Michael Günther
Marc Sens *Editors*

Ignition Systems for Gasoline Engines

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Contents

Requirements for Ignition Systems

Challenges to the Ignition System of Future Gasoline Engines – An Application Oriented Systems Comparison

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Abstract. Recent advancements of the gasoline engines combustion processes, e.g. a rightsizing or an alternative combustion process approach, make significantly higher demands on ignition systems than previous engine generations, especially with respect to charge dilution and gas exchange strategies. Among others, it is especially the optimization of the ignition system, which allows an extension of the current thermodynamic and combustion limits without drawbacks in engine performance. Besides the demands of the stationary operation one has to especially bear in mind the requirements originating from the transient operation of the engine.

In this presentation the potentials and limitations of ignition innovations are examined. With reference to a current series ignition system, both an optimization of the conventional spark ignition as well as alternative ignition concepts are analyzed. Both stationary and transient aspects will be covered. Furthermore realization relevant aspects and needs for the automotive implementation will be analyzed.

Keywords: Spark ignition · Corona ignition · Non-thermal discharge · Combustion

1 Introduction

The challenges as well as the chances of ignition have accompanied the last 150 years of the development of the gasoline engine. Hereby the activities focused for a long time on the development of low-cost, robust and as maintenance-free as possible ignition components to assure a reliable engine operation under all climatic conditions.

With rising awareness towards fuel consumption and exhaust emissions and for this reason increasing legislative requirements, the functional demands on the ignition increased considerably since the 1970's. The legislative restrictions with respect to the emissions of pollutants – gaseous as well as particulate emissions – are continuously tightened ever since. This is accompanied by the necessity of a continuous increase in fuel efficiency to match the steadily tightened CO_2 fleet emission limits.

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The resulting advancements and developments of the gasoline engine combustion processes, e.g. as a rightsizing or as an alternative combustion process approach, make significantly higher demands on modern and alternative ignition systems than previous engine generations, especially with respect to charge dilution and gas exchange strategies. Therefore, in addition to the measures to ensure a stable, fast and complete main combustion phase, such as an increased charge motion, it is especially the optimization of the ignition systems, which allows an extension of the current thermodynamic and combustion technology operation limits without drawbacks in engine smoothness, acoustic acceptability, as well as dynamic performance. These optimizations also help to ensure the compliance with respect to the enforced emission limit regulations in the complete range of the engine operation map. Besides the demands of the stationary operation one has to especially bear in mind the requirements originating from the transient operation of the engine as well as from the global market usability and from the increasing fuel quality diversification correlated with it.

Within the frame of this presentation the potentials and limitations of various ignition innovations are examined. With reference to current series ignition systems, both optimizations of the spark ignition as well as alternative ignition concepts, i.e. corona ignition and, for selected examples, passive pre-chamber ignition are analyzed. Besides the evaluation of the stationary potentials for selected combustion strategies with respect to their key operation parameters, one main focus of our presentation will be the transient and realization relevant aspects. The resulting needs as well as the potentials for the automotive implementation will be analyzed.

2 Challenges to Ignitions Systems Within the Engine Map

With increasing restrictions with respect to fuel consumption and emission-legislation the challenges to modern combustion strategies rise steadily. Hereby the thermodynamic and combustion necessities go significantly beyond the operation conditions of current engines.

Generally there is the demand for even higher power densities. However, this demand still requires the same engine smoothness quality for lower part load and idle operation, as current engines with less power densities do. This clearly enlarges the gap between the ignition capability in full load and the reliability of inflammation in lower part load. On the one hand we have to handle even higher pressures at the time of ignition, which can be covered by conventional ignition systems primarily by a reduction of the gap between ground and the center electrode. On the other hand higher power densities are naturally accompanied by lower overall compression ratios, which makes the part load and idle ignitability even more challenging. Thus the demands to an optimal ignition system rise significantly with part load.

Beyond the demand for even higher power densities there is a strong demand for a steady and sustainable reduction in fuel consumption synchronous with continuously more severe emission limitations. Considering the ideal thermodynamic cycle process for SI engines, there are two main pathways to rise the ideal efficiency of the engine: Firstly to rise the compression ratio and secondly to rise the dilution of the mixture either by air or by EGR, to achieve an overall better polytropic coefficient.

To achieve an overall high dilution ratio, both stratified and homogeneous approaches are known and are quite distinct in their demands with respect to the inflammation process.

For the stratified operation, the spray formation provides in principle very favorable ignition conditions at the time and the location of the ignition event, however in general dominated by a high temporal and spatial fluctuation of these ignition conditions. Thus, a suitable ignition system ideally covers a considerable ignition space and a considerable ignition time (multiple bursts or long duration), to average these fluctuation properly and guarantee a safe inflammation process in each combustion cycle [1, 2].

For homogeneous diluted mixtures, the demands appear in principal different. Due to the generally early injection timing, mixture gradients are by far on a larger scale in time and space. However the mixture itself at the time and location of the ignition event imposes by far harder thermodynamic inflammation requirements compared to the "merely" statistical coverage of the stratified operation. We again have the demand of an as large as possible inflammation area and the demand of sufficient long ignition duration, to assure a reliable initiation of the flame kernel formation, without the risk of the flame kernel being extinguished again. In the case of homogeneous dilution the size of the inflammation area reduces the burn delay and therefore improves the inflammation statistic and the ignition time necessary. For homogeneous inflammation conditions we in generally see a strong correlation between the average burn delay (within this paper defined as 0–5 % MFB duration) and the 5 % MFB timing statistics of the initial flame kernel.

To achieve a reasonable fast total burn rate and stable overall combustion, in general a high level of charge motion and turbulence is favorable. However, to create this charge motion level, efficiency losses in the gas exchange process have to be accepted. Furthermore, the heat transfer with the combustion chamber walls rises by the increase in charge motion. Higher compression ratios do ease the combustion and the inflammation process, however, do as well increase the heat losses due to wall interaction again.

For the ignition process, the ability to deal with and the necessity for a strong charge motion are important aspects regarding the overall efficiency. Ideally spoken, the ignition system should be capable to deal with both, very little and very high charge motion levels.

Besides the efficiency gained by better thermodynamic properties, diluted combustion offers considerable potentials for a reduction in fuel consumption in part load operation due to significant reduction of gas exchange losses. Furthermore, strategic valve train measures such as early inlet closing offer significantly increased advantages with respect to gas exchange losses. However, both measures impose severe challenges on the conventional ignition process, on the one hand by pure dilution effects, on the other hand by the effect of significantly lowering the charge motion level as well as the temperature level at the time of ignition. Especially the lower part load below 0.4 MPa IMEP poses considerable challenges to the concepts mentioned above. These challenges increase in general even more with rising revolution rate and with lower loads, for example for effective zero load or idle.

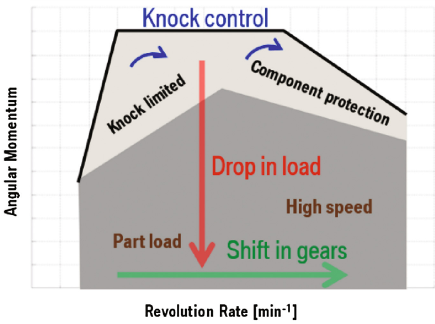
The other efficiency measure, the increase in the compression ratio, is generally correlated with the necessity to extend both, the knocking as well as the component protection limitation of the SI engine. Furthermore one has to consider the compliance with the worldwide available fuel quality standards. In the context of engine smoothness at full load, inflammation speed is one essential aspect, as well as short flame distances and a fast flame propagation. Further aspects are a moderate acoustic and vibration excitations have to fulfill the so called NVH requirements. Dilution and Miller concepts partly enforce these challenges, as they in principal make the inflammation process more difficult and thus less stable. On the other hand charge motion measures do increase pressure gradients and heat losses due to wall interaction. Thus ideally spoken, the perfect ignition concept would be capable of addressing at least a part of these challenges.

Another key challenge, which gains especially importance for diluted combustion concepts, is the capability to match the demands of transient operation, either as a drop or a rise in load. With respect to emission legislation requirements strongly rising challenges have to be met by the ignition systems especially during the warm up phase. This is particularly important with respect to particle emissions limitations, which gain notably importance due to engine start stop strategies. Aspects of particle free combustion, emission optimized warm up, resistance with respect to fouling of the ignition components as well as a high tolerance with respect to load change by means of a late center of combustion are of eminent importance for the dynamic operation of the engine.

An even further aspect of innovative ignition systems is the energy consumption of the ignition system itself. This aspects gains especially importance, since with the introduction of the new driving cycles such as WLTP, the state of charge of the vehicle energy sources is monitored before and after the specific test cycle. The overall system weight has, last but not least, also to be taken into account.

Figure 1 summarize the main challenges to modern ignition systems with respect to the combustion strategies (left side) and to the car integration (right side).

Combustion strategies demands
Homogeneous diluted
Stratified
Low load / high load
Low / high revolution
Compression ignition
High/low charge motion
Miller-cycle / rightsizing
Variable compression
Catalyst heating



Operation / integration demands
Load drop / load rise
Engine start stop
RDE-demands
NVH demands
Warm up phase
Cold start
Lifetime demands
Knock resistance
Component protection

Fig. 1. Challenges and demands of modern SI combustion systems to alternative ignition systems.

3 Test Setup and Procedure

3.1 Engines for Thermodynamic Testing

The experiments described below were carried out both on a single-cylinder [3], 4-stroke research engine and research inline multi-cylinder engines of three and four cylinders, with principal basic geometries based on the new BMW inline engine generation, respectively. Specific changes were, among others, especially the piston geometry, which was optimized to both, corona as well as charge motion. Within this publication we focus on the initiation and the main phase of the combustion process. The experiments and analysis were designed accordingly. The engines used were equipped with variable camshaft phasing (VANOS) on inlet and exhaust side and variable valve lift (Valvetronic) on the inlet side. The compression ratio was chosen between values of $\varepsilon = 9.5$ up to $\varepsilon = 12$ and will be stated accordingly with the results. Standard premium fuel with RON = 98 was used for the testing. The engine parameters are listed in Table 1.

Table 1. Engine data

Engine	1-Cyl.	3-Cyl. (2x)	4-Cyl. (2x)
Displacement	~ 500 cm^2	~ 1500 cm^3	~ 2000 cm^3
Bore/Stroke	82 mm/95 mm		
	12:1	9.5:1/12:1	10.5:1/11:1
No. of valves/valve-lift/cam-phasing	Four variable on inlet variable cam-phasing on inlet and outlet		
Cooled EGR	Yes	None/Yes	Yes/None
Injection system	Direct multi-hole injection central position		

3.2 Ignition Systems

Transistor Coil Ignition. A state-of-the-art transistor coil ignition system (TCI) was used as reference [3]. If not mentioned otherwise the spark plug had a single-electrode air gap with 0.75 mm distance. The energy of the plug top ignition coil on the secondary side amounted to 100 mJ.

Advanced Spark Ignition Systems. The advanced spark ignition systems (ASI) consisted in principle of a coil-based spark ignition system, which offers the option to vary the secondary current during the spark discharge both in current strength and current duration. Figure 2 displays a scheme of the principle discharge characteristics of a conventional high energy spark and an ASI. The approaches towards the technical realization for such kind of ignition concepts are manifold [4–6]. They have in common however the variability of the physical parameter duration and the secondary current of the elongated glow discharge.

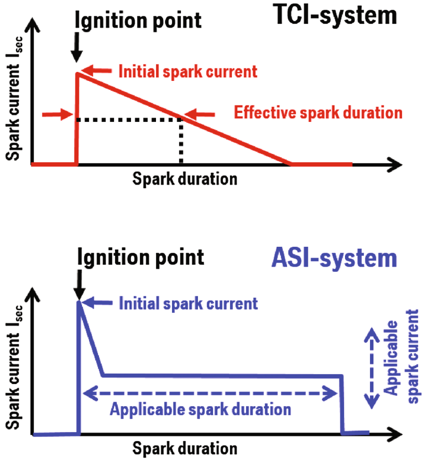


Fig. 2. Schematic diagram of a single coil spark discharge (TCI; top) and a spark discharge obtained by an advanced spark ignition system (ASI; bottom)

Radio Frequency Corona Ignition. The corona ignition systems used here generate high AC voltages in the frequency range of appr. 1 MHz to 5 MHz at the tip of the igniters. The frontend electrodes of the igniters were formed to a regular star with four or five equally shared tips. The combustion chamber acts as a counter electrode. Compared to a standard plug, the tips of the corona igniter have to be sharp for building a so called point-plane arrangement as illustrated at the top of Fig. 3. This electrode configuration generates a highly inhomogeneous electric field decreasing strongly from the tip towards ground. Plasma channels are formed in the area, where the ionization field strength is exceeded. Since the areas with the field strength below the ionization limit remain almost unchanged, no complete plasma channel is build up as for spark ignition (Fig. 3, bottom) and the energy input mainly accelerates electrons and does not heat up the gas considerably [7]. More details about the setup of a corona ignition system can be found in [2, 8, 9].

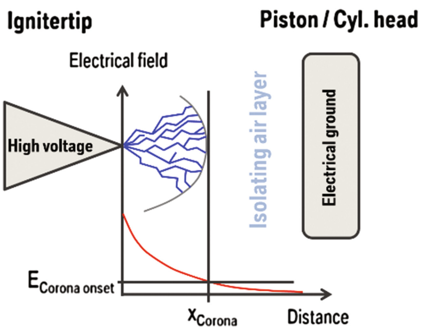


Fig. 3. Schematic diagram of a corona discharge [7]

Pre-chamber Ignition System. For the experiments presented we used a passive pre-chamber ignition sparkplug with orifices oriented almost tangential to the chamber walls of the pre-chamber. It was operated in passive gas exchange mode with a 100 mJ plug-top coil, as it was used for the TCI as well.

4 Results

Within this section we compare the performance and capabilities of an ASI system and a corona ignition system with respect to a series TCI system. We start with the comparison of the part load behavior (Sect. 4.1), where the largest advantages for both systems are sited. However, the two alternative ignition system display quite distinct differences with respect to the series reference and towards each other. These aspects will also be pointed out in the first part. In a second step (Sect. 4.2) we compare the corresponding performance characteristics in the medium load region, which offers advantages especially for the corona system. However, regarding emissions in lean operated mode, also the ASI system still do offer NOx emission advantages. The third subsection (Sect. 4.3) puts emphasis on the advantages of the corona system in the high load region of the engine map, especially in the context with high charge motion and restrictions due to knock and component protection needs. Especially for diluted and strongly Millerized combustion, the corona ignition system offers specific advantages especially within the knock limited region of the engine map. In interdependency with the engine map and the need for worldwide fuel compatibility these advantages do offer additional chances, such as enabling a general rise in the maximum possible compression ratio or options for acoustical improvements. Additionally a short prospect to a comparison with a passive pre-chamber spark plug is given within this context.

The next section (Sect. 4.4) highlights briefly some important transient aspects, such as torque reserves, optimized catalyst heating and an improved engine warmup.

The last section of this chapter (Sect. 4.5) is devoted to important aspects, which have to be addressed, when integrating such kind of ignitions systems into a series car environment.

In the subsequent result sections, the interconnecting lines among the measurement points of a data series serve merely the clarity of the illustration and do not necessarily represent a specific underlying correlation.

4.1 Potentials in Part Load

The demands in the lower part load region of the engine map regarding the ignition system are manifold and strongly dependent on the combustion strategies. One of the main sources of efficiency loss in the part load region of a conventional SI engine is the so called gas exchange loss or throttle loss.

For qualitative load control, as realized in the stratified operation [10], the engine can operate almost with open throttle, thus reducing the gas exchange losses to a minimum. The demands of stratified part load with respect to the ignition system have been widely studied and result in the need of a wide statistical coverage of the “ignition window", the time and space area, when an ignitable mixture is available at the point of ignition. Therefore we often see the usage of so called multi-spark solutions, which provide a reasonable long, but intersected coverage of the temporal "ignition window". The statistical coverage of this stratified ignition window by means of a spacious inflammation system, such as corona, offers significant advantages, which has been widely proven in several publications [2, 9]. It appears to be among one of the key performance areas of spacious ignition systems, which allows to extend the stratified operation of the engine to low loads with high EGR-rates [9] and very low NOx emission values, but also enables the conventional catalyst heating points [9]. The freedom to decouple in part the location of the ignition from the ignitor hardware location, as can be done in part with the corona principle, offers optimal boundary conditions to significantly avoid or reduce particle raw emissions, which might occur due to igniter wetting.

However, by far the vast majority of current SI engines operate on the basis of a quantitative load control, which allows a stoichiometric operation and therefore the use of a three way catalyst (TWC). To reduce the gas exchange losses for this operation mode of the engine, both strategies employing external EGR as well as modern variable

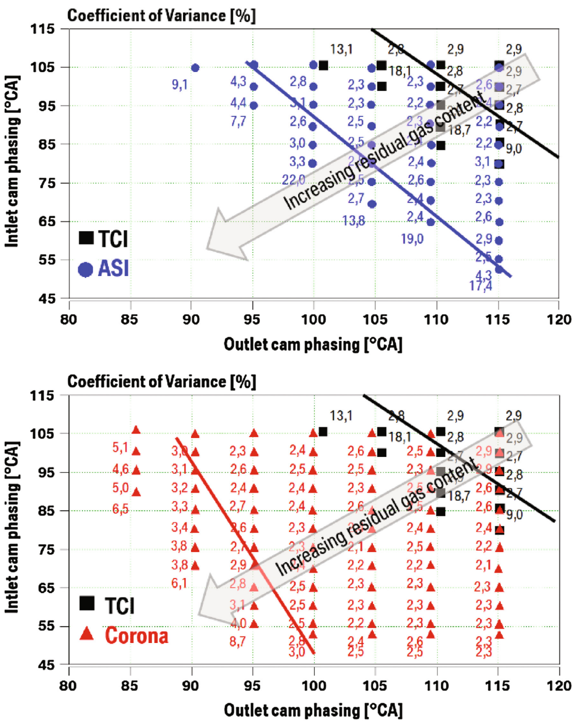


Fig. 4. Variation of cam-phasing for TCI (black) and ASI (blue) on the top and TCI (black) and corona (red) on the bottom. Depicted are the values for the CoV. The residual gas fraction increases significantly towards the lower left end of each plot. The solid lines symbolize the approximated limit for a maximum CoV of 3 % (1000 rpm, IMEP = 1 bar, CR = 12).

valvetrains can be used. Especially effective is the use of fully variable valvetrains such as the BMW Valvetronic, which allow the strategy of simultaneous late outlet valve closing combined with an early inlet valve closing (on an fully variable inlet valve lift) [11], which leads effectively to a strongly Millerized condition in lower part load and significantly reduces the gas exchange work loop of the p-V-diagram. This strategy however imposes significant challenges towards the ignition process, basically due to two reasons: Firstly the high internal residual gas fractions leads to a lowered laminar burning velocity, secondly the early inlet closing leads to a reduced charge motion as well as reduced temperature at the time of ignition. Both effects reduce the initial burning velocity significantly. To achieve a higher flame kernel stability for this operating condition, both the elongated spark duration (ASI) as well as the corona ignition do offer significant advantages. Figure 4 displays a TVDI-cam-phase variation for 1000 rpm and an IMEP of 1 bar. The outlet valve lift is 9.8 mm, the inlet vale lift is variable and in the range below 1 mm, thus regulating the amount of gas flow through the inlet valves. The upper side compares the conventional TCI ignition with an ASI, the lower side displays the comparison with a corona system.

The mechanism, however, by which the higher residual gas tolerance is achieved, is fundamentally different for corona and ASI. The corona ignition profits both from significant size, a freely adjustable duration and an inflammation mechanism rather independent of temperature and charge motion [3, 12]. Thus the burn delay is significantly reduced and so is the statistical standard deviation of the 5 % MFB point. This in average results in a better CoV and an improved fuel consumption even for the same amount of residual gas [3] as the TCI System. The ASI gains its advantage by providing a longer spark duration at sufficient current level. This helps to ignite even strongly diluted mixtures without the occurrence of heavily retarded cycles, thus enabling us to operate stable even for long burn delays. However, in contrast to the corona ignition, it does not significantly reduce the individual burn delay, besides statistical effects in the average burn delay. This principle mechanism is confirmed by the fact, that a multi-spark operation, with moderate intermediate interruptions of the spark, did not offer the same advantageous result, as a sufficiently long spark of the same total on time duration. Figure 5 illustrates these correlations by depicting the burn delay statistics as a function of the 5–50 % MFB burn duration for all three ignition systems. In Fig. 5 (top) plots the standard deviation for all TCI and all ASI points of the cam-phase variation of Fig. 4. The points match within the specific distribution range, since not every 5–50 % MFB burn duration is uniquely correlated to fixed burn delay (and thus std. dev.). However the distribution range of TCI and ASI becomes instable for longer main combustion durations, thus bending upwards for appr. 12°CA and 14° CA, respectively. With Corona we see almost no scattering and the stable region lasts until appr. >16°CA 5–50 % MFB combustion duration.

This results in the fact, that corona ignition can extend stable combustion to significantly higher residual gas fractions than ASI, which in average provides half the benefits corona offers in this conditions. Figure 6 illustrates the achievable residual gas fractions this for an operation point of 1250 rpm and an IMEP of 2 bar. The results where gained by means of a 1-dimensional gas exchange analysis (CR = 12).

The part load challenge to the ignition as well as its fuel efficiency benefits are especially high for the above mentioned TVDI operation. However for TVDI operation

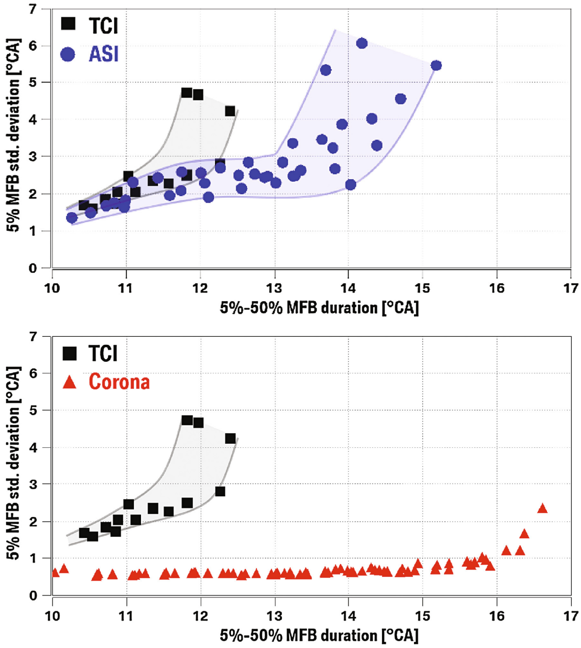


Fig. 5. Variation of cam-phasing for TCI (black) and ASI (blue) on the top and TCI (black) and a corona (red) on the bottom. Depicted are the values for the standard deviation of the 5 % MFB point. (1000 rpm, IMEP = 1 bar, CR = 12).

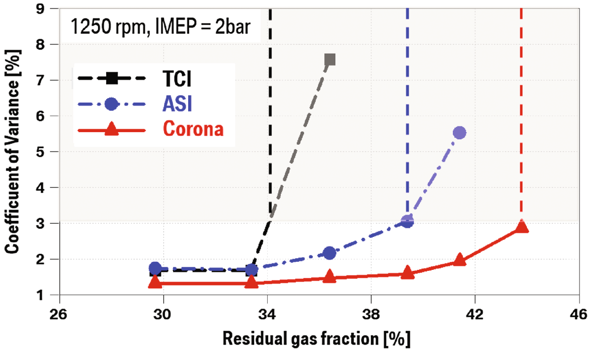


Fig. 6. Engine smoothness as a function of the internal residual gas rate for selected TVDI cam-phasings for TCI (black), ASI (blue) and corona (red). Depicted are the values for the CoV. Setting a CoV limit of 3 %, corona and ASI show both a considerable increase in the residual gas tolerance. Corona does display the maximum in the range of 44 % residual gas fraction (1250 rpm, IMEP = 2 bar, CR = 12).

the fuel efficiency is also significantly improved in comparison with the conventional TGDI operation [11].

Considering the challenges towards the ignition systems within the engine operation map, Wolf et al. [3] reported the ignition conditions for spark ignition to be considerable more challenging for lower load and for reduced charge motion. That naturally results in the highest spark duration demands for these operating conditions. As already stated in [13], the early inflammation process is to a considerable extent dependent on time based phenomena, where as the main combustion is, due to its turbulent character, predominately dependent on crank-angle based phenomena, since charge motion rises predominately with the average piston speed [14]. Thus the average burn delay rises on the crank angle scale with engine speed, resulting in continuously earlier and thus less favorable ignition timings [13]. Looking upon the demands towards the ASI duration, the minimal duration demand decreases significantly with speed, since the same spark duration covers for rising engine speeds an increasingly larger crank angle interval. This can be seen in Fig. 7, depicting the results gained for varying the spark duration until the misfire limit for a variation of the revolution rate at an effective zero load of the engine. A proper estimate is, that not more than a 30°CA equivalence is necessary as spark duration. Since the spark duration of the fully loaded TCI system is rather independent of the revolution rate, the relative advantages of an ASI regarding the spark duration have to decrease with rising revolution rate. Due to the overall shortened burn delay of the corona system, the relative advantages with respect to the TCI system rise with increasing revolution rate [1].

For engine operation employing external EGR, the EGR tolerance at zero effective load is a very important measure in dynamic operation. The reason is, that usually due to the volume of the inlet air/EGR path of a low pressure EGR-system, the EGR rate changes only comparatively slow. Thus, for a sudden drop in load, the engine will remain to be operated for a short transient period at a comparatively high EGR-level, but at significant lower load levels than before. However, since a misfire-free operation has to be assured under all circumstances, the EGR tolerance at low loads partly corresponds to the EGR levels allowed at higher loads. Here both, the corona as well as

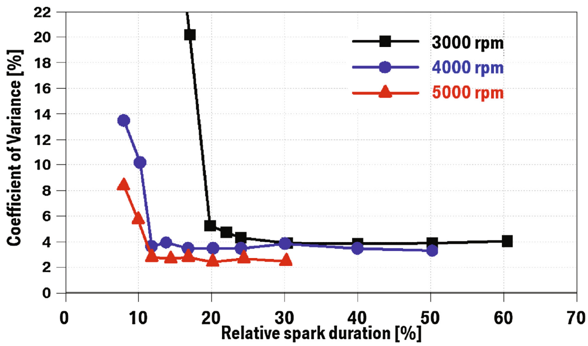


Fig. 7. Variation of engine speed for effectively zero load. The cam-timing was set for low residual gas content. The duration of the ASI System was varied until the misfire limit. The viewgraph displays the CoV as a function of the relative spark duration.

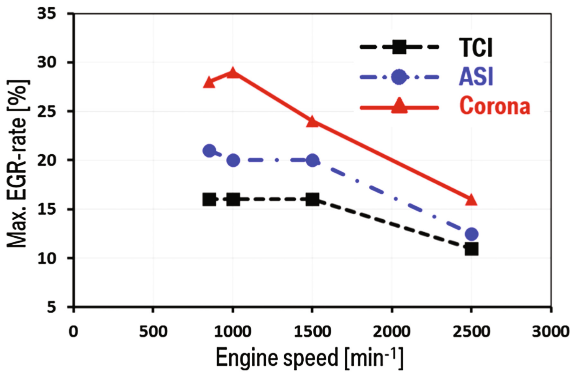


Fig. 8. Comparison of the maximal tolerable EGR-Rate as a function of revolution rate (IMEP = 0.8 bar).

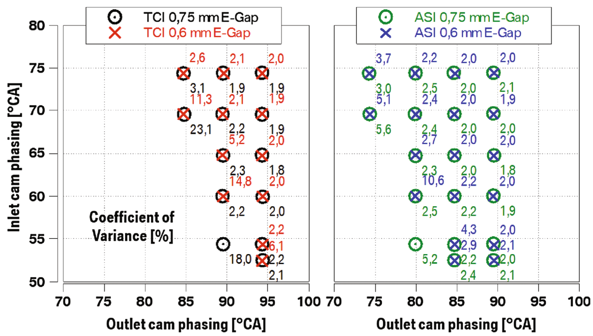


Fig. 9. Comparison of anelectrode gap variation (0.75 vs. 0.6 mm; 1000 rpm; IMEP = 2 bar). For both gaps a cam phase variation was performed, both for TCI and ASI, respectively. The resulting CoV's are depicted. The ASI outperforms the TCI Systems and for each electrode gap and can even overcompensate the disadvantage due to a reduced electrode gap.

the ASI ignition do help considerably, as can be seen in Fig. 8. It depicts the maximum tolerable EGR-Rate at a const. load of 0.8 bar IMEP.

With proclaiming higher and higher specific load demands [15], the densities at the time of ignition rise continuously. For a spark based system, this imposes even higher demands towards the necessary spark breakdown voltages. Since, however, the maximum bearable secondary voltage is often limited - by the coil system or by the spark plug ceramics or the maximum thread size diameter for the spark plug, which a cylinder head construction can offer- the main chance to achieve a stable spark formation is to reduce the distance of the electrode gap. However it is well known, that a larger spark gap provides a better part load performance. Under this constraint we investigated in the performance degradation involved in reducing the electrode gap of our TCI based from 0.75 mm to 0.6 mm, i.e. by 20 %, respectively. Figure 9 displays the results for a cam phase variation for 1000 rpm and an IMEP = 2 bar. It displays the important capability and advantage of the ASI System to even over-compensate a decrease in part load performance one might have to accept due to the need of a reduction in spark gap distance. This is an important advantage of the ASI System in the prospect of continuously rising ignition pressure demands.

4.2 Potentials in Upper Part Load

In the medium and upper part load region of the engine map, the combustion and ignition conditions become less critically, thus the differences among the various alternative ignition systems become less pronounced. One reason for the better inflammation condition might be seen in the higher level of turbulence. This effect has been already reported by Wolf et al. [3] for the comparison of TCI and corona systems. On the other hand, the higher the speed of the engine, the more pronounced are the relative differences between the corona and the spark ignition systems, even with the absolute overall dilution tolerance decreasing with rising engine speed [3].

How do advanced ignitions systems as the ASI fit in such a comparison? As already stated in the previous section, the ASI System does not in principle shorten the burn delay of the spark based inflammation. It simply avoids to a certain extent delayed combustion cycles and misfire. As the inflammation improves towards higher loads and deteriorates towards higher speeds, the in principle unchanged burn delay leads us to the typical results depicted in Fig. 10. It displays the achievable NOx levels, in a homogeneous lean combustion environment. The optimization was done by firstly optimizing for the best fuel consumption, and secondly choosing always the leaner and less NOx producing value of the lean out variation, presumed the fuel consumption does not deteriorate significantly. The principle tendencies of Fig. 10 are clearly pronounced. The corona system in generally provides the best lean burn results regarding the NOx emissions. It is followed by the ASI system. The poorest performance is displayed by our TCI reference system. However, progressing towards higher loads, the ASI System and TCI approach each other much faster with respect to the ignition performance, than it is the case for the corona system. The relative differences between corona and TCI become more pronounced for higher speeds, however the differences between ASI and TCI are reduced towards higher speeds for constant load. This is due to the fact that the less spark duration becomes necessary with increasing speed and therefore higher turbulence levels.

This behavior is confirmed when looking upon the results of an external EGR variation at 2500 rpm and an IMEP = 6 bar (Fig. 11). Here the TCI and the ASI perform already almost identically, the corona system however is still capable of providing an extended dilution limit and thus a fuel consumption benefit. However, taking into account the dynamic restrictions, i.e. the ability to perform a sudden load drop without the risk of misfires, the EGR limits are less than in the stationary thermodynamic optimum and often restricted by the low load tolerance (see prev. section). Thus indirectly we gain fuel efficiency benefits in the medium load operation also for the ASI system.

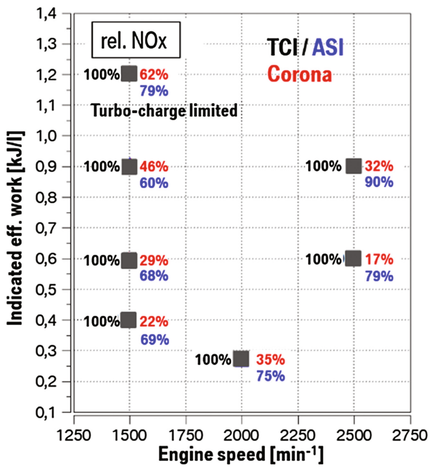


Fig. 10. NOx levels achieved for an air dilution variation at various points in the engine map. For each single comparison the cam-phasings were kept identical, only varying the air dilution level, the optimization was done with the focus on the best fuel consumption in combination with the lowest achievable NOx level. Below an IMEP of 3 bar we tolerated a CoV of 3 % in maximum, in the medium load region we reduced this limit to 2 %. The point at IMEP = 12 bar was primarily restricted by the amount of air available rather than by the lean limit.

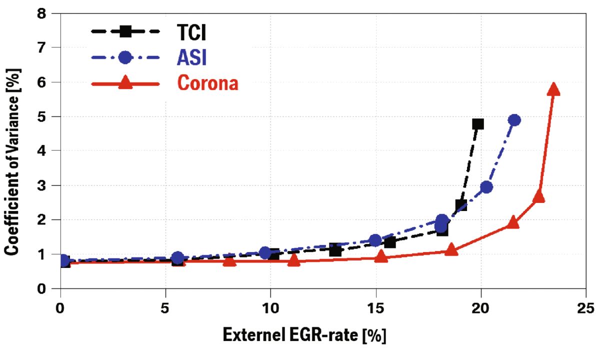


Fig. 11. Results of an external EGR-variation at 2500 rpm and an IMEP = 6 bar. Whereas TCI and ASI perform almost identical, the corona system still offers some advantage, as by a higher dilution limit and in an overall better CoV under diluted conditions, which also corresponds to a fuel consumption benefit.

4.3 Potentials at High Load

In the knock limited higher and highest load area of the engine map, the differences between the corona ignition system and the TCI reference are again more pronounced. The reason for this is the strong limitation of the combustion by knock on one hand and by the component protection on the other hand. Due its significantly better

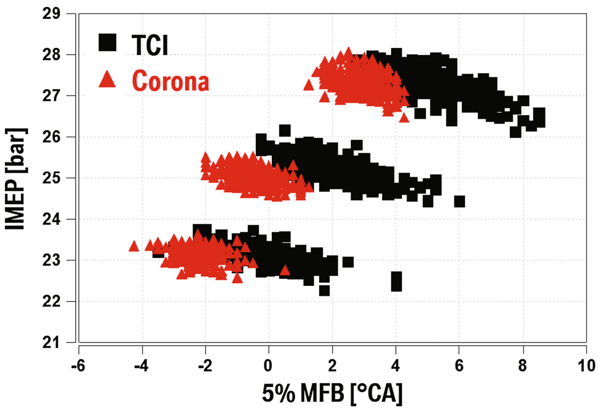


Fig. 12. Scatter diagram comparing spark and corona ignition at high load. The spark plug is colored black, corona ignition red. (4000 min^{-1}; IMEP = 23 bar, 25 bar and 27 bar respectively; CR = 9.5) [3]

inflammation statistics, corona does offer significant potential in the high load region, even at highest charge motion levels. This is clearly displayed in Fig. 12, which displays a load variation at 4000 rpm and for a strongly tumble oriented charge motion (CR = 9.5).

One should emphasize, that the corona application window for a given frequency is, among other parameters, primarily a function of particle density, distance between ground and electrode prong and the peak sharpness. Our results show, that these demands can be met properly even up to very high loads. It can be expected, that proper technological solutions are available to preserve the advantage of corona ignition even for very high load application. To our experience [3, 13] high charge motion did not prove to be an obstacle. It even seems in part to help to prevent the risk of power arc. Figure 13 displays as an example the accessible application window for a full load operation point at 2500 rpm and an IMEP = 27 bar. The upper voltage limit

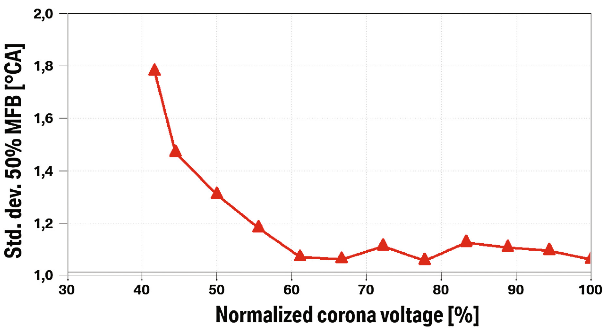


Fig. 13. 50 % MFB Std. dev. as a function of the applied voltage. (2500 min^{-1}; IMEP = 27 bar; CR = 9.5)

was due to internal system limitations. The lower limit represented the corona onset voltage.

Up to now, when presenting advantages of spacious ignition systems at high loads, publications focused on the better statistics of the 5 % and 50 % mass fraction burnt point. These improvements give the chance to move the combustion center closer to the knock limit as for a TCI system, thus gaining either a better full load efficiency or an improved torque without an increase in knock pressure [3]. However the full load advantages are even more farreaching, especially when applying corona to diluted and strongly Millerized combustion strategies. These aspect gain even more importance in combination with the need to comply also with low quality fuels. The underlying arguments become obvious, when applying for example EGR at an LET operation point, as depicted for 1500 rpm and an IMEP = 18 bar. Figure 14 displays the corresponding CoV's for a 50 % MFB sweep. Black lines represent the TCI results, the red the corona results, the dotted lines include a dilution with 8 % EGR and the solid lines represent an undiluted stoichiometric combustion. The left boarder represents the knock limit, defined by a specific level of knock pressure.

It can be seen clearly that the corona with EGR is even capable of reaching better CoV-levels than the TCI without dilution. The differences become even more pronounced for later 50 % MFB positions. If one considers the engine smoothness at LET as a possible limit for the choice of the compression ratio (bearing in mind hot country and low fuel quality environments), the corona can serve as an enabler for an overall higher compression ratio, especially in combination with dilution measures. This results in direct benefit in cycle relevant fuel consumption and customer acceptance regarding NVH behavior of the engine.

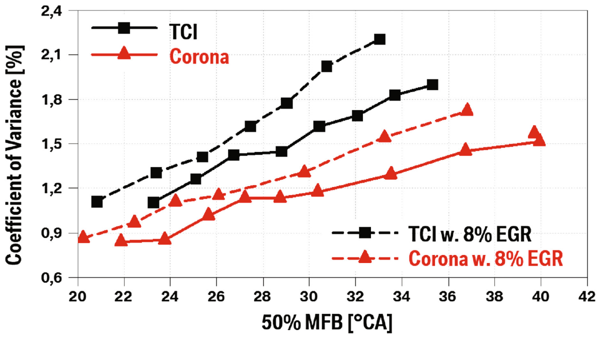


Fig. 14. 50 % MFB variation at high load. The black marks represent the TCI results, the red the corona results, the dotted lines include a dilution with 8 % EGR, the solid lines represent an undiluted stoichiometric combustion. The left boarder represents the knock limit, defined by a fixed level of knock pressure. (1500 min^{-1}; IMEP = 18 bar; CR = 12)

Similar potentials can be found when applying corona ignition to Millerized combustion. As an example we compare TCI, corona and a passive pre-chamber spark plug for a valve lift variation with keeping the inlet open timing constant. Figure 15

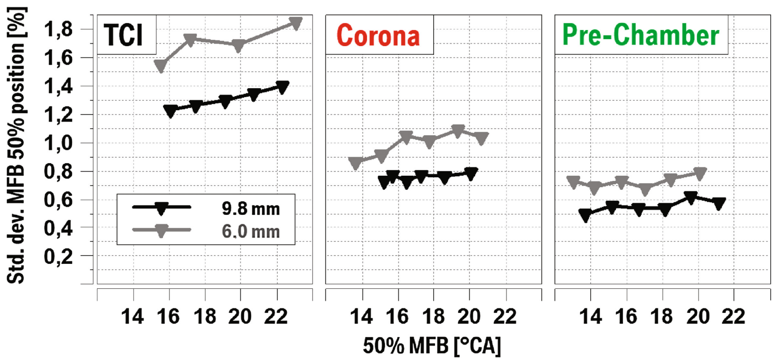


Fig. 15. 50 % MFB variation at high load for a variation in valve lift, with the inlet opening timing being kept constant. The black and gray lines represent 9.8 mm and 6 mm valve lift, respectively. The TCI, corona, and pre-chamber results are depicted from left to right, respectively. (2000 min^{-1}; IMEP = 18 bar; CR = 12)

displays the statistics of the 50 % MFB points achieved for an ignition timing sweep until the knock limit (left side). The results were gained by a single cylinder research engine (2000 rpm, IMEP = 18 bar; CR = 12). The corona displays significant advantages up to a factor of two, outnumbered only moderately by the pre-chamber ignition system.

However, the better statistics of the pre-chamber plug are achieved by an increase in main combustion speed of about 25 % compared to the TCI system. This results in an increase in pressure gradients, as can be seen in the scatter plot diagrams in Fig. 16, which in some cases might be undesired due to NVH reasons. The scatter-plots represent the corresponding cycle of the 50 % MFB sweeps. To illustrate the distribution

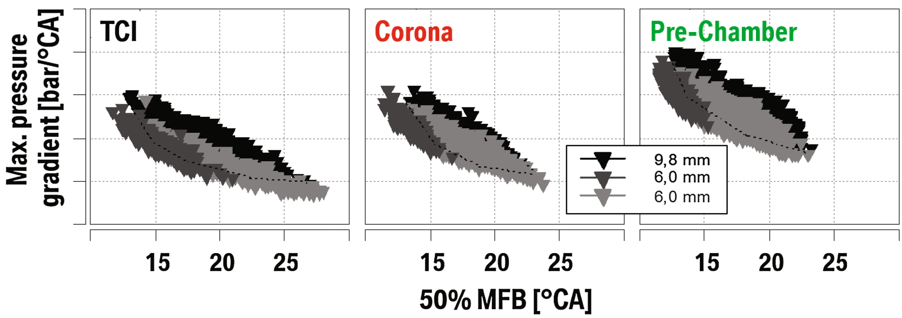


Fig. 16. 50 % MFB variation at high load for a variation in valve lift, with the inlet opening timing being kept constant. The black and gray dots represent the individual cycles of 9.8 mm and 6 mm valve lift, respectively. It has to be pointed out, that all cycle of one 50 % MFB-variation are plotted together in the diagram to pronounce the differences between the parameter variations. The TCI results are depicted on the left, the pre-chamber results on the right side, whereas the corona results can be seen in the middle diagram. (2000 min^{-1}; IMEP = 18 bar; CR = 12)

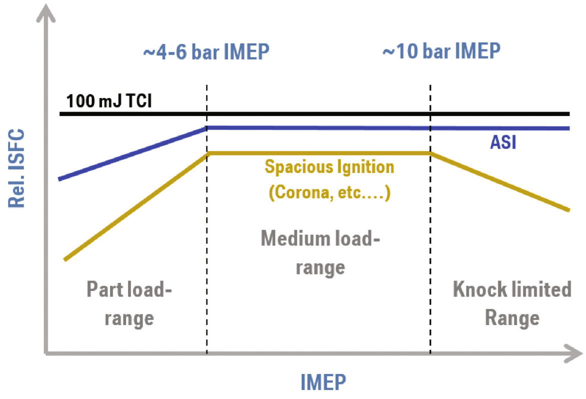


Fig. 17. Simplified scheme of the relative fuel consumption benefits for ASI and corona with respect to a 100 mJ TCI for moderately low revolution rates. In the part load range, we clearly see advantages for both alternative ignition systems. For increasing load towards the medium range primarily the corona system keeps part of its relative benefits, especially with respect to emissions. For high load the ASI system behaves similar to a TCI System. The corona, however, display strong high and full load advantages, especially for a highly Millerized or diluted approach.

for a single ignition timing, the earliest distribution of each 6.0 mm valve-lift sweep is depicted in dark grey. The ASI System is not taken into account in the comparison of this section, since it is expected to behave similar to the TCI System.

To summarize the stationary effects for varying engine loads, we consider Fig. 17 as a useful illustration of the principal relative differences. However, one has to keep in mind that the ASI system allows to achieve a spark breakdown even at operating pressure conditions by reducing the electrode gap of the spark plug and counter-compensating the part load drawbacks by an appropriate ASI parametrization.

4.4 Transient Behavior

For the implementation of alternative ignition systems in the environment of a series passenger car, not only the stationary, but especially the transient potentials are of immanent importance. This is especially the case for diluted and highly Millerized combustion strategies and increasingly dynamic emissions cycles.

One demand from the car integration is the so called torque reserve. This implies the amount of torque reduction possible by simply shifting ignition and therefore the 50 % MFB point towards later positions than the thermodynamic optimum, without making any changes of the relative air filling of the engine. Since the so called air path might be comparatively slow, the torque reserve is among the fastest measures to reduce and to build up momentum. It is limited either by the acceptable engine smoothness limit (CoV) or, at higher loads, by component protection temperature limit of the exhaust gases. As already seen in the case of the 50 % MFB sweeps in Figs. 14 and 15 the corona system offers here considerable advantages compared to spark

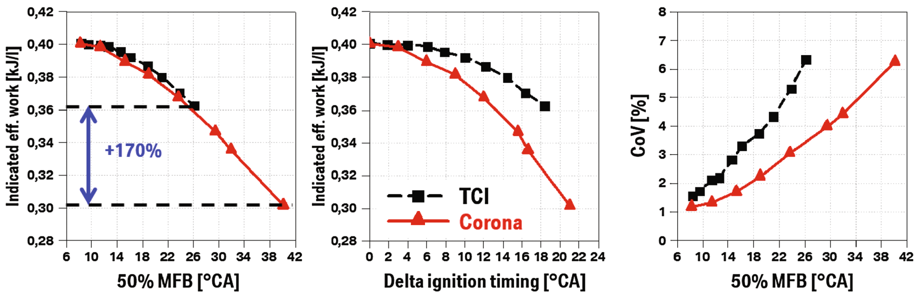


Fig. 18. Torque reserve for a stoichiometric operation points without dilution. The red marks represent the corona results, the black the TCI results. The right viewgraph depicts the IMEP as a function of the 50 % MFB position, the left plots the corresponding CoV. The middle graph depicts the IMEP as a function of the delta ignition timing with respect to 50 % MFB = 8°CA.

ignition systems. The reason is, that by reducing the burn delay for a given 50 % MFB point, the corona system results in a strongly improved 50 % MFB position statistics. Since for late 50 % MFB positions the standard deviation of the 50 % MFB position is directly correlated to the CoV, corona does provide a significant improvement in engine smoothness and therefore in torque reserve, except the case, where the temperature of the exhaust gases is the primary limit for the late shift of the 50 % MFB position rather than the engine running smoothness. These difference is becoming even more pronounced for diluted combustion, as can be seen in the previous chapter. Among others this provides considerable comfort in the handling of high EGR-rates in a diluted combustion concept, since it allows to faster decrease the external EGR rate in case of a sudden load drop. Figure 18 displays the gain in torque reserve for an operating point of 2500 rpm and an IMEP = 4 bar. The relative gain in torque reserve is additional 170 %. The graph in the middle indicates, that the torque structure for a corona application is different from a conventional spark and thus has to be adapted (see also next section).

The next advantage concerns particle emissions. Most conventional catalyst heating points with TCI systems employ a so called ignition injection to improve the catalyst heating stability towards late 50 % MFB positions, to allow a fast warm up of the exhaust after-treatment components. However, this strategy might lead to a moderate soot particle generation in the raw emissions of the engine, since the spray is directly targeted towards the spark gap and the initial fame kernel. Skipping these ignition injection avoids this particle generation, however, leads to unacceptable high CoV-levels. Corona ignition is capable to reduce this CoV to an even better level than with ignition injection, without having to employ an ignition injection at all. Thus corona ignition enables an effectively particle free catalyst heating operation, with even better engine smoothness and further improved potentials for a faster warm up. Figure 19 depicts the described phenomena for a 3-cylinder Engine with CR = 12.

Also in the general engine warm up, the corona ignition systems outnumbers the TCI system with respect to a significantly better idle smoothness, especially for cold environment temperatures (based on corona JIS tests for repetitive −10 °C starts).

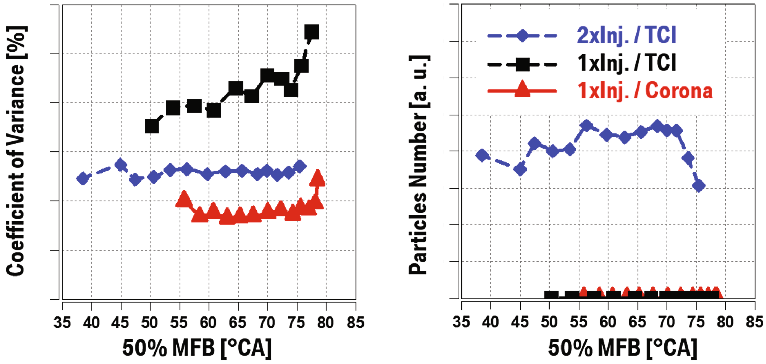


Fig. 19. Catalyst heating point with (blue) and without (black) an ignition injection, using a conventional TCI ignition system and without an ignition injection but with a corona ignition system (red). Clearly the better engine smoothness for the particle free catalyst heating employing the corona system can be seen.

4.5 Functional Integration Aspects

Integrating an advanced ignition system of the kind of ASI or corona does imply a variety of measures to be taken.

Speaking about the parameter space, for an ASI system the spark duration as well as spark current are varied, whereas a corona system needs the corona voltage and corona duration to be specified. Additionally, of course for all systems the ignition timing has to be specified as well. Besides the ignition timing, this leads us to two additional parameters compared with our reference TCI system (exactly speaking to one, if the charging time of the TCI is considered as a parameter as well). Since the ASI does in principle not change significantly the burn delay with respect to the TCI system, the additional application efforts can be restricted to energy parametrization

Table 2. Ignition parameters and their interdependencies.

System	TCI	ASI	Corona
Timing	System specific ignition timing		
Ignition parameters	– Energy	– Spark duration – Spark current	– Corona-Voltage – Corona-Duration
Interdependencies	Burn delay: – Independent of ignition parameters – Dependent on timing and operation point		Burn delay: – Strongly dependent on ignition parameters – Dependent on timing and operation point
Derating	Derating (fouling etc.) increases risk of misfire		Derating changes burn delay and has to be compensated

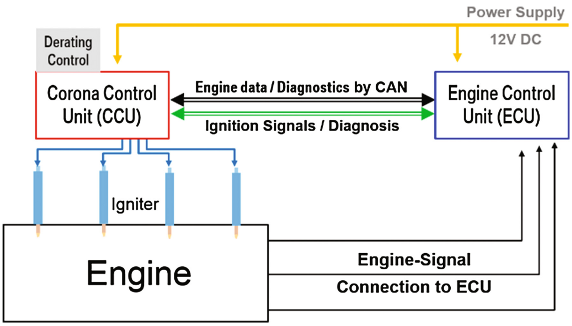


Fig. 20. Possible architectural scheme of a data communication for an implementation of a corona ignition system.

(spark current as well as spark duration). This leaves the maps of ignition timing and the torque structure models in principle unchanged. However, dynamic aspects, especially for diluted combustion, do make a more detailed energy parametrization and eventually a synchronous data communication in advance to each ignition event necessary. Table 2 summarizes these parameters.

In the case of corona system the key input parameters corona primary voltage (determining the corona size), corona duration and ignition timing have to be specified (Table 2). However, as we have seen by the results of previous publications [3, 9, 13], the burn delay strongly depends on the corona size and, to a somewhat weaker extent, on the corona duration as well. In contrast to spark ignition systems the burn delay in a specific operation point is not only a function of the engine operating point and ignition timing, but of the ignition parametrization as well. This offers the chance to parameterize burn delay as well, instead of only the ignition timing, but on the other hand it creates the need to actively control the burn delay (as a function of the ignition timing, duration and the corona size). Since overall Corona induced burn delay is changed significantly with respect to TCI systems, not only the ignition timing, but also the torque model of the engine map has to be adapted, when switching from a spark to a corona based ignition system.

In both cases, ASI and corona, we assume the need for a fast communication of the ignition parameters. One option would be to use the ignition trigger lines for that purpose, thus there would be no need for a significant change in cabling on the ECU side. For a corona system, due to a need of a separate corona control unit (CCU), an additional separate CAN communication would be helpful due to several reasons.

However, compared to the conventional ignition path, the electrical architecture of the corona system does cause necessary changes in the electrical infrastructure. Thus the CCU has to be implemented in the packaging of the engine or the chassis and the HV-coaxial cables have to be fed from the mounting location of the controller to the corona igniters. A scheme of a possible implementation is given in Fig. 20.

Since the size of the corona is essential for the burn delay and thus to the combustion, the corona size, or, better speaking, the resulting burn delay, has to be controlled over the lifetime of the engine. The control system has to be capable to detect fouling as well as eventual prong wear and to take the necessary countermeasures.

5 Conclusion

We presented an overview over the increasing challenges to the ignitions system for future SI engines. Generally higher charge motion and load dynamics as well as an increasingly diluted operation, combined with Miller strategies offer considerable chances in engine performance, however, imposing significant challenges towards future ignition systems. The improvement in conventional spark performance, such as the ASI system presented, can help to meet already a part of the challenges.

The major challenges, however, can be met only by a spacious ignition system, which provides both the improved combustion statistics and the stability needed for an advanced thermodynamic performance of future gasoline engines. From the currently known spacious ignition systems, the corona-ignition does display a highest level performance in the complete engine map, providing an ignition source with only very moderate energy consumption over the complete engine map. This provides ad-vantages in lower fuel consumption as well as lower engine out raw emissions, but also in driving comfort and dynamic behavior.

During the recent year in development the corona system proved itself to be a reliable and exceptional powerful ignition system, opening new pathways to combustion initiation for almost any SI engine combustion strategies. Taking into account our experience gained by successful corona-implementations in prototype demonstrators, by durability tests, both on engines as well as in laboratory setups, we are very positive that the tasks necessary for a series implementation of a corona system can be met in the near future as an enabler for combustion strategies of highest fuel efficiency. Successful results from cold start testing (−10 °C JIS repetitive cold-start) confirm this expectation.

Key demand of course remains the miniaturization of the CCU electronics. The possible future availability of a power supply at a voltage level higher than 12 V and also synergy options by implementing part of the CCU in the ECU could help on this pathway.

List of Abbreviations

5 % MFB	Crank angle position of 5 % mass fraction burnt
50 % MFB	Crank angle position of 50 % mass fraction burnt
ASI	Advanced spark ignition
CCU	Corona control unit
CR	Compression ratio
ECU	Engine control unit
IMEP	Indicated mean effective pressure
LET	Low end torque
NVH	Noise vibration harshness
TCI	Transistor coil ignition
TGDI	Turbo gasoline direct injection, i.e. in our case full valve lift and variable cam phasing
TVDI	Turbo Valvetronic direct injection
Valvetronic	BMW fully variable valvelift system