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Systematic approach to analyze and characterize pre-ignition events in turbocharged direct-injected gasoline engines

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ABSTRACT

Downsized direct-injected boosted gasoline engines with high specific power and torque output are leading the way to reduce fuel consumption in passenger car vehicles while maintaining the same performance when compared to applications with larger naturally aspirated engines. These downsized engines reach brake mean effective pressure levels which are in excess of 20 bar.

When targeting high output levels at low engine speeds, undesired combustion events called pre-ignition can occur. These pre-ignition events are typically accompanied by very high cylinder peak pressures which can lead to severe damage if the engine is not designed to withstand these high cylinder pressures. Although these pre-ignition events have been reported by numerous other authors, it seems that their occurrence is rather erratic which makes it difficult to investigate or reliably exclude them.

This paper describes a systematic engine dyno testing approach to force the engine into pre-ignition in order to study and characterize these events. A sensitivity study of various parameters shows that pre-ignition can occur repeatedly at the same load levels if boundary conditions are controlled sufficiently, meaning pre-ignition occurrence is less erratic than previously thought.

Several hundred pre-ignition events have been recorded and analyzed in this study. A post-processing tool was developed and applied to analyze and characterize all recorded pre-ignition events. The knowledge gained out of these investigations will help to better understand the pre-ignition phenomena and what combustion development activities need to be applied in order to avoid or counteract pre-ignition during an engine development program or afterwards during customer usage in a passenger car.

INTRODUCTION

The trend towards more downsized turbocharged direct injected gasoline engines has increased the priority to understand the root cause of pre-ignition. Pre-ignition itself is not a new phenomena and has been studied pre-dominantly previously in pure research activities. However, with increasing the operation load level of these engines into regions above 20 bar BMEP in combination with the desire to reduce turbo lag and achieve high torque levels already significantly below 2000rpm engine speed, the phenomena of pre-ignition now has to be included within production development programs. Reaching the necessary high boost levels is typically not an issue with the current available charging technology, but the sensitivity of individual combustion concepts to pre-ignition can be the limiting factor in the determination of the engine output torque curve. Figure 1 illustrates as an example the area within the engine operation map of a modern turbocharged direct injected gasoline engine where several OEMs have reported occurrence of pre-ignition.

In contrast to conventional engine knocking in gasoline engines, which is typically controlled by knock control algorithms in the ECU, pre-ignition is considered uncontrollable. According to Heywood [1] knocking is the self-ignition process in the end-gas regime prior to arrival of regular flame front and is dependent on temperature and pressure time history. It can be controlled by spark timing adjustments and all modern gasoline engine control units have specific knock control algorithms in order to react to knocking combustion. Pre-ignition on the other hand is characterized by a start of combustion prior spark ignition without the inducement of local component overheating. These sharp erratic cracks caused by the significantly increased fuel conversion rate can lead to significantly higher cylinder peak pressures, much higher than typically seen in knocking events. The peak pressures and maximum rise rates as measured during pre-ignition can lead to instant severe engine damages. Therefore it is important to understand the mechanisms which lead to pre-ignition in order to make engines less sensitive to pre-ignition. Only then it will be possible to push the envelope to even higher load levels within gasoline engines.

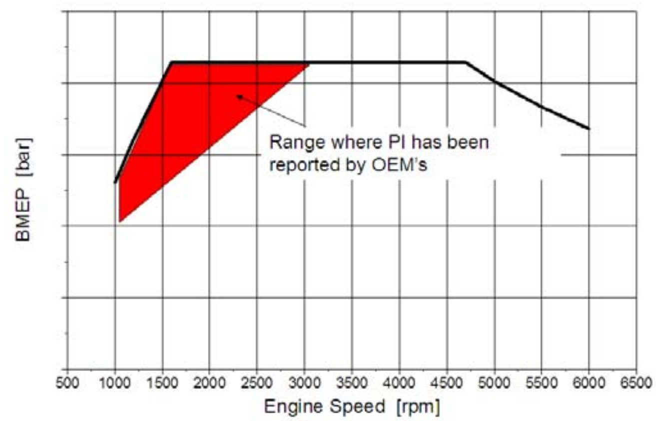

Figure 1 – Illustration of operation area where pre-ignition events have been reported in turbocharged gasoline engines.

In numerous technical publications potential root cause sources have been discussed [2, 3, 4, 5, 6, 7, 8]. Some track pre-ignition back to oil droplets and combustion chamber deposits as possible root cause [1, 5, 12]. However, some of the presented conclusions in these papers were generated more out of the exclusion of other reasons and not necessarily based on measured oil droplets or soot particles.

The engine dyno testing investigations within this study have taken these discussions into account and a comprehensive pre-ignition investigation test plan was developed. This included the determination of an engine pre-conditioning process in order to generate a defined deposit layer in the combustion chamber before any parameter of the test matrix was changed. Only then it was possible to assess if the deposit layer has an influence on the pre-ignition sensitivity of the engine.

The second part of this paper describes the development of a cylinder pressure based analysis tool which was used in order to characterize each captured pre-ignition event. It should be noted that the target application of these investigations was not specifically designed to withstand a large number of pre-ignition events. The study was conducted as the last testing section on this engine because of the potential risk of significant engine damage during testing. The authors of this paper are glad to report that it was possible to finish the testing without any engine damages and several hundred pre-ignition events were recorded and catalogued with the developed post-process pre-ignition analysis tool.

EXPERIMENTAL DESIGN

Since abnormal combustion phenomena like pre-ignition are expected to be up to a certain point random or stochastic events, a testing methodology had to be defined that ensured on the one hand statistically significant and robust results while limiting on the other hand testing efforts to an acceptable level. The used testing procedures in this study are based on the philosophy of quality control Design for Six Sigma (DFSS). Since DFSS itself is not a tool or a procedure but can be seen as a way of planning engineering processes in general, it was necessary to find also a lean and robust testing methodology fulfilling the quality and robustness requirements of a DFSS approach. For this study an experimental design according to Taguchi's design of experiment (DoE) was chosen.

The general purpose of DFSS methodologies is to obtain a comparably low change of quality in production or engineering in general that is below a σ-level of six. The standard deviation σ of a probability distribution can hereby be expressed as the square root of its variance.

$$\sigma = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n} x_i^2\right) - \overline{x^2}} = \sqrt{VAR} \tag{1}$$

n : sample size

x_i : individual value

$\bar{x}$: mean value of probability distribution

VAR : variance of probability distribution

A low standard deviation hence indicates that the data of the probability distribution tends to be close to the mean value (Figure 2 graph (1)), whereas a high standard deviation indicates that the data are spread out over a larger range of values (Figure 2 graph (2)). Transferred to engine parameter definition, DFSS therefore leads to procedures that deliver optimized levels of non-linear correlated parameters that are very robust regarding a potential parameter drift. Figure 3 expresses the influence of non-linear correlations on outcome distributions: It is visible that the same exposure distribution (e.g. caused by drift) can lead to significantly different outcome distributions at different positions due to the respective shape of a non-linear correlation.

Taguchi's design of experiment is in this context known to be first and foremost an approach for the robust optimization of parametric problems, hence leading to low standard deviations of the outcome variables. It is therefore widely used in the product development following DFSS standards. The basis of Taguchi's quality engineering is the definition of losses of concern that are considered to be all those caused by a product's critical performance characteristics deviating from the target value, even if these characteristics are still inside the tolerance limits. Taguchi's definition of quality includes a quadratic loss function that combines the demanded minimum loss of zero at the target specification with a growing continuous loss with growing variance. Figure 4 compares the widely used digital step loss function (black) with Taguchi's quadratic loss function (red). It is visible that the quadratic loss function also weights the quality loss inside the specification tolerance between the lower (LSL) and the upper specification level (USL) whereas the step function only assumes a loss when the specifications are missed.

Figure 5 expresses the general way to setup an experimental design according to Taguchi. The first step of this methodology is of course to define the problem and determine the objective by identifying the output characteristics (outcome or response variable). Subsequently, the variability control factors (or confounder, which are only affecting the variability of the response), the noise factors (noise) and the target control factors (or signal variables, which are only affecting the mean level of response) have to be defined by brainstorming possible influences on the considered outcome. The characteristic differences between these factors are statistically based and are therefore very important for the following experimental design: Whereas noise factors are defined as uncontrollable internal or external influences such as variations in environmental conditions or uncontrollable human variations in operating a product, the confounder and signal variables are controllable or design factors.

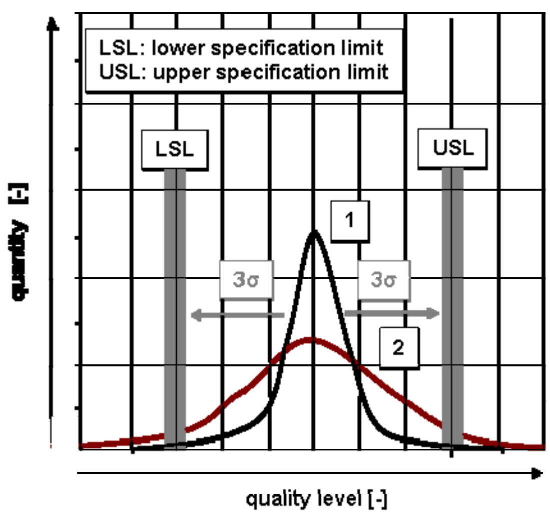

Figure 2 - Six-sigma probability distribution

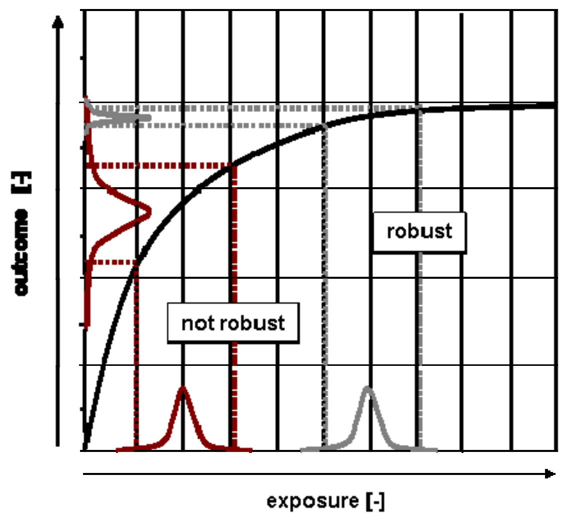

***Figure 3 - Influence of exposure variance on robustness according to** [9]*

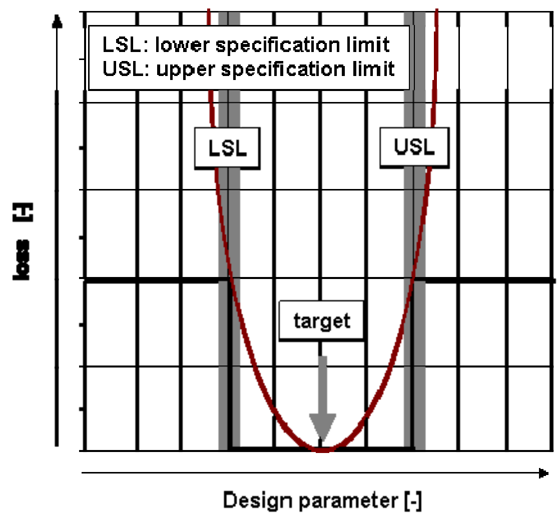

Figure 4 - Quality loss according to Taguchi

Through adjusting the confounder variables it is intended to reduce variability caused by noise factors while maintaining the required average performance through appropriate adjustments of the signal variables [10].In this context, the difference between signal and confounder variables is neglected though: All variables are considered to impact both average performance and variability without mutual interaction.

Figure 5 also shows the principle approach how to translate this theoretical experimental design into a real experimental grid or test plan. It is visible that two different arrays are created: A controllable factor array (or inner array, displayed in white) and a noise factor array (or outer array, displayed in black). The columns of the inner array are in accordance to the controllable factors whereas the rows indicate a specific combination of different confounder levels. In analogous form, the columns of the outer array are in accordance to the different noise factors whereas the rows indicate a specific combination of their different levels. Hence, a single test run is defined by one row of the inner array in combination with one setting of the outer array: Overall, this arises to n times m different test run setups. To arrange the possible combinations mostly for both of the inner and the outer array orthogonal arrays are used. These can be found in literature (e.g. [10]) or databases (e.g. [11]).

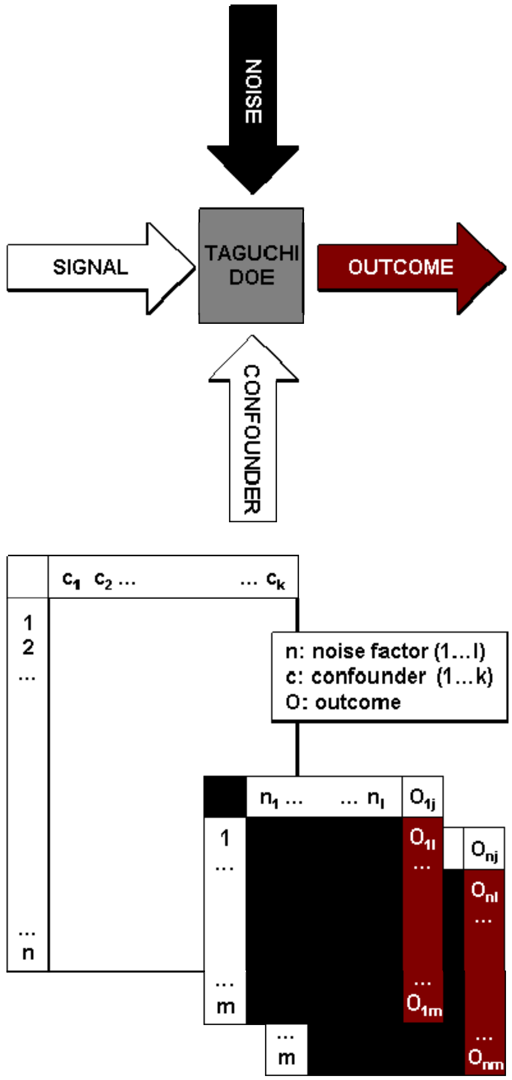

Figure 5 - General setup of an experimental design according to Taguchi

PRE-IGNITION TEST PLAN

Engine research and development projects added focus on the pre-ignition phenomenon since in recent times downsizing concepts achieve their peak torque already in the speed region below 2000 rpm and experience there this kind of abnormal combustion [12]. Based on a literature study around that subject eight control factors (injector design (A), fuel octane (B), coolant and oil temperature (C), intake temperature (D), spark plug design (E), exhaust backpressure (F), enrichment (G) and injection timing (H)) were chosen for this investigation. The analysis of their influence on pre-ignition probability targeted the definition for a robust optimum for the engine this study is based on. Seven of these control factors were adjusted in three different levels (e.g. enrichment: λ=0.9, λ=1.0 and λ=1.1), one control factor was adjusted in two different levels. Note in this context that the different levels are not necessarily sorted in ascending or descending order. Additionally to the eight control factors the in-cylinder pre-conditioning (“dirty” and “clean”) represents the only noise factor presented in this study. Through the combustion chamber conditioning discussed later in this paper a representative layer of deposits should have been produced which accommodate for their expected provocation of pre-ignition [12]. As mentioned before, noise factors are defined as uncontrollable internal or external influences such as variations in environmental conditions or uncontrollable human variations in operating a product whereas control factors are per definition controllable by adjustment or design. Combustion chamber deposits are neither completely controllable nor predictable [13, 14] and thus have to be seen as a noise factor (note e.g. deposit coating mainly depending on top boiling curve fuel fraction and engine operation). Fuel octane on the other hand can either be seen as a noise factor, assuming that the customer does not respect a specific requested fuel quality, or as a control factor whereas enrichment for example is clearly a control factor. In this study fuel octane was also analyzed as a control factor though, since the ECU can readjust on different fuels.

Having one control factor with two and seven more with three different specifications, an L18 (2^1 x 3^7) orthogonal array has to be applied to build up a Taguchi test matrix. Table A.1 shows the principle setup of an L18 orthogonal array according [10]. Note that the only interaction information that can be obtained from an L18 orthogonal array is that between the first two columns (A and B). Since the control factor featuring only two different levels has to be one of these first two factors interaction analysis between control factors is strongly limited using only this methodology. To analyze interactions further statistic analyses (e.g. regression analysis) are necessary.

To interpret the data gathered by the different settings, test setting specific performance measures are defined that enable thereafter the overall estimation and minimization of the effects of the observed noise and variability control factors. Equation (2) and (3) show two different measures to characterize noise performance and robustness. Equation (4) shows the formula to calculate the mean value of the response variable.

$$\frac{S}{N} = 10\log\left(\frac{\overline{Y}^2}{\sigma^2}\right) \tag{2}$$

S/N : signal to noise ratio

$\overline{Y}$: mean value of response variable

σ : standard deviation

$$R = 10\log\left(\frac{1}{\sigma^2}\right) \tag{3}$$

R : robustness

σ : standard deviation

$$\overline{Y} = \frac{1}{m}\sum_{i=1}^{m} Y_i^2 \tag{4}$$

$\overline{Y}$: mean value of response variable

m : number of responses

Y_i : individual response

According to Taguchi's quality engineering, the optimal level of a confounder is defined by its minimum variability, hence the highest signal to noise ratio. The optimal level for a signal variable is defined by that level obtaining a mean response being the closest to the target value or specification. Thus, the optimized parameters according to Taguchi DoE are defined. However, Taguchi's approach primarily analyzes qualitative influences of the considered confounders on a certain outcome. Hence, a regression model could give more information about the quantitative influences [15]. For the first step - to obtain a robust optimization of given parameter levels - the Taguchi method is a suitable methodology to meet both DFSS guidelines and presentable results though.

L_{18}	Injector A	Fuel Octane B	Coolant & Oil Temperature C	Air Charge Temperature D	Spark Plug E	Exh BP F	Enrichment G	SOI H
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Table 1 - L18 (2^1 x 3^7) orthogonal array according to [10]

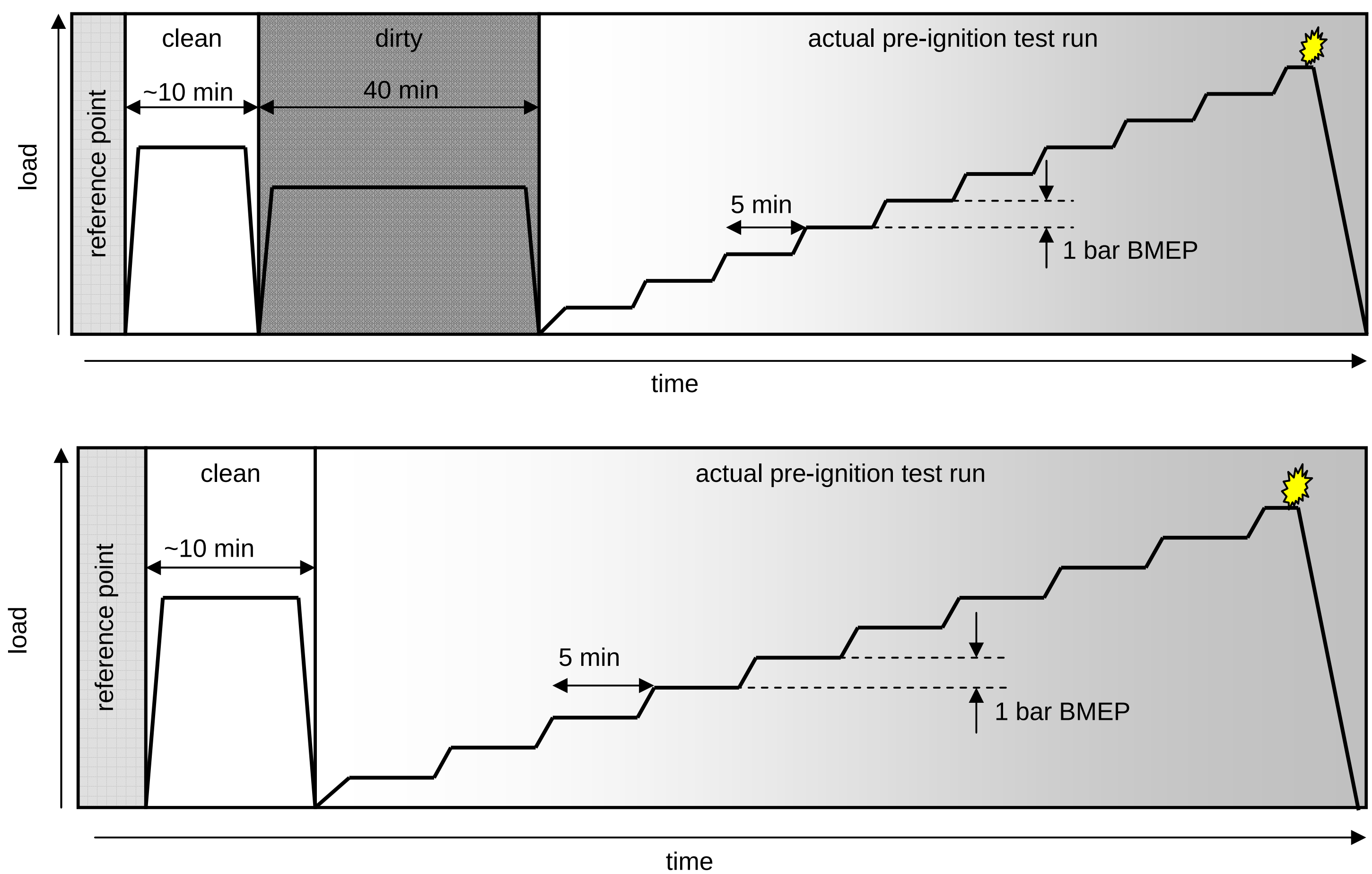

Figure 6 - Sequence of one L18 test run with reference point check and pre-ignition test in comparison (upper) with "clean" and "dirty" conditioning vs.(lower) only "clean" conditioning

TEST PROCEDURE

Pre-ignition testing was executed on a prototype inline four cylinder engine designed with homogenous direct-injection, dual independent cam phasing and twin scroll turbo charging. For increased variability during the gas exchange the engine was equipped with double overhead cams, establishing continuous variable cam phasing. The boosted prototype being engineered with a relatively high geometric compression ratio of 10:1 underlines the current developmental trends of more fuel efficient gasoline engines. The fuel injection system according to a common rail design is supplied from a flow controlled, cam driven, single piston pump feeding the centrally located multi-hole injectors equipped with solenoid actuators.

In an effort to avoid and minimize oil and particle formation within the intake and combustion system, the blow-by gas was alternatively discharged rather than being returned to the intake manifold. However, contamination of the inlet air by means of engine oil droplets could not be avoided entirely as the turbo charger shaft and valve guides are lubricated with oil. Additionally a particle layer was discovered atop the valves within the intake port believed to be the direct result of the valve overlap during part load operation. It is suspected that both of these circumstances are possible triggers for pre-ignition as previously mentioned.

Full access to the ECU was utilized to operate the engine in feed forward mode by deactivating any interfering control algorithm.

In comparison to the averaged measurement values collected during steady state engine operation the Combustion Analysis System was configured to trigger autonomously on specific pre-ignition characteristics. Therefore the erratic abnormal combustion could be recorded with high time and crank angle resolved resolution just within a configured measurement window of 250 engine cycles; solving the trade-off between data amount and information content. By means of this system configuration, three combustion parameters were individually monitored for each cylinder, triggering a measurement in the event any of the 12 predefined thresholds were exceeded. As apparent in table 2 these thresholds namely max. pressure rise and specific knock amplitude surpassed values typical for engine operation with normal combustion. By utilizing a ring buffer function every triggered measurement additionally included 50 engine cycles before the actual pre-ignition event, thereby revealing information of previous occurrences which could provide useful insight as to the cause of abnormal combustion.

Indication Parameter	**Threshold Value for Trigger Event**
cylinder peak pressure	130 bar
max. pressure rise	280 % permitted NVH target
peak to peak knock amplitude	830 % of permitted knock amplitude

Table 2 – Threshold values for pre-ignition trigger events

ENGINE CONDITIONING

The introduction presents publications listing oil droplets and particles as one source of pre-ignition initiation. As previously explained both occurrences can not be precluded entirely. For this reason the L18 test plan includes a noise factor representing by means of two different states of combustion chamber deposit loading the presumed pre-ignition triggers. According engine conditioning cycles were therefore developed, providing the targeted deposit loading and being implemented in the actual pre-ignition run prearrangements.

In preparation of every test run engine health and test cell operability had to be verified by performing and comparing reference point measurements. Thereafter a “clean” conditioning ensured that previous engine operation did not influence subsequent test results. Therefore the speed / load point 2500 rpm and 11.5 bar BMEP was adjusted with in regards to emissions optimized calibration values for fuel injection pressure and angle as well as valve timing. At the same time a marginal lean combustion air/fuel ratio and minor knock causing spark advance assisted with a 10 minutes continues water injection the flaking of deposits in the combustion chamber. To ensure equal distribution of the water mist over all cylinders the water nozzle was positioned directly upstream the throttle body.

The indication system parameters revealed an acceptable range of water distribution difference between the cylinders. Time limited operation beyond water shut-off ensured that no fluid remained in the engine air paths.

Depending on the noise factor state in the test plan a “dirty” combustion chamber conditioning cycle had to be subsequently performed before the actual pre-ignition testing started.

For the “dirty” conditioning the engine was operated for 40 minutes at 3500 rpm speed and 8.5bar BMEP. A relative air/fuel ratio set point of 0.95 with decreased injection pressure and engine coolant outlet temperature set to 70 ºC downgraded the cylinder charge mixture formation and emissions. To ensure an identical deposit coating in the combustion chamber independent of the fuel composition additionally the start of injection was advanced to a timing that resulted in a smoke number of 1.5 FSN. Reoccurring adjustment of the start of injection value guaranteed during this conditioning cycle a constant soot formation.

ACTUAL PRE-IGNITION RUN

The intended outcome of the performed study was to find the respective brake mean effective pressure (BMEP) level at which first pre-ignition occurs when the engine is operated for a certain time under every factor level combination of the L18 test plan described before.

To obtain this information a load sweep was performed starting at an engine operation regime where pre-ignition could be precluded. In one bar steps BMEP was increased from that initial operation point while holding engine speed constant and readjusting the spark timing to knock limit. However, to take on the one hand time based alterations such as the reduction or build-up of deposits into account and to provide on the other hand enough stabilization time for every load step a runtime of 5 minutes for every load step was chosen. This process was carried on until the indication system triggered a measurement based on a pre-ignition event or the peak load for that speed was exceeded by 10%. A graphical representation of the test process for the respective noise factor level (clean or dirty) is illustrated in figure 6.

The comparably short residence time at every load step however made it necessary to validate the results to gain significant results. Therefore all L18 test runs were repeated several times to check reproducibility of the individual BMEP values at which abnormal combustion occurred. The results are presented in a following part of this paper. At this point it can be stated though that the chosen runtime at each load step was considered sufficient for an engine intended to be representative for a passenger car application.

RESULTS & ANALYSIS

The following part of this paper focuses on the experimental results and their discussion. According to the testing methodology presented above the discussion is divided in two parts: First the methodology to gather optimized engine settings to reduce pre-ignition tendency is presented and validated. From these results one can already assume qualitatively influencing factors on pre-ignition, but as robustness is also strongly influencing the selection of the parameter level, a sincere quantitative conclusion is difficult. Therefore the second part of this paper focuses on how the gathered pre-ignition events could be grouped in a way to build up a database of characteristic values that can be used for a future analysis and quantification of both influencing factors on pre-ignition occurrence and influences on the actual pressure level during pre-ignition through descriptive statistics, association tests or regression models.

DESIGN OF EXPERIMENTS (DoE) RESULTS

The main objective of the performed Taguchi DoE was to find optimized engine settings to avoid pre-ignition in the operating range of this specific engine. As mentioned before, different control factors and control factor levels were defined to perform these tests. Signal to noise ratios and mean values were then used to interpret the data gathered by the different test run settings.

According to Taguchi’s quality engineering, the optimal level of a control factor is defined by a minimum variability of its response, hence the highest signal to noise ratio. Furthermore the optimal level for a signal variable is defined by that level obtaining a mean response being the closest to the target value or specification, in this case the highest value possible. Figure 7 and Figure 8 show the calculated mean response and signal to noise graphs for the performed test runs. The x-axis indicates the different control factors and control factor levels whereas the y-axis indicates the signal to noise ratio and the mean response value respectively. It is visible that only one control factor features a combined optimum both optimizing signal to noise and mean value at the same time (B2): For this factor the optimum setting for both the highest pre-ignition threshold and pre-ignition threshold robustness against noise factors such as the different levels of combustion chamber deposits or general control factor drift is the same. In all other cases a compromise between a high pre-ignition threshold and good robustness had to be found. Table 3 presents the optimum settings regarding robustness, pre-ignition threshold and table 4 the chosen compromise between these two settings.

From the results obtained by the performed DOE test runs it can be furthermore derived that fuel quality (B) seems to have by far the biggest impact on pre-ignition threshold variance (8bar), followed by enrichment (G) and intake temperature (D), whereas spark plug design (E), and injection timing (H) strongly influence pre-ignition threshold robustness. A further quantitative analysis of the different influencing factors is not part of this work since interaction analysis between control factors is strongly limited using only the Taguchi approach.

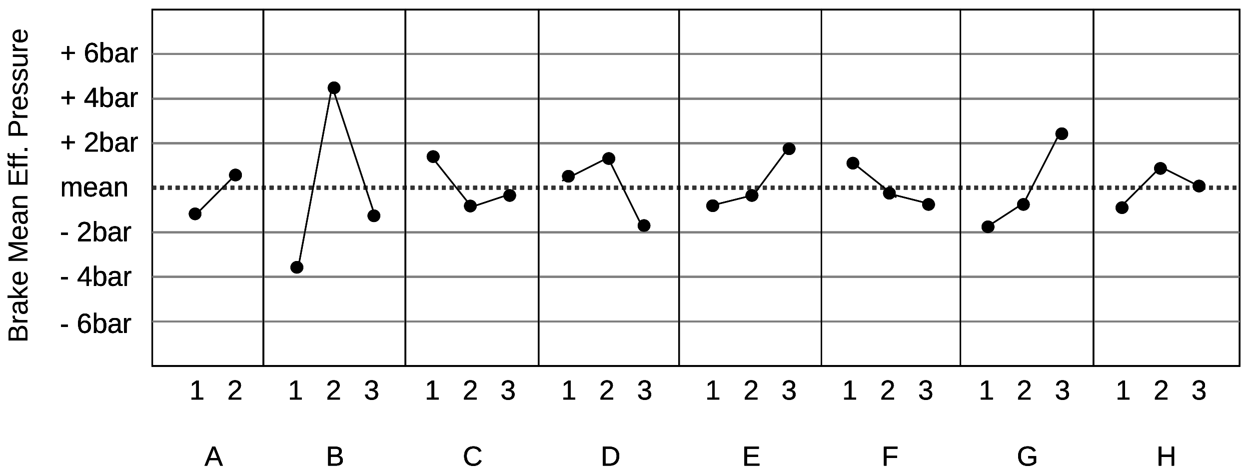

Figure 7 - Mean response graph (See table 1 for explanation of factors)

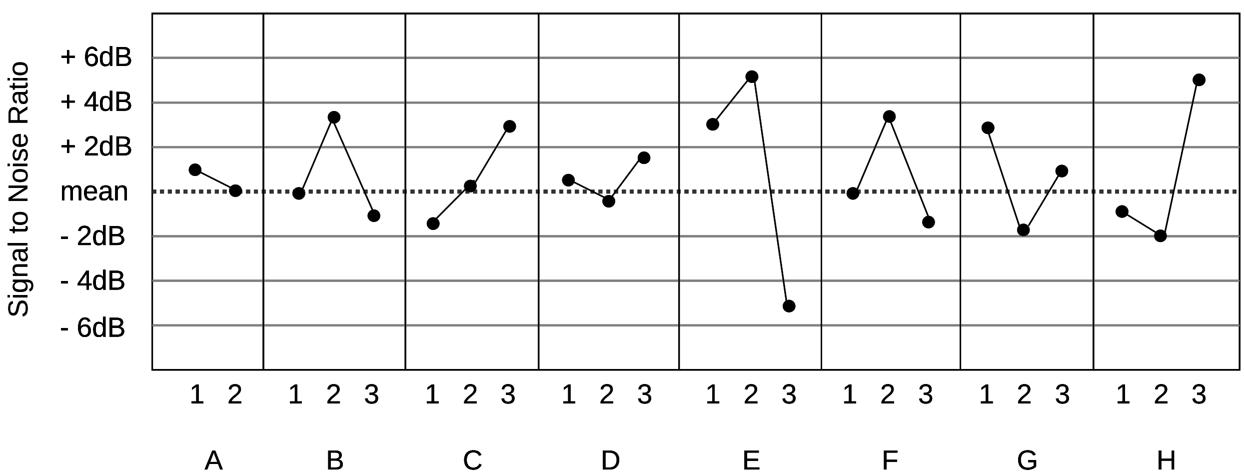

Figure 8 - Signal to noise response graph (See table 1 for explanation of factors)

	A	B	C	D	E	F	G	H
S/N	1	2	3	3	2	2	1	3
Mean	2	2	1	2	3	1	3	2

Table 3 - Optimum settings according robustness and mean response (See table 1 for explanation of factors)

	A	B	C	D	E	F	G	H
optimum	2	2	1	1	2	2	3	3

Table 4 - Optimum settings according to DFSS L18 (See table 1 for explanation of factors)

	A	B	C	D	E	F	G	H	pred. BMEP @ PI	BMEP @ PI
Validation 1	2	2	1	1	2	2	3	3	engineering target +1,1 bar	engineering target +0,3 bar
Validation 2	2	2	2	1	2	2	3	3	engineering target +0,8 bar	engineering target +0,7 bar

Table 5 - Validation points for DFSS L18 Taguchi DoE (See table 1 for explanation of factors)

Important for the Taguchi DoE methodology are validation test runs that confirm the optimum derived from the performed test run matrix. Table 4 shows the chosen validation test run settings and the difference between predicted and actual pre-ignition threshold. It is visible that the prediction by this simple Taguchi model is astonishingly accurate. The optimum settings are therefore considered to be correct.

Figure 10 shows the BMEP level at first pre-ignition occurrence in relation to the engineering target of this engine for the 18 different test run settings according to the L18 test matrix. It is visible that all settings, except from #4 and #13 do not reach the engineering target without pre-ignition. Note also the astonishing repeatability of the BMEP level, at which first pre-ignition occurs: These results indicate that pre-ignition events seem far less random as previously assumed. The last test setting marked O represents the pre-ignition threshold according to the optimum settings as shown in table 4. It can be maintained that pre-ignition can effectively be avoided in the operating range of this engine through these settings, thus leading to the first conclusion of this study that pre-ignition can be avoided in a given engine setup by adjusting engine parameters only.

Figure 10 also expresses the influence of combustion chamber pre-conditioning on the BMEP level at first pre-ignition. It is visible that dirty pre-conditioning really seems to have a strong influence on pre-ignition. This is especially interesting since the pre-conditioning methodology used for dirty pre-conditioning of the test engine cannot guarantee a quantitative but only a qualitative chamber pre-conditioning. However the effectiveness of the two conditioning cycles can be seen in figure 9. The left shown picture of the combustion chamber roof after "clean" conditioning shows hardly any deposits. In comparison the "clean" followed by a "dirty" conditioning visible on the right leads to an overall increase of deposit load especially on the intake valves and the roof area nearby. Further information on deposit formation in gasoline engines and their influence on combustion can be found in [13, 14]. Note that the few test runs where pre-ignition after clean pre-conditioning occurred at lower BMEP levels than pre-ignition after dirty pre-conditioning have generally high BMEP levels of first pre-ignition occurrence, thus resulting in long-lasting pre-ignition test runs: The long engine operation might have broken deposits loose before the other boundary conditions were favorable enough to let pre-ignition occur. Note also the unexpected high degree of reproducibility through all test run settings.

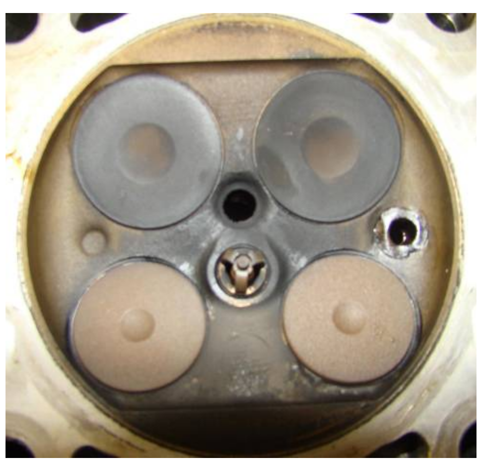

Figure 9 - Combustion chamber roof after “clean” conditioning (on top) vs. “clean” followed by “dirty” conditioning (underneath)

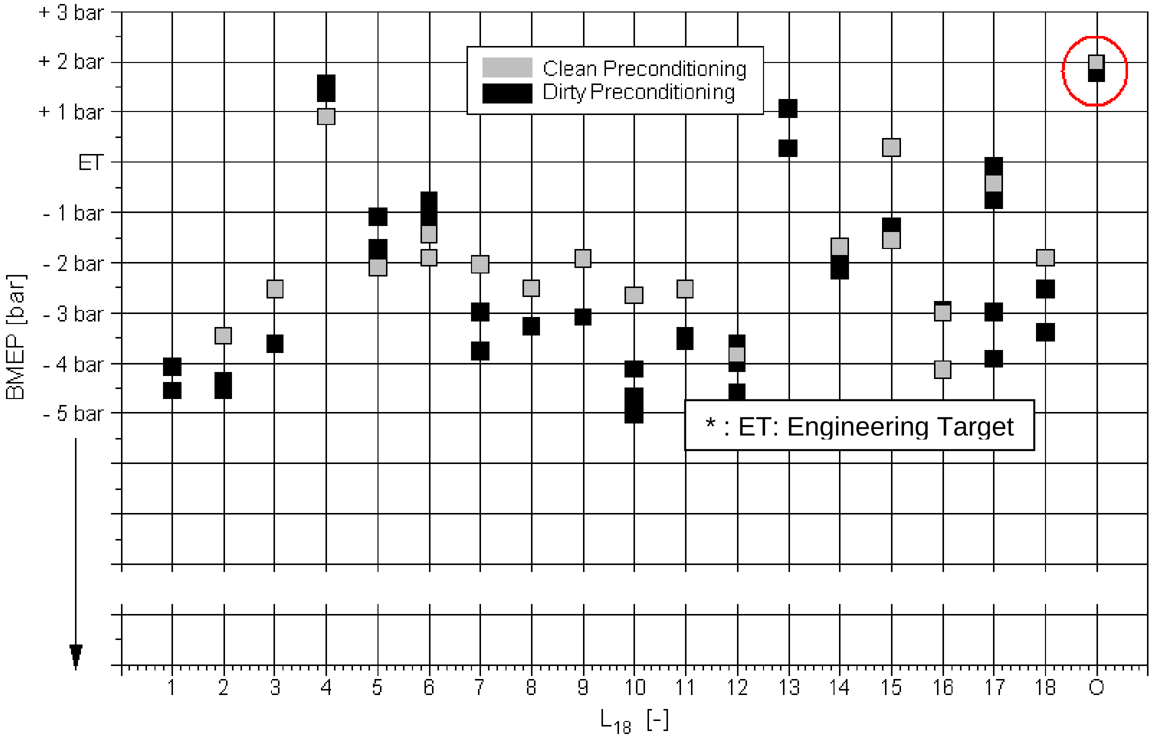

Figure 10 - BMEP level at first pre-ignition occurrence for the different L18 test run settings

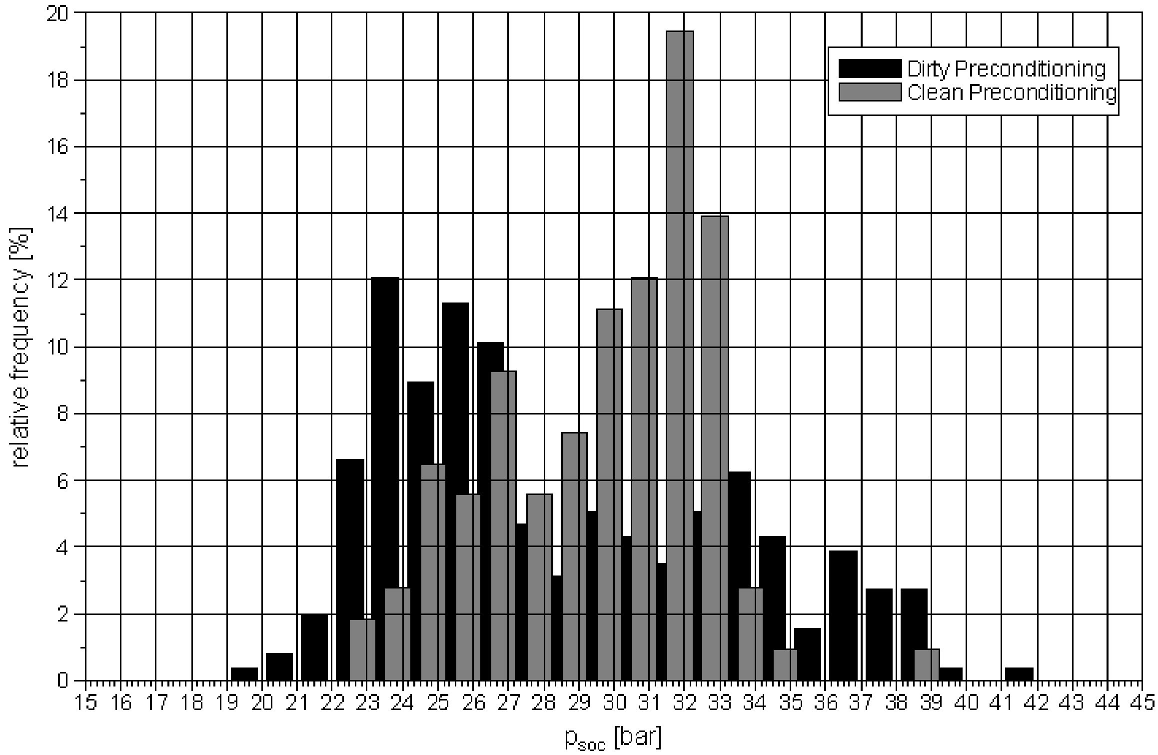

Figure 11 - Pressure at start of combustion for dirty versus clean pre-conditioning

Figure 11 shows the relative frequency of pressure at start of combustion for dirty versus clean pre-conditioning. The distribution of the relative frequency again shows a strong influence regarding the type of pre-conditioning: It is visible that clean pre-conditioning clearly shifts the pressure level at which pre-ignition occurs to higher values, thus supporting the hypothesis presented before.

PRESSURE TRACE ANALYSIS

Besides the analysis performed according to the parametric DoE approach discussed above, the measured pressure traces of this survey were used for statistic evaluation of all recorded pre-ignition events. For that purpose a post-processing tool was developed and applied that is not only able to automatically detect pre-ignition cycles, or abnormal combustion but to also calculate characteristic values regarding combustion, injection and ignition. The individual pressure trace information of several hundred pre-ignition cycles detected during the performed DoE test runs was thus compiled in a database. Based on this data pool, it is hereafter possible to conduct further investigations regarding the probability and influencing factors concerning pre-ignition or abnormal combustion in general. However, the statistical post processing is not part of this paper. The respective methodologies and results will be presented later in a following publication.

As described in an earlier part of this paper, the pressure indication system was configured to save 50 engine cycles prior, and 250 engine cycles past the first pre-ignition event during one specific pre-ignition test run. However, in many cases subsequent pre-ignition events after the first initial pre-ignition were recorded in the latter 250 engine cycles, making an automatic pre-ignition detection tool necessary to handle and post-process the amount of data gathered during the testing process and prepare the dataset for further analysis.

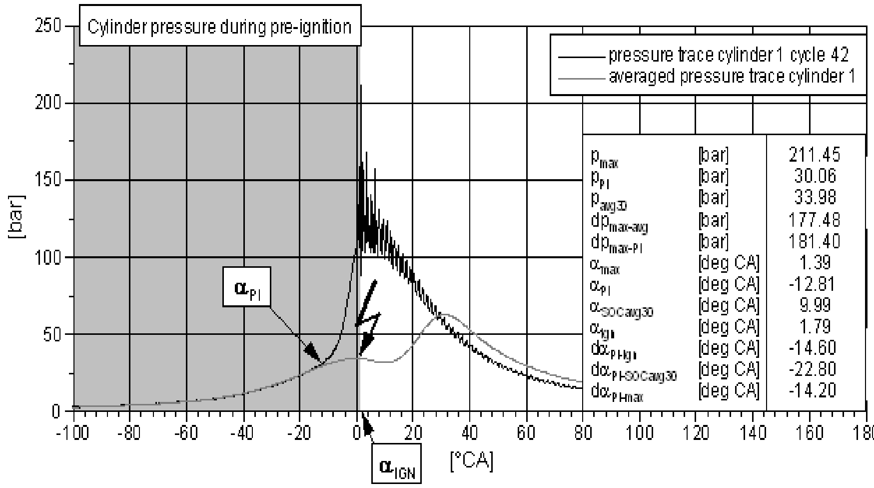

Figure 12 - Pre-ignition detection criterion

In order to determine the pre-ignition cycles an algorithm was developed to characterize the baseline reference level. A pre-determined number of normal combustion cycles was captured which to generate a baseline mask. This baseline mask is being used to characterize the pre-ignition cylinder pressure trace based on differentiating criteria, e.g. value or location of cylinder peak pressure rise. Through the calculation of characteristic values of the combustion a quality control was installed to make sure that no misfiring or pre-igniting cycles are used for averaging the pressure trace. Figure 12 shows an example for a typical medium intensity pre-ignition cycle in comparison to the averaged pressure trace. Note the area marked in grey: Only a combustion starting in this area will be recognized as a pre-ignition using the detection method presented above.

It is needless to say that this approach does not take into consideration those pre-ignitions whose first measurable pressure rise rates occur between ignition timing and normal start of combustion during the burning delay of the intended, spark initiated combustion. Another criterion using maximum pressure exceeding a nominal threshold compared to the reference trace and cycle statistics as indicator for abnormal combustion was therefore implemented to check the importance of abnormal combustion phenomena after spark ignition and also during regular combustion burning delay time (Note that this criterion does not analyze only pre-ignitions during burning delay but also other abnormal combustion events such as mega knocks for example). Figure 13 compares these two detection criteria. It is visible that the pressure level significantly decreases the closer you get to the normal start of combustion: Even at pre-ignitions close to full load, the maximum in-cylinder pressure in general does not hit the pressure limitation (only exception marked “X”).

Hence, for this paper the analysis focuses on pre-ignitions occurring before the spark timing only.

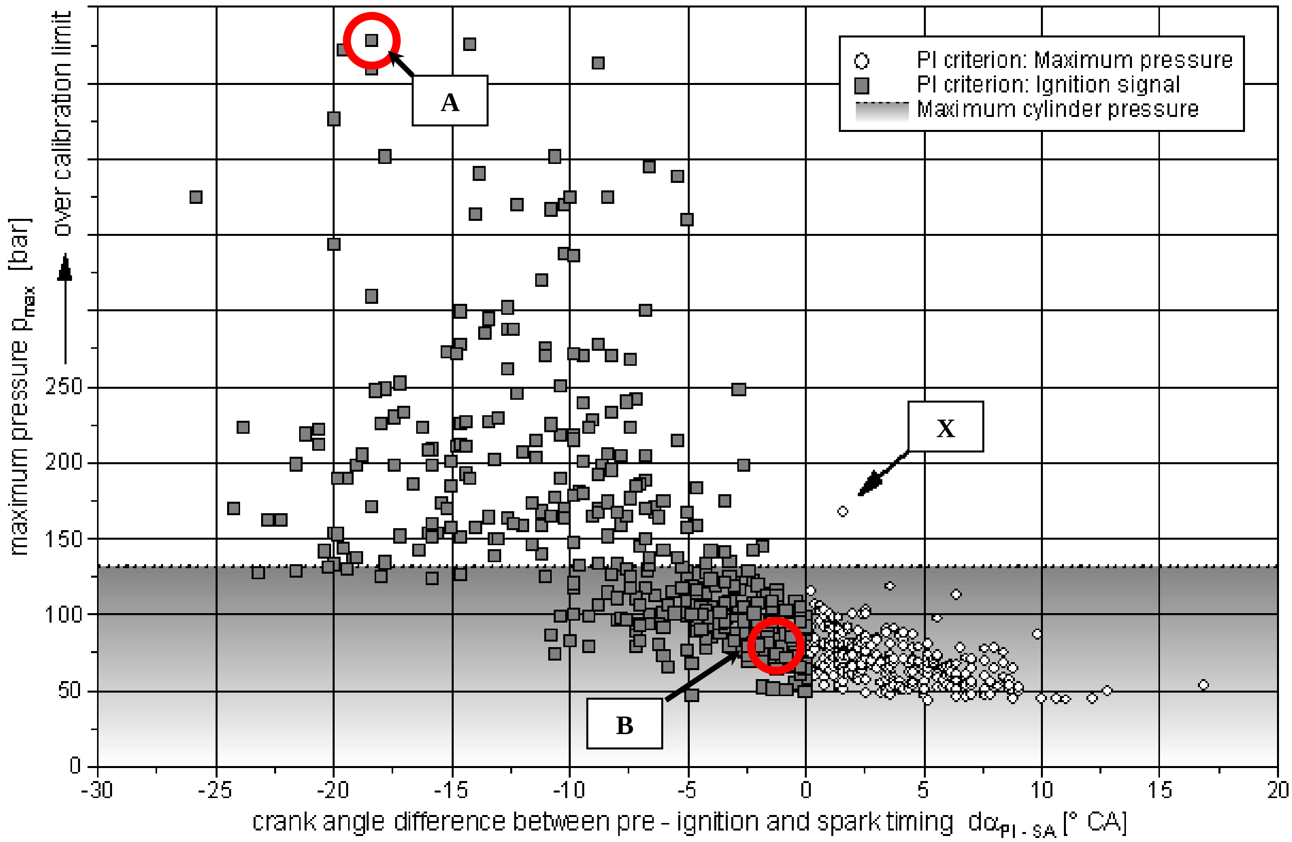

Figure 13 - Pre-ignition maximum pressures with different detection criteria

It is also visible in figure 13 that not every pre-ignition event measured during the test runs has to be considered critical regarding possible engine damage. Hence pre-ignition characteristics have to be defined that further subdivide pre-ignition events and especially help to analyze influencing factors causing severe pre-ignitions. For that purpose the post-processing tool described above was upgraded by a methodology that is able to detect and read out cycle individual characteristic values for the combustion. Some characteristic values are presented below. Note that these characteristic values represent only a small selection of possible characteristics of abnormal combustion engine cycles. Especially the severe pressure oscillations occurring during some pre-ignition cycles (see e.g. figure 14) are also of higher interest in this context.

Basic characteristic values analyzed during this study are:

p_{max}: maximum pressure

p_{PI}: pressure when pre-ignition occurs

p_{avg}: pressure of the averaged pressure trace at maximum cycle pressure

α_{max}: crank position when maximum pressure occurs

α_{PI}: crank position when pre-ignition occurs

α_{SOCavg}: crank position of start of combustion of the averaged pressure trace

α_{ign}: crank position of spark ignition

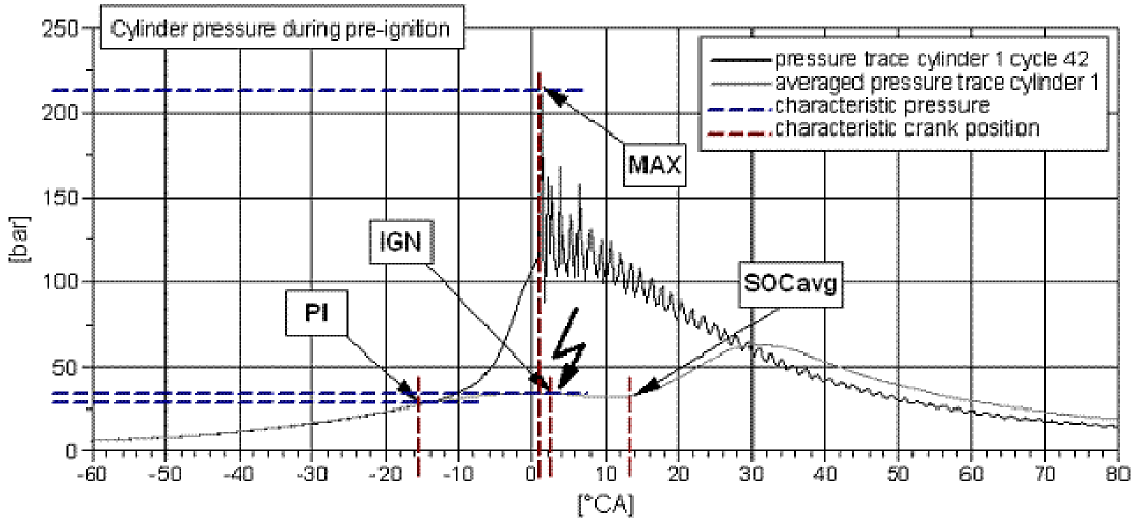

Figure 14 - Characteristic values

It is already visible from figure 13 that pre-ignition events close to normal spark timing tend to have lower maximum pressures, whereas in reverse pre-ignitions with high maximum pressures in excess of 130 bar seem to be considerably more uniformly distributed. Hence $p_{max} > 120$ bar is the aspect of the analyzed characteristics a closer look might be interesting on in the following.

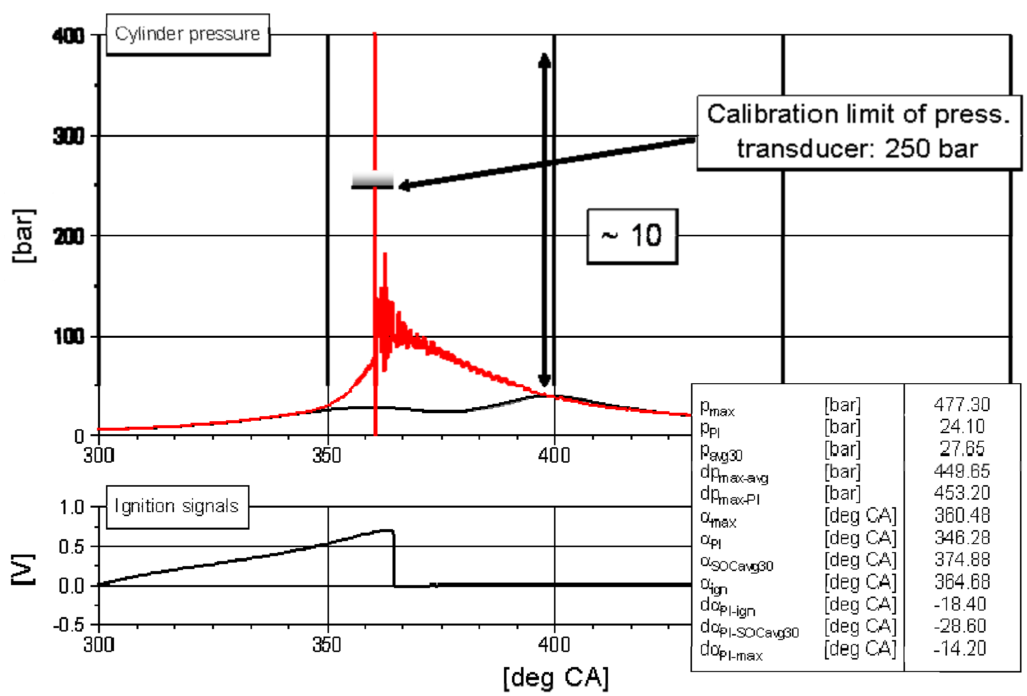

Figure 15 - Example for a severe pre-ignition event (A), test run settings: # 9 after dirty pre-conditioning

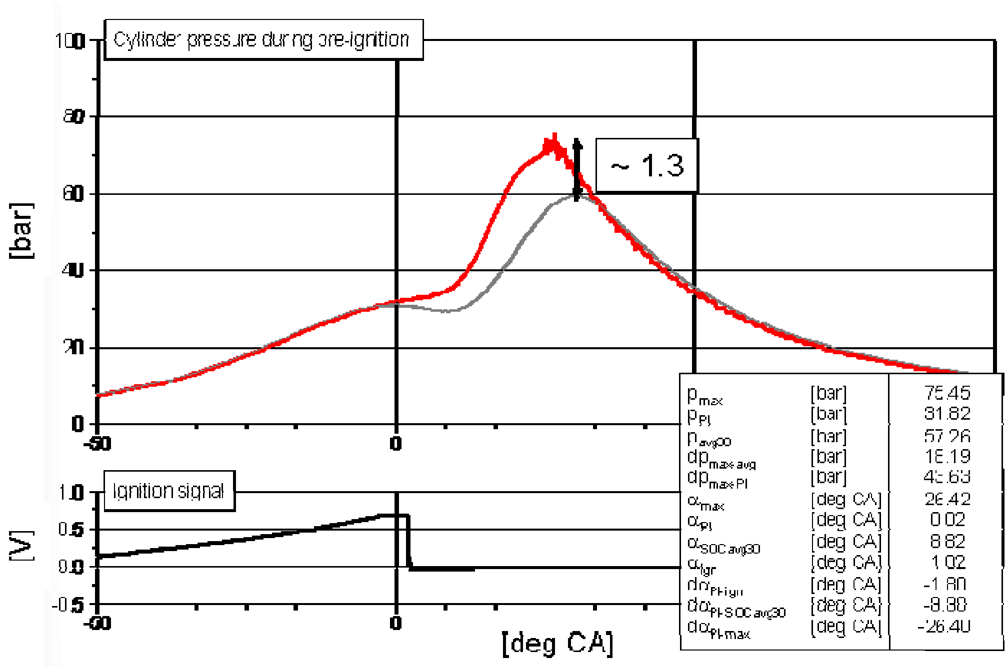

Figure 16 - Example for a modest pre-ignition event (B), test run settings: # 6 after clean pre-conditioning

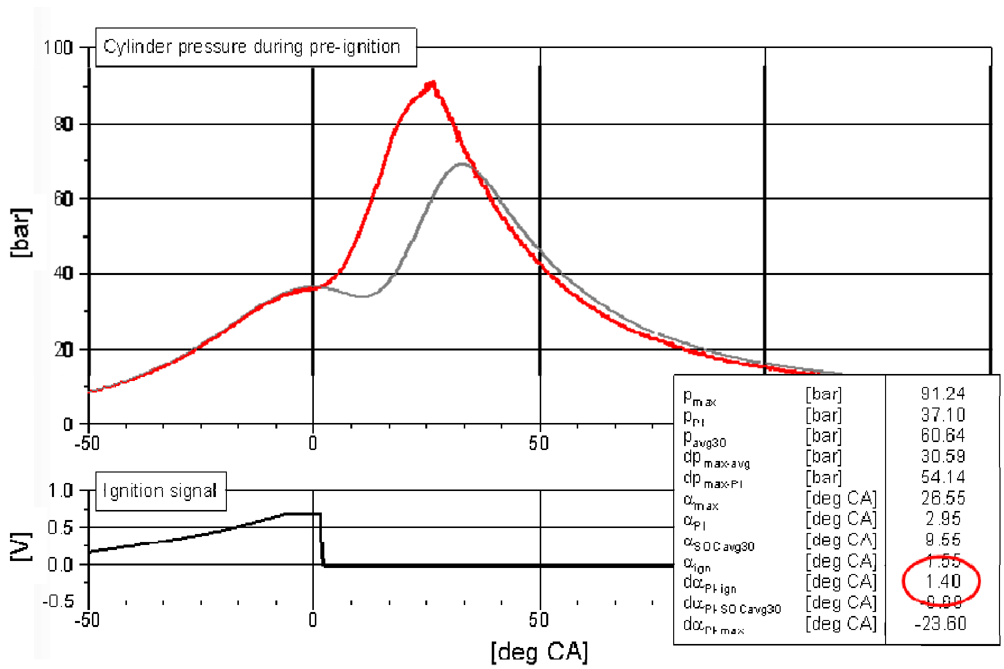

Figure 17 - Example for a pre-ignition event occurring shortly after spark ignition during burning delay, test run settings: Validation point after clean pre-conditioning

Figure 15 and figure 16 show two examples for one severe / early and one modest / late pre-ignition event. It is visible that the early pre-ignition event not only features a much higher maximum pressure but that also the pressure oscillations and the pressure gradient are significantly higher. Figure 17 shows an example for a pre-ignition event occurring shortly after spark ignition during burning delay. Although this study is not intended to analyze this type of pre-ignition, note the minor ringing in this pressure trace. It seems that the closer pre-ignition takes place to spark ignition, the fewer oscillations occur.

The reason for the characteristic pressure oscillations are known to be shock waves and their reflections [1]. These shock waves are caused by the sudden local release of the fuel's chemical energy, hence producing local temperature and pressure gradients. Since these pressure oscillations are, apart from the high peak pressure and the increased heat flux of the knocking combustion, strongly connected to engine damage during knocking cycles, this again underlines the need to avoid first and foremost early pre-ignition events: The later pre-ignition occurs, the less dangerous for the engine is the particular pre-ignition cycle because of its smaller probability to have high pressures and strong pressure oscillations.

CONCLUSIONS AND FUTURE OUTLOOK

Summarizing the results of the experimental approach it can be concluded that, apart from defining a robust optimum calibration that prevents pre-ignition events in the relevant operating range of the engine map of this specific engine application, some probable influencing factors for pre-ignition occurrence have been identified. It seems that combustion chamber pre-conditioning strongly influences pre-ignition occurrence. Flaking particles deposited during pre-conditioning might work as "exothermic centers" that ignite the air fuel mixture under certain boundary conditions. Of high impact concerning these boundary conditions were intake temperature level, enrichment (especially the cooling effect through fuel evaporation), mixture formation and fuel quality. Additionally, the investigations have shown that pre-ignition events are not occurring as random as previously thought since so many events were recorded under similar boundary conditions at similar loads that showed repeatable pre-ignition characteristics. Hence, although it will not be possible to control all boundaries in the vehicle applications of the target engines, the knowledge gained out of these investigations will help to determine appropriate engine operation strategies in order to prevent pre-ignition events to a certain extent.

The developed post-processing tool can be used in common engine development programs in order to characterize and assess the severity of pre-ignition events. The capturing of several hundred pre-ignition events will establish the baseline for a detailed statistical analysis of influencing factors regarding general pre-ignition occurrence and also critical pre-ignition characteristics. As discussed before, not all pre-ignitions show characteristics that could potentially cause severe engine damage. This leads to the necessity to particularly analyze influencing factors on severe pre-ignitions that might differ from influencing factors on general pre-ignition occurrence. However, the results of the respective statistic analysis will be presented in a future publication since further test results from other engine programs are necessary in order to enhance the findings and lead to the statistical significance which is necessary in order to derive appropriate conclusions.

This paper is just the beginning of further research activities which have to be conducted in order to fully understand the phenomena and root cause of pre-ignition. These pre-ignition investigations will be continued with statistical analysis, multi-zone combustion simulations and optical engine investigations and will be presented in future publications.

REFERENCES

1. J.B. Heywood
Internal Combustion Engine Fundamentals
McGraw Hill; 1988
2. M. Pirelli, F. Di Caprio, E. Torella, G. Mastrangelo, P.Pallotti, A. Marangoni
Fun to Drive and Fuel Economy: The New 16V Turbo Gasoline Engine from FIAT Powertrain Technologies
SAE Technical Paper 2007-24-0062, 2007
3. G. Prochazka, P. Hofmann, B. Geringer, J. Willand, C. Jelitto, O. Schäfer,
Selbstzündungsphänomene an einem hochaufgeladenen Ottomotor und Abhilfemöglichkeiten
26. Internationales Wiener Motorensymposium, Wien, 2005
4. J. Willand, M. Daniel, E. Montefrancesco, B. Geringer, P. Hofman, M. Kieberger
Limits on Downsizing in Spark Ignition Engines due to Pre-ignition
Motorentechnische Zeitschrift, 70. Jahrgang, 05|2009
5. C. Dahnz, K.M. Han, H. Kubach, M. Magar, R. Schießl, U. Spicher, U. Maass
Untersuchung des Auftretens und der Ursache von Selbstzündungen vor Zündungseinleitung bei aufgeladenen Motoren mit hohem Verdichtungsverhältnis

Abschlussbericht über das DFG Vorhaben Nr.931, Heft R547, 2009
6. J.M. Zaccardi, L. Duval, A. Pagot
Development of Specific Tools for Analysis and Quantification of Pre-Ignition in a Boosted SI Engine
SAE Technical Paper 2009-01-1795
7. B. Réveillé, A. Duparchy
3D CFD Analysis of an Abnormally Rapid Combustion Phenomenon in Downsized GasolineEngines
Oil & Gas Science and Technology – Rev. IFP, Vol. 64 No. 3, 2009
8. S.S. Merla, P. Sementa, C. Tornatore, B.M. Vaglieco
Optical Investigations of the Abnormal Combustion in a Boosted Spark-ignition PFI Engine
SAE Technical Paper 2009-01-0697, 2009
9. Y. Taguchi, Y. Soga, A. Mineno, H. Kuzuya, I. Horiuchi, Y. Ueda, T. Miyazaki
Development of an Automated Manual Transmission System Based on Robust Design
SAE Technical Papers Series 2003-01-0592, 2003
10. N. Logothetis, H.P. Wynn
Quality Through Design – Experimental Design, Off-Line Quality Control, and Taguchi's Contributions
Oxford University Press, 1989
11. N.N.
Orthogonal Arrays for Taguchi Designs
University of York, Department of Mathematics
www.york.ac.uk/depts/maths/tables/, 12.05.2010
12. C. Dahnz, K. Han, U. Spicher, M. Magar, R. Schiessl, U. Maas
Investigations on Pre-Ignition in Highly Supercharged SI Engines
SAE Technical Papers Series 2010-01-0355, 2010
13. G. T. Kalghatgi
Deposits in Gasoline Engines - A Literature Review
SAE Technical Papers Series 902105, 1990
14. G. T. Kalghatgi
Combustion Chamber Deposits in Spark-Ignition Engines: A Literature Review
SAE Technical Papers Series 952443, 1995
15. R.G. Easterling, G. E. P. Box
Discussion to Off-Line Quality Control, Parameter Design and the Taguchi Method
Journal of Quality Technology, Vol. 17, No. 4, 1985

DEFINITIONS/ABBREVIATIONS

m : number of responses

n : sample size

p_{avg}: pressure of the averaged pressure trace at maximum cycle pressure

p_{max}: maximum pressure

p_{PI}: pressure when pre-ignition occurs

R : robustness

S/N : signal to noise ratio

VAR : variance of probability distribution

$\bar{x}$: mean value of probability distribution

x_i : observed frequency of a level of the outcome variable

Y_i : individual response

α_{ign}: crank position of spark ignition

α_{max}: crank position when maximum pressure occurs

α_{PI}: crank position when pre-ignition occurs

α_{SOCavg}: crank position of start of combustion of the averaged pressure trace

σ : standard deviation

NVH Noise, Vibration, Harshness

AVG Averaged

BMEP Brake mean effective pressure

CA Crank angle

CAS Combustion analysis system

DFSS Design for six sigma

DI Direct injection

DOE Design of Experiment

ECU Engine control unit

LSL Lower specification limit

MAX Maximum

OEM Original equipment manufacturer

PI Pre-ignition

RPM Revolutions per minute

SOC Start of combustion

SOI Start of injection

USL Upper specification limit

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