A STUDY OF COMBINING GASOLINE ENGINE DOWNSIZING AND CONTROLLED AUTO-IGNITION COMBUSTION

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Abstract

In recent years European automotive CO_2 emissions targets have largely been met through increased diesel sales. However, the distillation of crude oil results in high proportions of both gasoline and diesel fuel and ultimately this has resulted in Europe being "diesel lean" at times. In order to meet future global emissions goals, in the short term it will be necessary to improve the fuel consumption of the gasoline engine and in the longer term source sustainable alternatives to crude oil. The objective of the current work was to investigate the optimum trade-off between the opposing engine operating requirements of gasoline engine downsizing and Controlled Auto-Ignition (CAI) combustion for use in a family-sized passenger car. Experimental fuel consumption and emissions data were produced for four sizes of spark ignition engine, varying from 1 to 2 litres in capacity. The additional benefits of two experimentally developed CAI operating methodologies were evaluated in each engine using drive cycle simulation software. The first CAI mode was based on novel use of combined internal and external EGR to attain higher loads. The second involved the adoption of turbocharging at part-load for yet higher output via so-called lean-boosted CAI. It was concluded that, for such a vehicle, a compromise exists where best fuel economy can be obtained from a moderately downsized CAI-capable engine. Compared to the baseline 2 litre engine, it was possible to obtain fuel economy benefit equivalent to that offered from an aggressively downsized 1 litre unit but using a moderately downsized 1.4 litre CAI engine, without the need for any complex boosted operation or expensive emissions after-treatment systems. As capacity was reduced below 1.4 litres, the benefit of CAI diminished at an accelerated rate due to progressive failure to capture key higher load sites visited across the European drive cycle.

Keywords: *road transport, combustion engines, fuel economy, controlled auto-ignition, downsizing*

1. Introduction

Controlled Auto-Ignition (CAI) is a unique form of engine combustion that presents one possible solution for improved gasoline engine fuel economy. The basic principle is to invoke auto-ignition of the fresh mixture at multiple sites throughout the chamber. This ultimately results in a combustion process that is relatively fast and more akin to an idealised combustion event. In order to avoid excessive levels of heat release a high level of dilution must be used, usually in the form of recycled burned gases, excess air or combinations of both. The arising ability to operate the engine at or near to wide-open throttle at low engine load enables significant improvement in fuel consumption; with up to ~45% of the energy in the fuel released as useful work compared with ~25% in a typical gasoline Spark Ignition (SI) engine. An additional benefit of CAI is that low peak gas temperatures are generated, with considerable reduction (~99%) in engine-out emissions of NOx possible.

For four-stroke engine applications, two common approaches have emerged for heating the charge to the point of auto-ignition. The first involves use of high [1] or variable [2] geometric compression ratio in combination with auxiliary inlet air heating and/or exhaust gas heat recovery. This method is commonly denoted as Homogeneous Charge Compression Ignition (HCCI) and is arguably more difficult to implement due to the harsh transient requirements of such heating during real world driving conditions. The second approach involves use of conventional SI engine geometric compression ratio while trapping or re-cycling large quantities of hot burned gases. This technique, first reported during the early 2000's, is often alternatively referred to as CAI and is considered to offer significant advantages on a transient basis cf. the previous HCCI approach; with the engine valvetrain used to govern the mass of residuals trapped and hence degree of heating of the incoming fresh charge [3-5]. As per HCCI, the CAI technique suffers from a limited operating window but previous studies including those by the authors have shown how simple cost-effective mechanical valvetrains can be used to achieve fast and robust transition between SI and CAI combustion and vice versa as the boundaries of the CAI map are encroached [6].

Despite the advantages, significant challenges remain before CAI can be brought to market. These include maximising the operating envelop and implementing sophisticated control systems to manage variation in the timing of the CAI event and in turn maintain acceptable vehicle driveability. Increased engine noise and potential annoyance due to variation in noise during switching from CAI to SI and vice versa must also be considered [6]. Significant efforts have therefore been made over the last decade to overcome these challenges. Numerous workers have shown how multiple pulse direct fuel injection can be used to achieve a degree of control [7, 8] and/or extend the CAI operating limit via, for example, reformation of part of the fuel [9]. Other methods used to expand the operating window include variable compression ratio [2], spark-assisted operation [10] and combined internal and external EGR [11]. Most notably, intake air pressure charging has also been shown to enable relatively high engine output during CAI. Increasing the intake air pressure may be used to advance the ignition and hence allow more stable operation under leaner high load conditions, while maintaining low levels of engine-out NOx. Earlier studies by the authors [12] and elsewhere [13] have shown that loads up to ~2bar Brake Mean Effective Pressure (BMEP) higher can be achieved albeit reliant on boost pressures of over 1bar gauge being available under such part-load conditions. These studies clearly demonstrated the importance of turbocharger matching and efficiency on net fuel consumption. To date, considerable efforts remain underway within a large US-based consortium to push the CAI upper load limit at far as possible using advanced boosting [14]. These workers and others elsewhere [15] have also developed "feed forward" engine control strategies to help overcome the CAI ignition timing problem.

In parallel to these CAI activities, significant research efforts have been underway to bring "downsized" turbocharged SI engines to market [16, 17]. Such technology is now considered to be sufficiently developed for short-to-medium term introduction, with moderately downsized production solutions now beginning to emerge [18]. The basic principle of downsizing is to reduce the capacity of the engine and hence enforce a larger proportion of operation to higher loads. As a result, both the friction and pumping losses of the gasoline engine can be significantly reduced for a given road load requirement. In order to compensate for the inherent power loss, some form of intake air pressure charging is usually required, together with direct fuel injection and variable valve timing to help cool the charge and optimise scavenging respectively. In addition, recent studies have also found that provided sufficient headroom in engine torque may be made available in highly boosted engines, such downsized units also lend themselves to simultaneous use of a longer final drive ratio (reduced gearing in the differential) to force the engine to operate in a more efficient region during the legislative drive cycle assessments. This so-called “downspeeding” effect has been reported to allow up to an additional ~10% improvement in fuel economy under typical part-load conditions but knock-on effects on vehicle performance must also be carefully balanced [19].

Downsizing and downspeeding are conflicting in requirement to CAI, given the increased frequency of operation at higher loads outside of the CAI window. However, the most aggressively downsized engines are not without problems, including issues with supercharger parasitic losses, transient response due to turbocharger lag [20, 21] and an abnormal combustion phenomenon referred to as Mega or Super Knock, the violent combustion associated with which can lead to catastrophic engine failure [22]. It seems prudent to assume that not all future powertrains will be aggressively downsized. Furthermore, downsized engines must still operate at part-load during urban conditions, hence it was considered important in this work to evaluate the nature of the fuel consumption trade-off between such engine operating modes.

2. Vehicle Simulation

In order to assess the benefits of combining CAI and downsizing a series of vehicle modelling work was performed using the commercial modelling package, “GT-Drive”. This software enables the user to build a virtual vehicle driveline and assess it over a drive cycle. GT-Drive has been written to link directly to MATLAB/Simulink software, allowing the user to assemble vehicle control systems within that environment. The driveline is constructed using a library of elements for simple modelling of components such as wheels, clutches, gears, electric motors and batteries. The software is configured to execute in either forward or reverse mode. During the forward mode operation used throughout this work, the model of the vehicle was effectively “driven’ in a similar manner to a real vehicle, with a “virtual driver” required to convert the drive-cycle speed requirement into throttle, brake and clutch inputs to the vehicle.

The basis of any drive cycle simulation is estimation of the road-load losses incurred by the vehicle throughout the cycle being assessed. These losses are effectively the sum of the rolling resistance of the tyres, vehicle body and tyre aerodynamic drag, road gradients and (when applicable) inertia effects. The associated brake power (P_B) required overcoming these losses may be computed as:

$$P_B = mv\left[\mathrm{a}(1+\varepsilon) + gY + gC_R\right] + 0.5\rho C_D A_F v^3 . \tag{1}$$

Where corresponding parameters are defined later in Tab. 1, with the exception of the rotational mass factor ε (~0.1), air density ρ (~1.2 kg/m^3) and gravimetric constant g (9.81m/s^2). Other terms which vary over the drive cycle include the vehicles acceleration (a), velocity (v) and road gradient (Y, expressed as the tangent of the angle of inclination as a percentage).

Such simulation usually requires experimental input data for the vehicle aerodynamic drag and tyre losses, commonly measured experimentally when a real vehicle is taken to a test track and put into neutral gear at high speed then allowed to “coast down” to low speed. Experimental engine fuel consumption operating maps are also required to ultimately determine the fuel being consumed at any instant in the cycle. For best results, the model should finally then be correlated against cumulative fuel consumption data measured in the real vehicle during a “rolling road” chassis dynamometer drive cycle assessment (as undertaken in this work).

The vehicle used in this study was a Model Year 2009 VW Passat class D vehicle fitted with a 2.0 litre Turbocharged Gasoline Direct Injection (TGDI) engine and manual transmission. This vehicle was used because the maximum torque of its 2.0 litre TGDI engine is very similar to that of a 1.2 litre three-cylinder downsizing demonstrator engine being developed by MAHLE [17] and also intended for evaluation in the present work. Fig. 1(a) shows a comparison of the maximum torque data for both engines. Corresponding tractive force “cascade” diagrams, when installed in the baseline vehicle, are shown in Fig. 1(b). Such cascade diagrams show the tractive force at the road wheel in each gear. For the subsequent drive cycle simulation work, the transmission gear ratios and final drive ratio remained unchanged regardless of the engine case being modelled. The key vehicle data required by GT-Drive as input to characterise the baseline vehicle is summarised in Tab. 1.

a)

b)

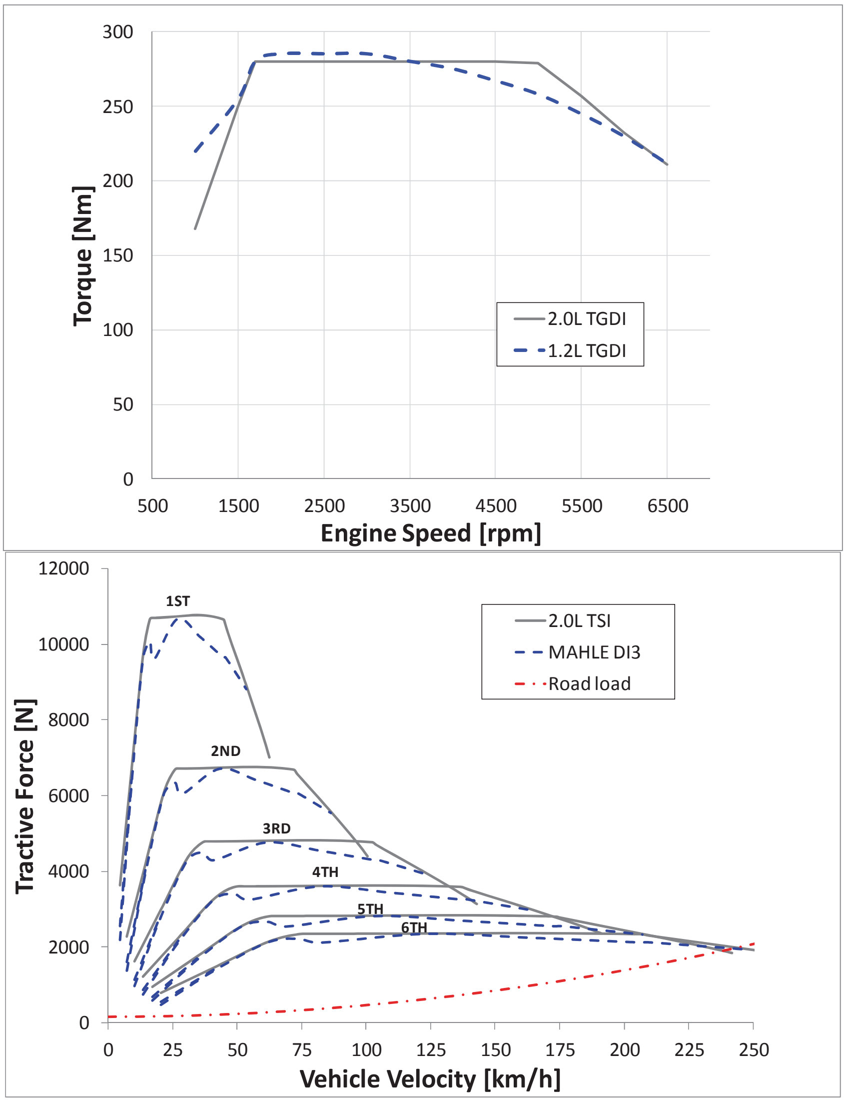

Fig. 1. a) Comparison of torque curves for the 2.0 litre TGDI baseline engine and downsized 1.2 litre engine and b) corresponding cascade diagrams when installed in the class D vehicle ("1st" denotes first gear)

The drive cycle used for the bulk of the analysis was the New European Drive Cycle (NEDC). This standard cycle defines vehicle speed and gear versus time for a vehicle fitted with a manual transmission. The NEDC is made up of two distinct portions. The first 775 seconds, known as the European drive cycle (ECE R15) is formed by four identical sections designed to represent city driving. The next 405 seconds, known as the Extra Urban Driving Cycle (EUDC), is designed to simulate higher speed, rural and motorway driving.

The GT-Drive model of the baseline vehicle and 2.0 litre TGDI engine was correlated to physical drive-cycle measurements performed on a rolling road at MAHLE. The "standard" model parameters that were subsequently adjusted to achieve the correlation included the cold idle speed correction, cold fuelling factor and cold engine friction correction, which were all set to linearly decay over a finite time during the initial portion of the cycle, and the overrun fuelling cut-off parameters. Additionally the gear efficiency values were adjusted to give a good correlation with instantaneous experimental fuel flow data during the constant speed portions of the cycle. The model was then fit for purpose, with the agreement between the total measured and computed fuel consumption over the cycle maintained within 2% error for this baseline case.

Tab. 1. Baseline vehicle data

Parameter	Units	Vehicle Data
Vehicle data		
Unladen kerb weight (m)	(kg)	1615
Wheel base	(m)	2.71
Frontal area (A_F)	(m^2)	2.235
Drag coefficient (C_D)		0.31
Wheel data		
Wheel rolling radius	(m)	0.314
Wheel rolling resistance (C_R)		0.01
Driveline data		
Wheel inertia	($kg.m^2$)	0.6
Final drive ratio		3.94
Final drive efficiency		0.96
Gearbox data		
Number of gears		6
Individual gear ratio & efficiency		1st, 3.36, 94%, 2nd, 2.09, 95%, 3rd, 1.47, 96%, 4th, 1.1, 97% 5th, 0.87, 96%, 6th, 0.73, 95%
Engine data		
Swept volume	(litre)	1.984
Idle speed	(rpm)	850
Maximum engine speed	(rpm)	6000
Engine inertia	($kg.m^2$)	0.15

In addition to the NEDC, a limited number of simulations were also performed using the ARTEMIS drive cycles. These cycles were developed from a long-term European based research project, which considered actual "real world" driving of vehicles across Europe. The ultimate goal of the project was to overcome some of the apparent shortcomings of the legislative cycles in terms of real world fuel consumption figures, which was at least partially attributed to underestimated transient engine operation. The cycles developed were argued to present a significant advantage as they were derived from a large database, using a methodology that was widely discussed and approved throughout industry and academia [23]. The gear shifting strategy prescribed for each vehicle was dependent on vehicle power-to-mass ratio and third gear ratio, with the second category (low motorised) adopted in the currently reported work. Otherwise, the modelling factors remained set as correlated for the baseline vehicle over the NEDC.

3. Experimental Engine Data

Experimental engine fuel consumption maps were required as input to GT-Drive. Set out in Tab. 2 is a comparison of key features for the five engines considered in the currently reported work. All of these engines were previously fully mapped on the test bed at MAHLE for best fuel economy and emissions. The first four engines represent the baseline case and three possible downsized SI engine replacements. The 2.0 litre and 1.4 litre engines were production items, representative of the current state-of-the-art with Europe. The 1.2 litre engine was produced by MAHLE as a demonstrator as previously mentioned to highlight the potential future fuel economy gains of aggressive downsizing [17]. Finally, the 1.0 litre engine data was in reality produced using a second 2.0 litre TGDI four cylinder engine, similar to the baseline as shown and previously described [24]. Set out in Fig. 2(a) is the map of measured fuel consumption for the 1.2 litre unit. Shown in Fig. 2(b) is the corresponding interpolated map ultimately provided as input to GT-Drive. In summary, the quality of the experimental fuel consumption data was very reliable (<1% error for all engines discussed). In order to simulate a 1.0 litre capacity using this 2.0 litre unit, the fuel consumption measurements were obtained at twice the Brake Mean Effective Pressure (BMEP) required for a 2.0 litre capacity. This approach neglected differences in friction due to downsizing and other potential differences such as bore sizing, flow etc. As a result, the 1.0 litre engine data must be treated with some caution when making quantitative observations. The final engine (2.0L CAI) was that used in previous research to produce a viable CAI fuel economy benefit map, which could then be applied to all other fuel consumption maps to quantify the additional benefits of CAI when combined with differing engine capacities.

Tab. 2. Key data for the engines considered

Engine	2.0L TGDI	1.4L TGDI	1.2L TGDI	Simulated "1.0L" TGDI	2.0L CAI
No of Cyls.	4	4	3	4	4
Bore	82.5	76.5	83	87.5	87.5
Stroke	92.8	75.6	73.9	83.1	83.1
Comp. Ratio	10.5:1	10:1	9.75:1	9:1	11.2:1
Variable Valve Timing	Inlet only (42°c.a.)	Inlet only (40°c.a.)	Dual independent (40°c.a. inlet, 40° exhaust)	Dual indept. (35°c.a. inlet, 55° exhaust)	Dual indept. (35°c.a. inlet, 55°c.a. exhaust)
Fuel Injection	Side, multi-hole	Side, multi-hole	Central, piezo	Side, multi-hole	Side, multi-hole
Aspiration	Single Turbo	Compound super-turbo	Twin Turbo (Series)	Single Turbo	Natural or Single Turbo
ECU	Open	Open	Open	Open	Open
Fuel	98RON	98RON	98RON	98RON	98 RON
Peak Torque	280Nm	240Nm	295Nm	200Nm	N/A - prototype
Peak Power	147kW	125kW	144kW	112kW	

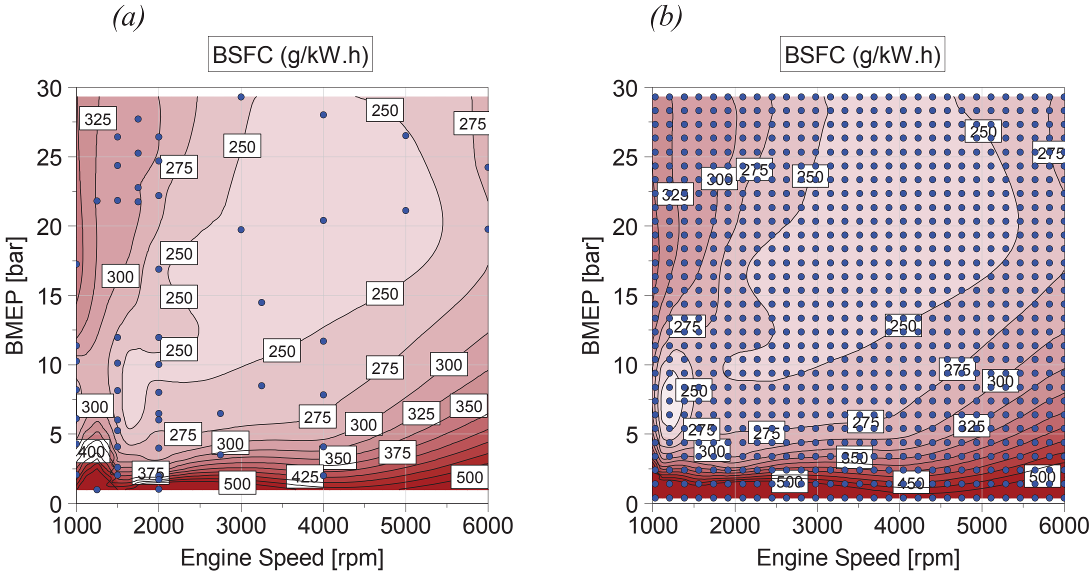

Fig. 2. a) Experimentally measured and b) fully interpolated maps of Brake Specific Fuel Consumption for the MAHLE 1.2 litre downsizing demonstrator engine (BMEP denotes Brake Mean Effective Pressure)

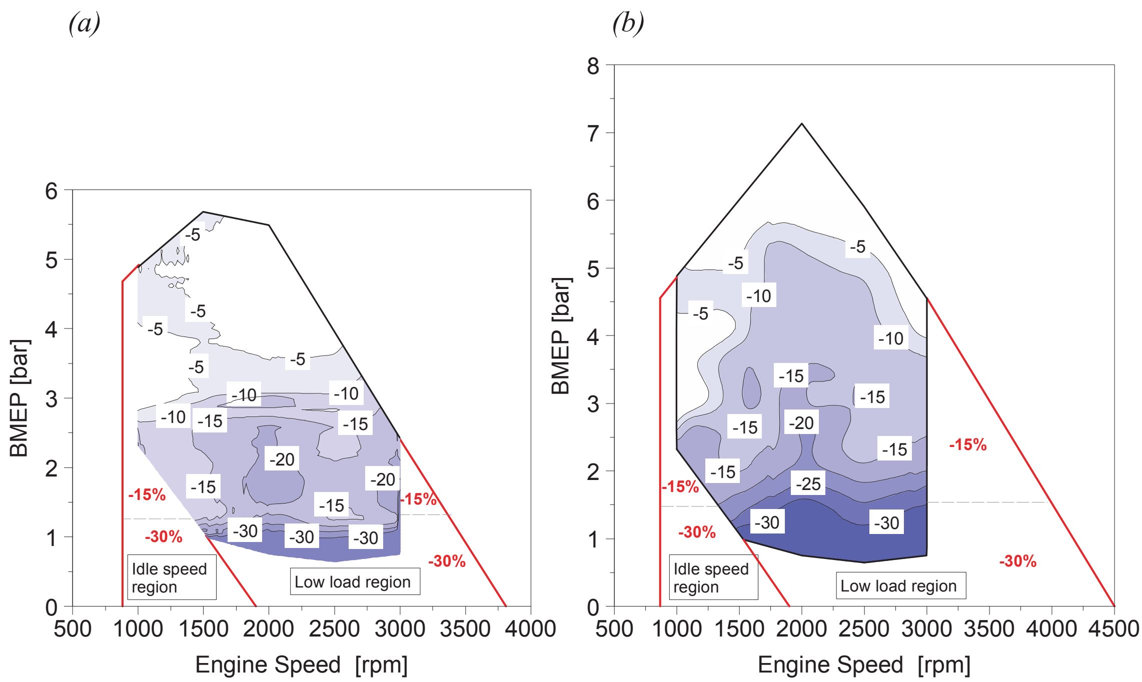

Fig. 3. Experimentally mapped a) naturally aspirated and b) boosted CAI maps, with "idle speed" and "low load" areas of map extrapolation identified (isoline numbers refer to percent fuel consumption change)

Shown in Fig. 3(a) is a map of percent change in fuel consumption achieved via CAI operation in the "2.0L CAI" engine (compared to conventional SI operation). This map was previously measured using negative valve overlap to trap the residuals, combined with external EGR to widen the CAI map [11]. The approach of combining internal and external EGR was highly novel at the time and has been patented by MAHLE. As previously described [11], the use of relatively low amounts of supplementary external EGR (8-12% EGR) enables loads up to 65% higher to be reached during CAI mode by effectively reducing in-cylinder gas temperatures, retarding the point of auto-ignition, decreasing the rate of heat release and reducing the propensity to knock. The area of the map above 3 bar BMEP was produced using combined internal and external EGR under stoichiometric fuel-air conditions; with such fuelling levels required to maintain acceptable tailpipe NOx using a standard three-way catalyst. At lower loads (<3bar) it was found favourable to run using internal EGR alone and fuel-lean, with the relative air-to-fuel ratio increased to λ~1.55 at the lowest loads. In this zone, ultra-low engine-out emissions of NOx were recorded (<10ppm), hence the powertrain remained emissions legislation complaint without any expensive lean NOx aftertreatment (as currently needed on diesel engines). The 2.0 litre engine used to obtain this data was the naturally aspirated version of the engine used to simulate the 1.0 litre TGDI. The main differences were slightly higher compression ratio and the adoption of shorter cam profiles to allow CAI to be invoked via the Negative Valve Overlap technique.

The purpose of the CAI map was to correct the fuel consumption data of each other engine to simulate the additional benefits of CAI operation over a proven CAI operating regime. However, also identified in Fig. 3(a) are two areas where the original experimental CAI map has been extrapolated. The first extrapolation ("Idle speed region") was required to capture idle in CAI mode, as recently demonstrated to be possible by Najt and co-workers at GM [25] using a similar level of engine hardware to that previously used by MAHLE [11]. The second extrapolation was the lower load regime underneath and to the right-hand side of the map. Although this area had not been mapped by MAHLE, it has since been shown by GM [25] that such areas are within reach. As can be seen, the fuel consumption benefit of 15% or 30% within these areas was assumed similar to that within the adjacent area of the original map, which was also in good agreement with previous research at GM. In short, the extrapolation of the CAI map should be considered to be valid.

Set out in Fig. 3(b) is an equivalent CAI map produced using the same 2.0 litre CAI engine but fitted with a small off-the-shelf turbocharger to extend the high load CAI limit even further via lean-boosted operation (with lean operation used across the majority of the map). As previously reported [12], the adoption of boost enables increased mass of air to be inhaled, which not only serves to favourably raise the ratio of specific heats for improved thermal efficiency but also acts as an additional method of charge dilution, reducing the rate of heat release and allowing higher loads to be reached. In order to reach the highest loads intake plenum boost pressures of up to 1.2bar gauge were required (with the relative air-to-fuel ratio increased to λ=1.9). During the currently reported work, this boosted CAI map was extrapolated at lower loads and used in an identical manner to the naturally aspirated CAI data.

4. Drive Cycle Simulation Results

Set out in Fig. 4 are predictions of fuel economy benefit for each of the four engines operating in the different CAI modes whenever possible during the NEDC. The first mode is the baseline case (SI combustion only). The second mode (SI/CAI) is the fuel economy benefit obtained when operating in CAI whenever the original experimental CAI data sets were encroached i.e. reliant on measured data only. The final two modes take into account the additional benefits of capturing the two extrapolated regimes. Two data lines are shown for each capacity of engine, the first represents naturally aspirated CAI and the second lean-boosted CAI (with the extra cost of the turbocharger). Observing the baseline 2.0 litre case, the benefit in capturing the two extrapolated regimes is clear, particularly the engine idle condition (which accounts for ~30% of operating time over the NEDC). Assuming idle can be efficiently reached in CAI mode, or at least spark-assisted CAI mode as previously demonstrated by Najt et al. [25], the fuel consumption benefit of CAI improved from ~11% (without idle) to ~16%. These values were obtained using naturally aspirated CAI operating with internal and external EGR. When the supplementary external EGR was deactivated, the corresponding peak benefit reduced by ~2% due to failure to capture as many of the high load sites. In summary for the baseline engine case, the total fuel consumption benefit of CAI ranges from 16-20% for NA to boosted CAI operation respectively. Such numbers are substantial, especially in the context of the sustained feasibility of using a three-way catalyst alone. However, it is important to reiterate the assumption made that the engine would operate in CAI mode whenever the CAI map was encroached. Whether such an assumption is valid is highly dependent on the future availability of rapid engine warm-up systems and robust CAI combustion timing and noise control.

With reducing engine capacity, an increased amount of time is forced to higher loads outside of the limited CAI operating window. Nonetheless, with the use of the 1.4 litre unit, the estimated peak fuel economy benefit available from naturally aspirated CAI was still ~12%. This benefit was again predicted to fall by 2% if supplementary external EGR was unavailable. Otherwise, it is interesting to note that the benefit of CAI seemed to diminish more rapidly at capacities below 1.4 litres. Furthermore, the additional benefit in adoption of lean-boosted CAI reduced significantly at all capacities below 2.0 litres. These effects can be explained by considering the "bubble plot" fuel consumption data at key sites on the NEDC as set out in Fig. 5. Two sets of bubbles are shown; the first time-weighted and the second fuel consumption rate-weighted. The larger the bubbles, the more time or fuel expended respectively. As shown in Fig. 5, when using the 1.2 litre engine a group of operating points (highlighted by the shaded box) can be seen to migrate outside of both the naturally aspirated and boosted CAI regimes. While these higher load sites were not most significant on a time weighted basis, the equivalent fuel weighted data bubbles illustrate that a reasonable mass of fuel was expended within this regime. The original 2.0 litre engine captured these highlighted sites in boosted CAI mode, which explained the relatively high benefit of lean-boosted CAI operation for the baseline engine. However, for all other capacities the single turbocharger would have failed to capture these sites [12].

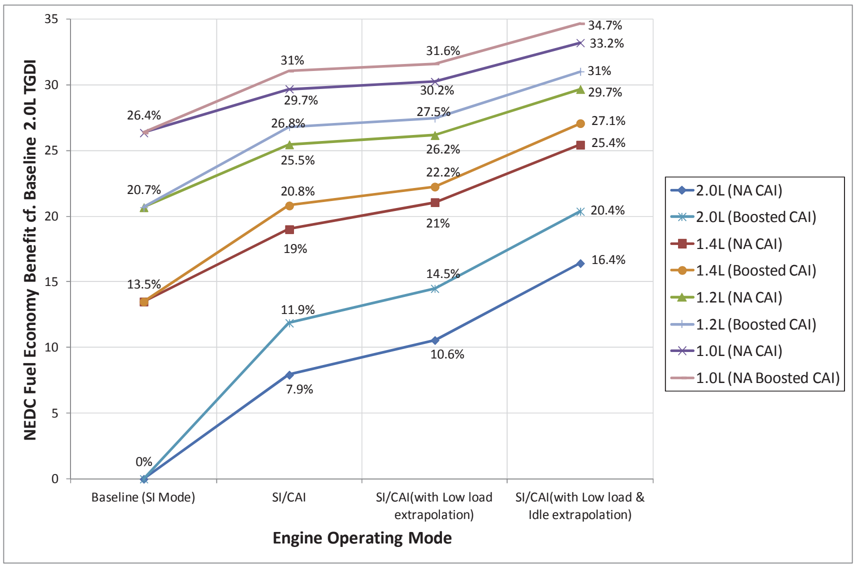

Fig. 4. Combined effect of engine downsizing and CAI combustion on vehicle fuel economy over the NEDC for all engines and CAI conditions examined

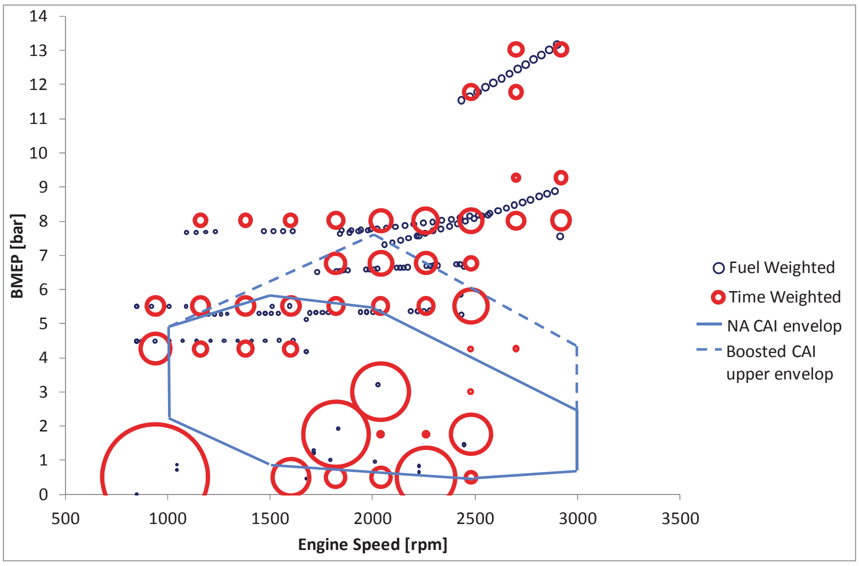

Fig. 5. Fuel consumption "bubble" plots for the 1.2 litre engine with the CAI operating windows superimposed (shaded box area shows the sites lost from the CAI window at capacities below 1.4 litres)

Set out in Fig. 6 are predictions of fuel consumption over the three "real world" ARTEMIS drive cycle modes. The only CAI mode shown is the naturally aspirated case, including extrapolation to the low load region. The benefits of capturing idle or lean-boosted CAI operation were therefore neglected in this part of the work. The urban mode fuel consumption values were very similar to those previously predicted over the NEDC for such CAI operation (within 2% fuel consumption agreement). The average vehicle speed during this mode was 17.5km/h, with 29% of time at idle, 69% at low speed (<50km/h) and 2% at medium speeds (>50<60km/h). For the rural-road mode, the average and peak vehicle speeds were 58km/h and 112km/h respectively, with 59% of time spent between 50-90km/h and good benefits still achieved using CAI. However, for the motorway mode it was apparent that downsizing alone would be a much more fruitful strategy, with the small benefit offered from CAI falling from 2% to ~1% as capacity was reduced from 2.0 to 1.0 litres. Such poor performance was due to significant time spent at higher vehicle speeds and hence moderate engine speeds and loads outside the reach of the CAI maps. During this motorway operation the average and peak, vehicle speeds were 97km/h and 132km/h respectively, with less than 15% of time within reach of CAI mode. When the motorway mode simulations were then repeated for the lean-boosted CAI cases, the benefits of CAI were approximately doubled up to ~ 4% but significant, fuel was still being expended at speeds and loads out of reach (e.g. 3000-4000rpm, 5-10bar BMEP for the baseline engine case). It was therefore concluded that CAI can only offer real world fuel consumption benefits during urban and lower speed rural cruising conditions. For motorway conditions, aggressive engine downsizing appears to offer substantially greater rewards as it is still capable of providing fuel consumption benefits at the moderate speeds and loads outside of the CAI window.

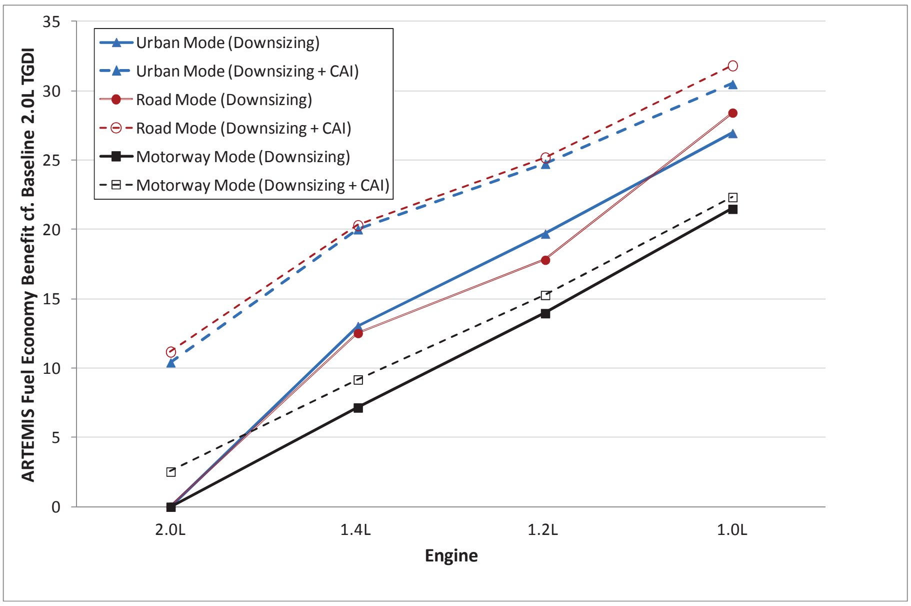

Fig. 6. Combined benefits of downsizing and CAI over the ARTEMIS drive cycles

For such a large passenger car as considered in this study, the current state-of-the-art in terms of minimum gasoline engine fuel consumption may be considered to be a ~1.4 litre TGDI powertrain, as available, for example, in current model year Volkswagen D-segment Bluemotion vehicles (90kW). The engine in these vehicles includes single-stage fixed geometry turbocharging, homogeneous direct fuel injection and variable valve timing. From the drive cycle simulation work performed here, it is also apparent that such a capacity of engine is probably around the smallest viable for combination with CAI combustion, particularly if single-stage boosting can be retained to help alleviate the costs of CAI. The additional hardware requirements for such operation would include external EGR and Cam Profile Switching on both the inlet and exhaust banks. In summary, the results obtained in this work demonstrate that moderate downsizing (in this case around ~30%) and CAI could be used together for high thermal efficiencies but only with single-stage turbocharged engines of low-to-moderate output (for acceptable on-cost) and provided that the remaining barriers to combustion control can somehow be overcome in a practical manner.

5. Conclusions

The effects of combining gasoline engine downsizing with CAI combustion have been estimated using comprehensive experimental engine fuel consumption data and correlated commercial drive cycle simulation software. When simulating the baseline class-D vehicle fitted with a 2.0 litre engine and operating over the NEDC, the following conclusions were made:

– the importance of capturing engine idle in CAI mode was clear, with CAI fuel consumption benefit improved from ~11% (without idle) to ~16%. These values were obtained using naturally aspirated spark-assisted CAI with internal and external EGR,

- when the supplementary external EGR was deactivated, the corresponding cycle peak fuel economy benefit reduced by ~2% due to failure to capture as many high load sites in CAI mode,
- the alternative use of lean-boosted CAI enabled fuel consumption benefits of up to ~20% cf. the baseline SI engine, albeit requiring part-load boost pressures of up to 1.2bar gauge.

As engine capacity was then reduced, the following observations were made over the NEDC:

- with reducing capacity, an increased amount of time was forced to higher loads outside of the limited CAI operating window. Nonetheless, with the use of the replacement 1.4 litre unit, the additional fuel economy benefit available from naturally aspirated CAI still ranged between 10-12%, depending on whether the supplementary external EGR was available,
- with this 1.4 litre engine the individual benefits of downsizing and naturally aspirated CAI were similar, together providing fuel savings ranging from 19-25%,
- as engine capacity was reduced further below 1.4 litres the benefit of CAI diminished more rapidly due to decreasing ability to capture key sites at higher loads where fuel consumption rates were high,
- for a 1.4 litre CAI-capable engine, the avoidance of compound boosting seems essential to maintain acceptable cost-benefit. As a result, it was concluded that CAI and downsizing can be best used together in current large passenger cars of low-to-moderate engine performance,
- for all capacities below 2.0 litres, the additional benefits offered by lean-boosted CAI were much less. For the baseline engine, lean boost had allowed most of the upper loads to be reached (with some only just reached) but for all other capacities key sites were lost from within the CAI map.

When reprogramming the simulation software for the ARTEMIS “real world” drive cycles the following additional observations were made:

- the ARTEMIS urban and rural road fuel consumption values were very similar to those previously predicted over the NEDC, for all engine capacities and CAI cases,
- for the motorway mode, it was apparent that downsizing alone would be a much more fruitful strategy, with small benefit offered from CAI (~1-2%) due to significant time spent at moderate engine speeds and loads outside of all CAI maps. Less than 15% of the duration of the motorway cycle was spent within these CAI regimes.

From these results it can be concluded that moderate downsizing (with in this case around ~30% capacity reduction) and CAI could be used together for high thermal efficiencies but only pragmatically in single-stage turbocharged engine variants and also provided remaining barriers to combustion control can be overcome in a practical manner.

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