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REALISTIC LIMITS OF ICE EFFICIENCY

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KEYWORDS

Internal combustion engine limits, low temperature combustion, early stage of concept, feasibility assessment, optimization of thermodynamic cycle

ABSTRACT

The paper deals with theoretical potential of future design of ICE in terms of efficiency. The results were achieved by means of detailed thermodynamic simulation using system approach (0-D/1-D) – two engine models were applied. The first one is a turbocharged 3-cylinder 1.0L and the engine is supposed to be equipped with expensive technology to enable high flexibility (variable compression ratio, VVA, high efficiency turbocharger, etc). Different combustion concepts, namely standard SI, standard CI and ideal reaction controlled CI (RCCI) were evaluated. The engine setting was optimized to maximize BMEP (full load) and to minimize BSFC (part load). The concepts were compared from thermodynamic point of view. The second engine model is diesel 4-cylinder engine which was optimized without any constraints in several variant with the same maximum output parameters and different level of downsizing. Optimized parameters were similar to first engine but only CI combustion was applied. The geometrical parameters such as bore to stroke ratio was also optimized and it resulted into several variants of engines with fixed geometry optimized in wide range of speed and load. Fuel consumption of those engines was compared in vehicle driving cycle simulation.

TECHNICAL PAPER

INTRODUCTION

Internal combustion engine (ICE) is under increasing pressure to improve its efficiency while decreasing pollutant production. This has been the trend in the last decades, which lead to significant improvement of ICE output parameters. However, there are certain theoretical limits – this mainly concerns engine cycle efficiency. Based on that, nowadays ICEs are relatively efficient and hence, the potential to improve its efficiency is limited. The main contribution has been done by turbocharging-downsizing in recent period. There are certain new 'promising' technologies which may allow further improvement of ICE – this mainly concerns non-standard combustion modes. In the past, homogeneous charge compression ignition (HCCI) was the main topic – it turned out that it is difficult to achieve that under ever-changing operating conditions of ICE, hence it is still not in mass production although it has been developed for over 20 years. Additionally, lean mixture and high EGR poses new requirements on pressure charging of ICE.

Recently, reaction controlled compression ignition (RCCI) emerged as interesting approach – theoretically, it may allow full control of combustion process in terms of rate of heat release (RoHR), i.e., both combustion duration and combustion timing can be controlled. Wide range of air excess/EGR is possible without negative effect on RoHR properties – this allows decreasing in-cylinder temperatures significantly hence, decreasing NOx as well as heat losses. However, to be able to control combustion process, dual-fuel system is needed – there is a main fuel (gasoline) and 'diesel-like' fuel (hydrogen or any other hydrocarbon which has relatively low cetane number), which enables controlled auto-ignition in the whole combustion chamber.

Based on that, there may be only single type future engine (presently we have 2 types – spark ignition and compression ignition engines). Moreover, this combustion concept may overcome two major disadvantages of spark ignition (SI) ICE, namely throttling and knocking, while maintaining all its advantages (especially very low pollutant production without NOx/PM issues).

The research of this promising combustion concept is still in its early stage. There may be some significant issues which will not allow for its application in future ICEs. This paper is not intended to deal with details of RCCI approach nor its development/application. The main goal of the paper is to estimate the theoretical potential (in terms of efficiency and maximum performance) of ideal RCCI combustion system in a case of small

SI ICE for passenger car application. The paper also involves the issues of new combustion modes in terms of downsizing.

MATHEMATICAL MODEL

The results are achieved by means of detailed thermodynamic modelling using 0-D/1-D approach (c.f. [1]) – although there are certain simplifications, the most important phenomena are modelled properly (at least qualitatively), hence the results are supposed to be reasonably realistic. To enable fair assessment of the results, classical ICE (i.e., using both standard SI operation and classical CI operation) is modelled as well using the same simplifications. Two virtual engine models were applied on this study. Both of them were derived from already existing engine models, which were calibrated with respect to experimental data and they are based on mass production ICEs.

First engine model is a 3-cylinder 1.0 litre turbocharged engine. The model is supposed to be a representative of a future design of ICE. Moreover, it is a 'variable' one as it is equipped with fully variable valve train system (allowing nearly arbitrary changes of valve lift profile and/or timing) and variable compression ratio device. On top of that, additional high-efficiency devices are supposed to be applied (e.g., very efficient turbocharger, highly efficient intercooler, pipe systems with low pressure losses, low friction losses, etc). More details can be found in [2]. Concerning combustion mode, the engine is supposed to be able to run in standard SI mode (knocking is taken into account), classical CI mode (Woschni recalculation is applied to consider engine speed and air excess) and ideal RCCI mode (ideal case is considered – both combustion timing and combustion duration can be set independently).

Second engine is a 4-cylinder diesel engine of 1.65 dm3 displacement (bore of 80mm, stroke 82 mm) and BMEP 25 bar in the range of 1000 – 4000 RPM. The initial parameters, including pressure losses, discharge coefficients and mechanical efficiency, are based on real engine tests. BMEP has been increased up to 35 bar during the current optimization, keeping the power at different speeds equal to the initial diesel engine. The displacement was thus reduced. The engine was equipped also with fully variable valve train and fictive turbocharger surrogating two stage turbocharger group with average turbocharger group efficiency of 60 % derived from [4]. Virtual compressor was not limited by surging or choking and it was using reasonable compressor efficiency dependent on compressor pressure ratio and turbine map derived from original one by multiplier of mass flow rate which substituted the VNT, again with feasible averaged rated efficiency. The bore to stroke ratio was optimized in two cases with different level of downspeeding. The peak pressure has not been limited, as well as piston surface temperature, turbine inlet temperature, etc., which is a novelty of this approach.

To automate solution process and provide integration with CAD software, the new version of Design Assistance System (DASY2 or DASY already described in [4] and [5]) was used. The system features descriptive model definition, numerical solvers and optimization algorithms. Any parametric model in DASY is described with available knowledge, and definition of input and output parameters is separated from the model definition. This allows swapping of input and output parameters and solves both direct and reverse design tasks. In this study DASY was used for geometry optimization coupled with optimization of engine thermodynamics and to provide a preliminary estimation of engine mass.

The comparison of fuel consumption of downsized engines with the same power output was calculated for middle class car. The results of fully optimized engines were used as an input of vehicle dynamic simulation of driving cycles.

COMPUTED CASES

The engine parameters are evaluated under steady operation only. The main emphasis is put on low load operation, however full load performance is also considered. Due to high variability, time-demanding multi-variable optimizations were performed to find thermodynamic optimum:

- Minimum BSFC at prescribed engine load
- Maximum power

The optimizations are constrained by the following limits:

- Max. in-cylinder pressure: 17.5 MPa (if not explicitly stated otherwise)
- Compressor surge is checked (and avoided if surge limit is reached)
- Turbine inlet temperature: 1373 K
- Knocking (standard SI operation only): 10%
- Max. internal EGR (standard SI operation only): 25%

- Max. free oxygen at exhaust gasses (standard SI operation only): 5%

The optimal solution is found by genetic algorithm [3] – it was verified many times in the past that the genetic algorithm is very robust and reliable tool for solving multi-variable problem(s) with many constraints.

The following labels are used in figures (of the 1st engine, i.e., 3-cylinder 1.0 litre):

- **ideal_RCCI** – ideal RCCI combustion is considered, engine is equipped with all variable devices: variable compression ratio (range: 9 – 25), fully variable valve train (VVA)
- **standard_SI_ICE** – standard SI combustion is applied, knocking is considered as additional constraint, constant air excess (rich mixture at full load, stoichiometric mixture at part load), constant compression ratio (10.0), cam phasers (VVT) at intake/exhaust valves
- **fullyVariable_standard_SI_ICE** – standard SI combustion is applied, all other parameters are the same as for the case **ideal_RCCI**, the only exception is compression ratio range, which is limited to max. value of 15.5 due to the fact that the knock model was calibrated (based on experimental data) in the range of compression ratio 8.5 – 15.5
- **fullyVariable_standard_CI_ICE** – standard CI combustion (diesel-like) is applied, all other parameters are the same as for the case **ideal_RCCI**

If text label 'no_pMax_limit' is applied, it means that maximum in-cylinder pressure constrain is not taken into account. If text label 'min_LAMBDA=1.3' is used, it means that minimum air excess limit of 1.3 was applied (it concerns only CI combustion mode).

The second engine was optimized to find the best engine for each operation condition, the optimization constraints were pushed far behind the border of real engine limits, and extreme flexibility of control was assumed. The optimized parameters were: start of injection (Woshni combustion length dependence on speed and air excess was applied with reference length of 35 degrees CA), valve timing and the length of lift profile, turbine mass flow multiplier representing VNT position, compression ratio and stroke of the engine. The size of valves and ports and dimensions of combustion chamber in piston were proportionally modified to engine bore. The limit of minimal air excess was set to 1.2. The BSFC was minimized to find the highest possible value for all efficiencies.

To take advantage of downspeeding the optimal engine geometry from optimization results of two engine speeds (1000 RPM and 2000 RPM) was used to create two versions of fixed geometry engines for each downsizing step (maximum BMEP 30 and 35 bar). The optimization settings were used same as mentioned above with exception of geometrical parameters such as bore, stroke and compression ratio, which were fixed. The engine was optimized in wide range of speed and load to create a complete map of the engine. Lookup tables with engine output parameters, including fuel consumption, were used in vehicle dynamic simulation model. The fully dynamic model is currently being prepared. The vehicle was defined by the total mass of 1400 kg, frontal area of 2 m^2 and drag coefficient of 0.3. The gear ratios of manual 5-speed gearbox were optimized for the base engine with maximum BMEP 25 bar and the gearbox was identical for all other engines. To use advantage of long stroke engines would be profitable to adapt gear ratios to keep the engine speed at lower level than in other engines. To highlight the differences in fuel consumption, only resulting from various engine designs, the gearbox was used without changes for all cases. Two variants of the driving cycles were simulated, NEDC and CADC 150 (ARTEMIS).

DISCUSSION OF RESULTS

The results concerning full load operation are shown in Figure 1 – there are actually 8 subfigures which represent important engine parameters (BMEP, BSFC, air excess, total EGR at IVC, maximum in-cylinder pressure, engine compression ratio, angle position of 50% MFB and combustion duration). Regarding maximum achievable engine BMEP, there is little difference between the RCCI case without the limit of maximum in-cylinder pressure (pink curve) and the one including this limit (dark blue curve). This confirms the well-known fact that if certain BMEP level is reached, it does not make sense to increase it (peak pressure) as it only leads to higher maximum in-cylinder pressure while BMEP is almost constant. This fact is related to non-linearity nature of ICE – too high pressure/temperature levels lead to high heat transfer, high pumping losses and low mechanical efficiency. Classical diesel engine (light brown curve) has almost the same potential as RCCI one, however it should be stressed that air excess is set to the value of 1.0 (to have a fair comparison with other variants), which would lead to possible smoke issues. This assumption is important due to the same requirements on energy coverage for boosting. The higher boost pressure is, the more energy demand of a turbine occurs. Simultaneously, temperature of exhaust is decreased, which limits enthalpy head of a turbine. It results in lower gain of positive work during gas exchange. This factor should not be neglected, especially if high EGR rates are required.

Standard SI (green curve) operation is limited by knocking, hence BMEP is significantly lower. If variable compression ratio and VVA system is applied (light blue curve), it is possible to gain approximately 5 bars of BMEP as it enables to lower 'dynamic' compression ratio of ICE. As engine speed is increased, the difference among all variants becomes smaller due to turbocharger speed limit. Concerning combustion timing at low engine speed range, it is shifted strongly into expansion stroke (late combustion) to increase turbine inlet temperature and to decrease in-cylinder heat transfer – this is the case for all variants. Moreover, SI cases are affected by knocking, hence the combustion is delayed even more.

Combustion duration is also important parameter – with the exception of RCCI mode, it cannot be controlled, hence it is a result of empirical models taking into account engine operating conditions (e.g., engine speed, air excess). On the other hand, ideal RCCI mode allows setting an arbitrary value – in other words, it is a result of optimization to achieve highest possible BMEP. It can be seen in Figure 1 that optimal combustion duration is almost constant regardless of engine speed. The exception is very low engine speed range where higher exhaust temperature is needed to increase turbocharger speed. It is interesting to note that the optimal combustion duration is comparable with SI combustion mode. Moreover, duration of CI combustion (diesel) is clearly different but it achieves almost the same BMEP. This leads to conclusion that combustion duration is not that critical – it has its optimal value which is not that different when comparing with standard combustion modes (SI, CI).

The same applies to compression ratio which has its optimal value at different engine load/speed. Concerning VVA system – the optimal setting leads to high valve overlap at low engine speed range to increase mass flow rate (hence improving turbocharger performance), which also improves the knock issue for SI cases. Weak Miller cycle (early IVC) in combination with high compression ratio is convenient at high engine speed range – as the turbocharger operates at its speed limit, the only way to increase BMEP is to improve engine efficiency. Final comment concerns the fact that the main limiting factor (in terms of optimizations) is maximum in-cylinder pressure (RCCI and CI) or knocking (for the SI cases).

It is well-known that a typical automotive engine spends most of its time at low load/speed range, hence it is more important to compare all cases under low load. The BMEP level of 4 bars was selected and the results are plotted in Figure 2 and 3. Although the optimization target is different (to minimize BSFC) when compared with full load operation (to maximize BMEP), the results are similar. The best variant is RCCI one (dark blue curve), however variable CI case (diesel; light blue curve) is very similar. The worst case is standard SI engine (pink curve) while variable SI case (green curve) is between CI and standard SI. Knocking and maximum in-cylinder pressure is not an issue any more.

To analyse the main reasons of BSFC differences, energy balance was evaluated – it is shown in Figure 3 (it consists of six subfigures, most of them are relative values with respect to 'useful' fuel energy – heat transfer, exhaust gas energy, indicated efficiency, mechanical efficiency, indicated efficiency of high-pressure phase and pumping work). The dominant factors are HP indicated efficiency, heat transfer and pumping work. Despite high compression ratio of RCCI and CI variants, heat transfer is better due to significantly higher air excess (SI variants are forced to use stoichiometric mixture due to proper TWC operation). Higher compression ratio also leads to higher indicated efficiency of HP phase of engine cycle for CI cases.

Pumping work is also better (or comparable) due to absence of throttling. SI variants are controlled by throttle, however they operate on EGR limit of 25% (there is no external EGR, hence the EGR value is equal to internal EGR caused by valve timing) to minimize negative effect of throttling. Mechanical efficiency is slightly worse due higher pressure in cylinder.

All these factors lead to a final result that CI variants (RCCI and CI) are clearly better in terms of efficiency (at this engine load, the difference is at least 30 g/kW/h, which is relatively about 10%). Comparing combustion parameters, the following can be stated – combustion is significantly delayed at low engine speeds to minimize heat transfer and optimal combustion duration (RCCI) is almost independent of engine speed (slightly faster when compared with full load operation). The above stated conclusion about potential of ideal RCCI combustion is confirmed for low engine load levels as well – there seems to be very little BSFC potential, hence combustion duration is less important. Concerning VVA system setting, the Miller cycle is used at high engine speed range and the valve overlap is relatively constant regardless of engine speed. Similar comparison was done for other engine load levels (BMEP of 2, 4, 6, 8, 10 and 12 bars) and qualitative conclusions are the same.

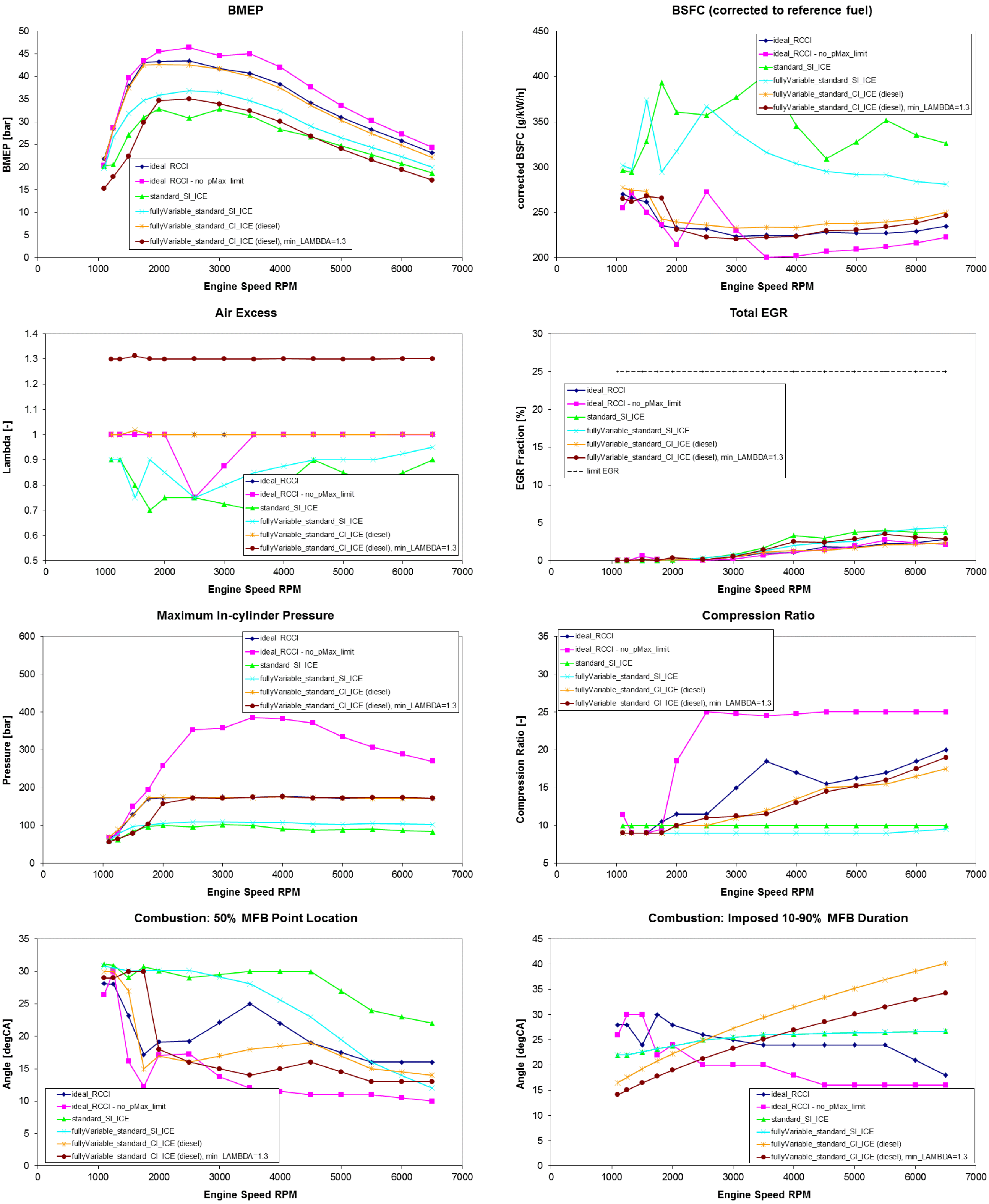

Figure 1: Comparison of considered variants under full load – important parameters of engine operating conditions.

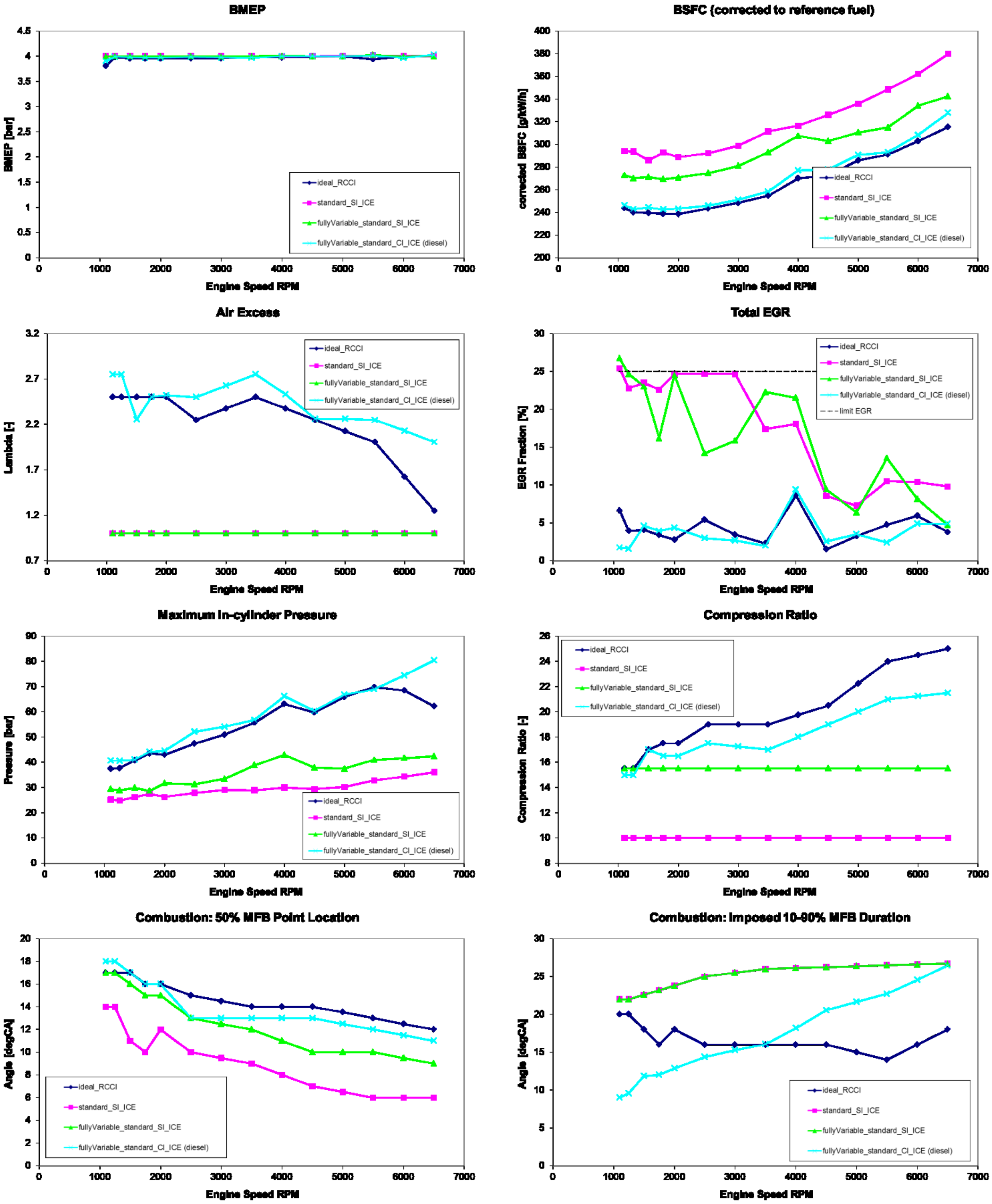

Figure 2: Comparison of considered variants under low load – important parameters of engine operating conditions.

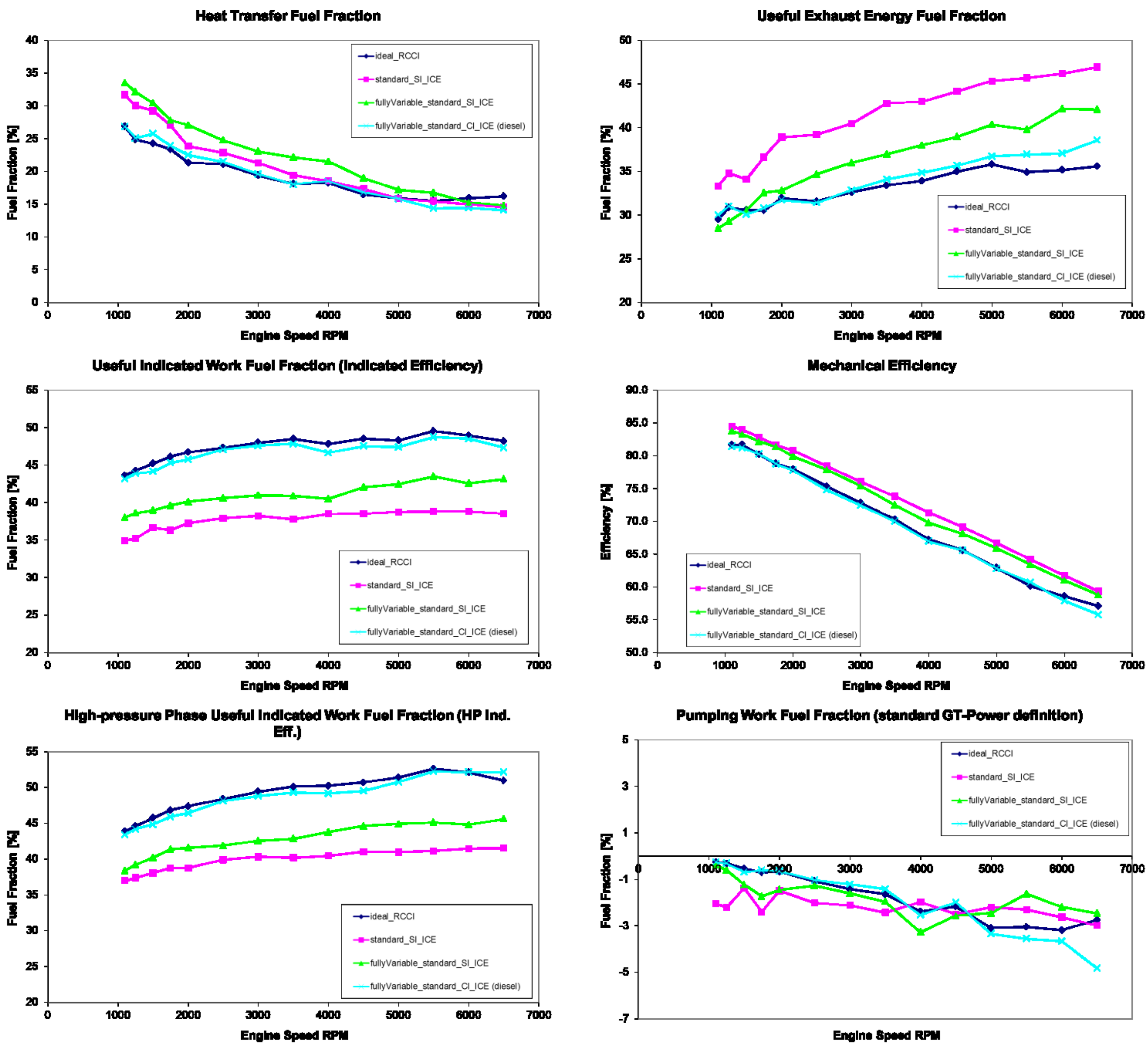

Figure 3: Comparison of considered variants under low load – energy balance.

All above stated results are also valid for of the second diesel engines optimization results. Figure 4 shows dependency of BSFC on the piston stroke. Two values of stroke are compared with optimal stroke for each engine speed for BMEP of 30 bar. Stroke of 120 mm was result of optimization in engine speed of 1000 RPM and stroke of 88.4 mm was optimal in engine speed of 2000 RPM. While at low engine speed both engines are quite comparable, the high engine speed shows disadvantage of too high engine stroke, which is mainly caused by higher pumping losses due smaller valves and ports. The different position of the BSFC optimum can be observed at the full load maps of the engines, which are shown in Figure 6 and 7 for engine with maximum BMEP 30 and in Figure 8 and 9 for engines with maximum BMEP 35. The load-and-speed averaged power in driving cycles is for considered car less than 10 kW. Nevertheless, only small area of BSFC map is taken into account since the engine is powerful enough. The results of driving cycle simulation of the identical car for all engine variants are shown in figure 5. The positive influence of the engine downsizing is promising, however the potential of engines with long stroke was not utilized. To keep engine speed low the gearbox can be adapted or continuously variable transmission (CVT) can be used. Nevertheless, the excessive downspeeding could cause increased fuel consumption not only outside the driving cycle.

In preliminary phase of vehicle design the right engine design could be chosen with help of DASY to predict change in vehicle mass in dependence on level of downsizing. The changes of engine mass are significant if engines themselves are compared but they are not very important for the whole vehicle, making only 1-2 % difference on vehicle mass and driving resistance.

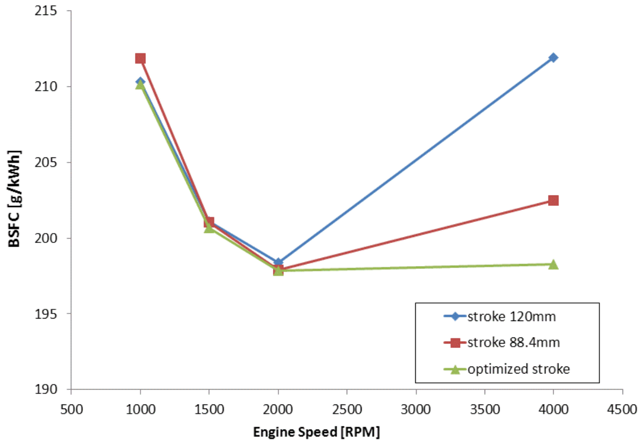

Figure 4: Comparison of BSFC of engines with maximal BMEP 30 bar with different piston stroke.

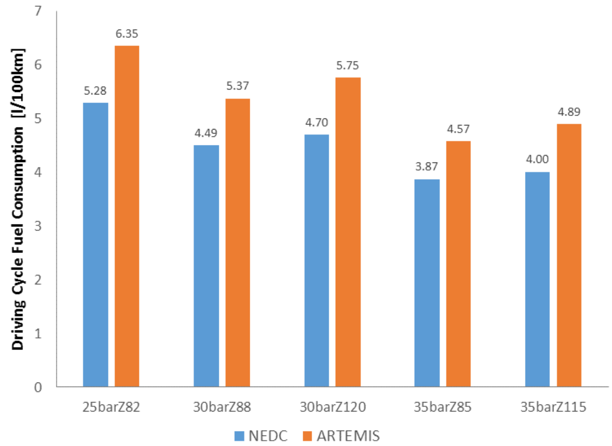

Figure 5:Driving cycle fuel consumption for several downsized engines with different level of maximum BMEP and different stroke.

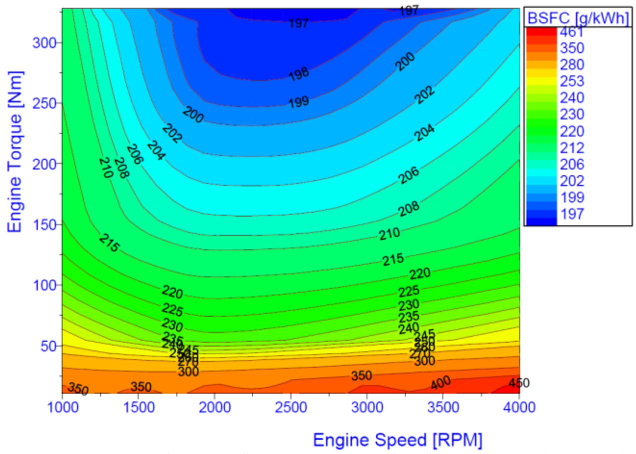

Figure 6: Map of BSFC of engine with stroke of 88.4 mm and maximal BMEP 30 bar.

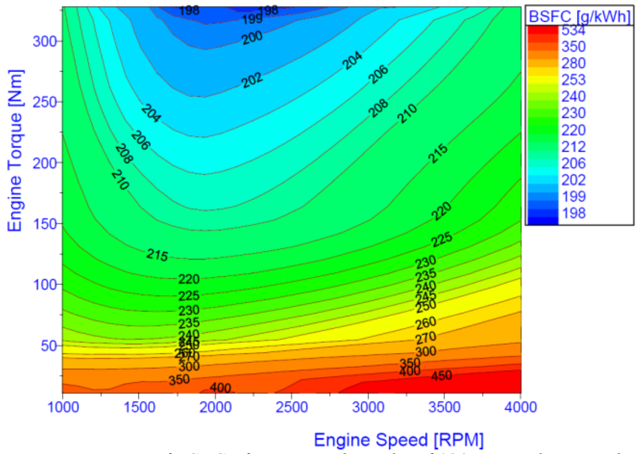

Figure 7: Map of BSFC of engine with stroke of 120 mm and maximal BMEP 30 bar.

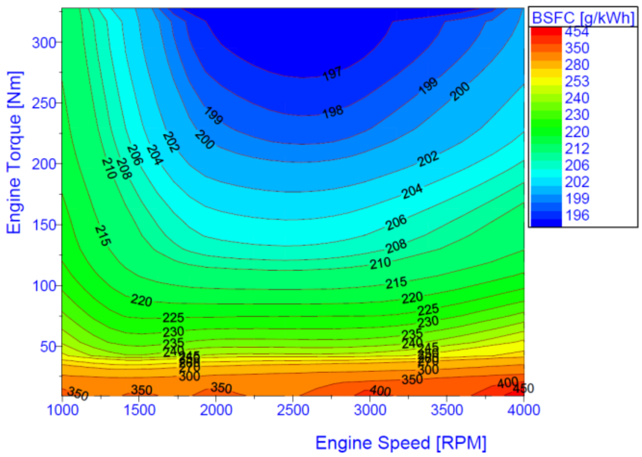

Figure 8: Map of BSFC of engine with stroke of 85 mm and maximal BMEP 35 bar.

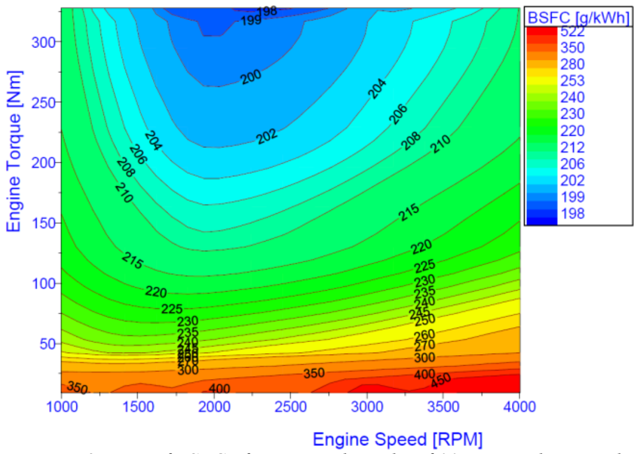

Figure 9: Map of BSFC of engine with stroke of 115 mm and maximal BMEP 35 bar.

CONCLUSIONS

The main target was to estimate the potential of future design of ICE – different combustion concepts were considered: standard SI, standard CI and ideal RCCI. The results were achieved by means of system simulation using 0-D/1-D tool. Although certain simplifications/estimates were made, the mathematical model is relatively detailed and complex as it is based on existing multi-cylinder engine(s) and it takes into account all important phenomena of the ICE physics.

All considered variants were compared under full load and part load (BMEP of 4 bar). All variants were fully optimized using genetic algorithm, which means that multi-variable multi-constraint single-target optimization problem was solved. Especially in a case of 'fully flexible' ICE, there is a lot of variables to be optimized. Use of the unconstrained fully variable engine geometry is obviously not realizable in design. On the other hand it yields the ideas about ultimately achievable limits of efficiency.

Regarding full load operation, RCCI is the best variant (in terms of max. BMEP), however standard CI (diesel) is very similar if air excess of 1.0 is considered (which might be feasible for short time period). Both SI cases (standard and fully flexible) are clearly worse due to knocking issue. The difference among variants gets smaller at high engine speed range due to turbocharger operating on its speed limit. Dealing with part load, the conclusions are similar. The best variant (in terms of BSFC) is RCCI one while standard CI is only slightly worse. Both SI variants are clearly worse due to higher heat transfer (caused by stoichiometric air excess), throttling and limited possibility to change 'dynamic' compression ratio.

Generally speaking, the combustion duration parameter is less important than initially expected – it has its optimal value for each engine operating point, hence very fast combustion is not of advantage in terms of overall engine cycle efficiency. Heat transfer is the most dominant factor at low engine speed range – it can be minimized by means of high air excess, delayed combustion and reduced compression ratio (each parameter has its optimal value under considered operating conditions). The 'dynamic' compression ratio is a key parameter – it can be influenced by engine 'geometrical' compression ratio and intake valve timing (mainly IVC). Based on that, VVA is really of advantage as it enables to use standard/non-standard engine cycles (mainly Miller cycle, i.e., early IVC). Moreover, it enables strong scavenging (due to high valve overlap) at low engine speed range to improve compressor stall issue and to decrease in-cylinder temperature, hence improving knock resistance for SI cases. However, high efficiency turbocharger is needed to take advantage of VVA potential. Based on all the facts, RCCI offers little advantage in terms of BSFC when compared with standard CI. However, it might be significantly better when dealing with pollutants. Hence, RCCI may be a solution taking advantages from SI and CI concepts.

The unconstrained thermodynamic optimization (no limits for peak pressure, fire surface or exhaust gas temperatures, very short duration of combustion, reasonably matched turbocharger efficiency, etc.) does not call either for extreme peak pressures or very short combustion durations as it was presented at [4]. Surprisingly, new combustion patterns pertinent to HCCI-like and dual-fuel systems (PCCI, RCCI, ...) may be important if connected to simpler and less expensive exhaust gas aftertreatment systems, but they do not contribute directly to engine efficiency, if the complete engine cycle (including pumping loop) is taken into account. Moreover, high level of EGR called for by those systems, cannot improve thermodynamic parameters over the limits found by the current study.

The results of unlimited optimization constraints have shown the importance of cooling loss at reduced engine speed and the need of a long-stroke engine design, if low speed is used dominantly in engine operation.

Downsizing may be accompanied by downspeeding, reflected in lower cycle frequency (speed in rpm), which positively increases time for unsteady events during combustion and gas exchange while the cycle cooling loss and the threat of knocking is increased, as well, and mechanical losses are reduced. According to the current results, more can be achieved if downspeeding in terms of mean piston speed is done only by moderate mean piston speed reduction. Especially in the diesel (CI) engine case the stroke can be increased for a downsized engine, reducing mean piston speed less than proportionally to dimensions at the same engine speed while downsizing the engine. All those conclusions are closely connected with correct prediction of heat transfer to cooled walls, especially at low engine speed. The cooling loss importance should be focused by the future investigations, starting with checking validity of used empirical formulae for engine heat transfer coefficient. The efficiency limits presented in this paper for downsized small car four-stroke diesel (achieved values of 40 - 44%, optimum at 2 000 rpm) cannot be used as absolute ones. There are still some possibilities of BSFC reduction if mechanical efficiency is increased by approx. 3% or pressure losses in EGR systems are reduced.

Nevertheless, those limits show that there is a problem to achieve more than 46% in any case without waste-heat recovery or extremely efficient turbochargers.

The next steps for diesel engines should consider compromised but fixed stroke and compression ratio of engines, especially for downspeeded designs. The comparison of fuel consumption in driving cycle shows the potential of downsizing should be connected with proper use of engine speed gaining the advantage of downspeeding as well.

Considering future ICE improvement, the relevance of correctly simulated model of wall heat transfer inside a cylinder calls for further experimental investigation of this issue together with assessment of wall insulation, low thermal inertia materials. The second decisive factor is turbocharger or supercharger efficiency improvement. The future research will be focused on coupling waste-heat recovery cycles to current ICE performance considering the size and weight of appropriate systems with impacts to vehicle performance, which is possible in DASY.

Using DASY focused on the complete vehicle, the whole optimization may be followed with usable results even in the early stage of development. This goal is currently intensively elaborated. The overall experience with ICE optimization stresses that holistic approach is the only way to a better engine. The separated optimization of details cannot achieve this target. The rightsizing and rightspeeding is the goal for reaching total optimum obviously.

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DEFINITIONS/ABBREVIATIONS

BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
CA	crank angle
CI	compression ignition
CVT	continuously variable transmission
DASY	design assistance system
EGR	exhaust gas recirculation
HCCI	homogeneous charge compression ignition
ICE	internal combustion engine
IVC	intake valve close
NOx	sum of polluting nitrogen oxides
RCCI	reaction controlled compression ignition
RoHR	rate of heat release
SCR	selective catalytic reduction of NOx
SI	spark ignition
VNT	variable nozzle turbine
VVA	variable valve timing

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