operation, the results seemed to be very much dependent on the set-up. The described set-up introduced high pumping losses that impaired the results for fuel consumption. Nevertheless, turbocharging is still a potential way to increase even further the achievable CAI load range and to contribute for the evolution of the CAI technology.

5. ACKNOWLEDGMENTS

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