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Glow plug with integrated combustion pressure sensor: A key component for controlled diesel combustion

Glow plug with integrated pressure sensor: a key component
for closed-loop-combustion control

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Summary

BERU has developed a Pressure Sensor Glow Plug (PSG) which will go into mass production in 2007. The measuring principle is based on a movable heating rod that is used as a transmission element to a piezoresistive strain gauge sensor in the rear area of the glow plug. The piezoresistive sensor detects the cylinder pressure that is used in the engine control system to control the combustion process. It is the pressure sensor glow plug which has made closed-loop combustion control possible for the first time. This glow plug controls primarily the start and the center of combustion by evaluation of the heat release process. As a result future emission regulations, can be satisfied better, especially with regard to NO_x. Other conceivable applications also include the dynamic determination of TDC, a peak pressure check as well as the model-based assessment of EGR, NO_x and the air mass.

1. Introduction

The future emission limits in Europe (EU6) and the current limits in USA (Tier2, BIN5) for Diesel cars require active after-treatment of exhaust gases for particles and NO_x. The necessary particle reduction can be achieved with modern particle filter systems. Two systems are being discussed with regard to NO_x reduction: an SCR system based on liquid urea, and a NO_x storage-type catalytic converter. As the realistic degree of conversion of a NO_x after-treatment system is restricted and the volume must be kept small for cost reasons, it is still necessary to reduce raw emissions of the engine [1].

Combustion methods that avoid the range of thermal NO_x formation are purposeful in this regard for the part-load operational range. These alternative combustion methods (HCCI, HCLI, HPLI...) are not open loop controllable without any additional measures, as was the case with the diesel engine until now [2]. For setting up the closed-loop combustion control, the cylinder pressure is the preferred input signal as it contains the entire time-based and thermodynamic process information. Long-term stability of the raw

emissions can thus also be ensured. Besides, other potentials such as dynamic determination of TDC, peak pressure control, cylinder equalization, acoustic optimization, adaptation to varying fuel qualities, model-based assessment of EGR, NO_x and air mass are conceivable. Due to its position in the combustion chamber, the glow plug is ideal as support for this sensor. **Figure 1.**

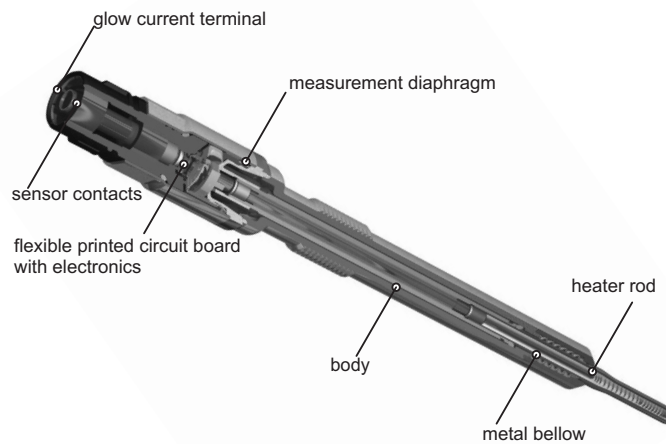


Figure 1: Components of the pressure sensor glow plug

2. Components of the pressure sensor glow plug

2.1 Sensor

We focused on three measurement methods for the sensor: optical, piezo-electric, and piezo-resistive. During decision making, BERU considered primarily five important characteristics:

- Measuring accuracy
- Long-term drift
- Robustness
- Technical maturity, and
- Costs.

After intensive evaluations, the piezo-resistive method [3] was chosen as it combines extremely accurate measuring values with a very low drift of the values over the entire life cycle. It is the well-engineered Microfused Strain Gage (MSG) technology, which is already used by the sensor supplier Sensata Technologies (ST) for the measurement of brake and fuel pressure in the automotive sector.

One of the greatest challenges during the development of the sensor consisted in the very small available assembly area (15 mm diameter and 35 mm installation height). The glow current connection already takes up a considerable part. There was thus not sufficient space available for an ASIC with a standard SO8 housing. A flexible printed circuit board (PCB) with two levels arranged on top of each other and a flip chip ASIC directly soldered onto the PCB were therefore chosen, **Figure 2.**

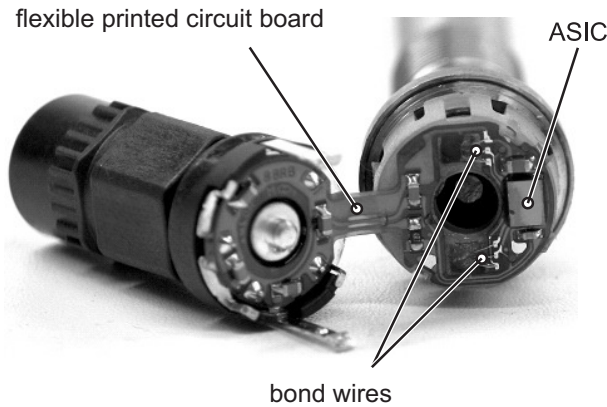


Figure 2: Sensor with flexible printed circuit board and ASIC

The fitted printed circuit board is soldered directly to the contact pins of the plug. The bottom half of the circuit board is glued with a plastic support that forms the mechanical connection to the measuring diaphragm. The attached silicone strain gauges convert the pressure signal into an electrical signal.

Bond wires lead the signal of this Wheatstone bridge to the ASIC on the flexible printed circuit board. The bond wires are embedded in a gel and thus protected against fatigue failure. This structure is enclosed by a deep drawn cap made of stainless steel and welded to the measuring diaphragm. The hexagon molded to the deep drawn cap transfers the screw-in and release torques of the PSG up to 30 Nm.

2.2 Heating rod and bellows

The heating rod of the PSG is based on the BERU Diesel Instant Start System (ISS) glow plugs [4]. However, the heating rod is not press-fitted in the glow plug body, as it is normally the case, It is elastically supported as a movable component in order to transmit the pressure to the measuring diaphragm onto which the actual sensor element is attached, **Figure 3**.

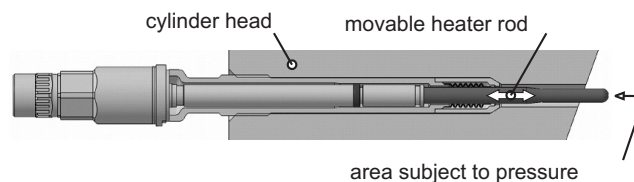


Figure 3: Section through the pressure sensor glow plug with movable heating rod

The sensor is positioned at the rear end of the PSG, as the necessary installation space is only available there and the environmental conditions are favorable. The combustion pressure is present at the front end of the PSG, which protrudes into the combustion chamber. The transmission mechanism must therefore fulfill the following requirements:

- friction and hysteresis-free transmission of the combustion pressure onto the sensor element
- Equalization of the heat expansion during glow operation of the PSG
- Uncoupling of the cylinder head deformations of the sensor element
- Seal from the combustion chamber.

Based on this task, a movable heating rod in connection with a metal bellow as sealing and equalization element was developed. This combination of components that have proved successful in automotive technology fulfils the defined requirements excellently. The combustion pressure present at the heating rod and the bellows produces a force component in the direction of the sensor element. The deformation of the measuring diaphragm is recorded by the sensor element as a value that changes proportionally with the combustion pressure, and is evaluated by the electronics.

In order to facilitate the assembly of the bellows, the glow plug body has been designed as two parts while the wall strength in the bottom area has been reduced. As the design is open on the combustion chamber side, the combustion gas can flow in between the bellows and the body, generating a high thermal stress at the body lower part. Due to the temperature stress, the body is made of stainless steel with mechanical strength necessary in high temperatures in order to withstand the pretensioning force of the assembly without any plastic deformation. On the other hand, this design generates special flow conditions thus safeguarding against sooting of the gap, **Figure 4**.

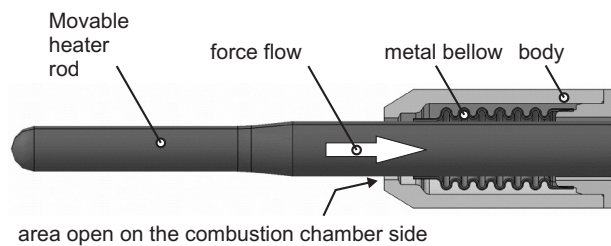


Figure 4: Section through the pressure sensor glow plug with bellows.

As the stiffness of the bellow is relatively small compared to the stiffness of the power-transmitting assembly including heating rod, extension and sensor element, any deformations of the cylinder head as well as an equalization of the strains inside the PSG during glow operation can be compensated by deformation of the bellow. Analytically, it is a parallel circuit of two springs, as shown in the block diagram, **Figure 5**.

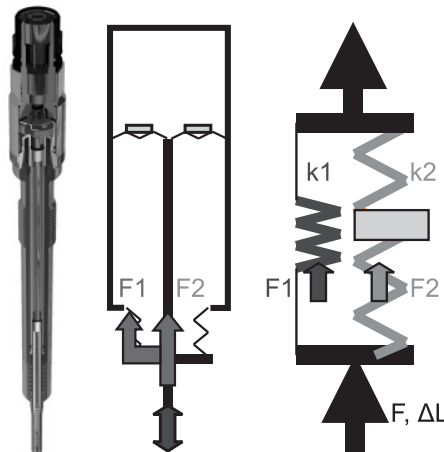


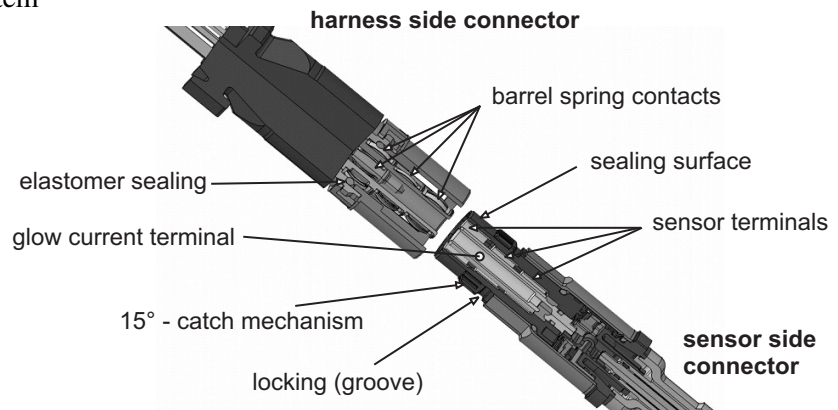
Figure 5: Power spring system of the PSG

The bellow additionally permits the movement of the heating rod in the pressure cycles. Due to these basic conditions, the geometry of the design and the selection of the material are very demanding. They must permit the relatively large movements of thermal expansion in this narrow installation space, and simultaneously be pressure-stable at high temperature stress. Furthermore, the function of the PSG may not be impaired. These tasks are best fulfilled by a double-wall bellow made of a titanium stabilized austenitic stainless steel. The metallic design ensures almost friction and hysteresis-free transmission of power.

2.3 The connector system

Another innovative element of the PSG is a coaxial connector system, a joint development by BERU and Hirschmann Automotive. It consists of a system made up of a coupling on the cable side and a plug on the glow plug side. This solution was necessary as no series connector system was available for the combination of approximately 7 mA for the sensor and 50 A for the glow function, **Figure 6**.

Figure 6: Coaxial connector system



In this connector system, the three sensor contacts with different diameters are arranged on three levels concentrically around the glow current. This new development with an outer diameter of only 16 mm on the coupling side requires very little installation space. When fitting, the plug is lead through the central glow current contact and is protected against lateral twisting by a 15 degree catch mechanism. Thanks to the small division of the catch mechanism, almost position-free fitting is nevertheless possible. The locking is force-locked by snap-fits that engage in a groove at the insulator on the sensor side. An elastomer seal provided in the plug in the upper part of the glow plug ensures tightness of the system.

The glow current contact is uncoupled from the movable heating rod by a spring connection provided between the inner pole and the glow current connection. As the barrel spring contacts of the plug are slotted, high contact normal forces are generated that make the push-fit system highly resistant to vibration. All requirements in the engine compartment are fulfilled thanks to the high IP protection class with IP69K and a temperature resistance from -40 to +150 degrees Celsius.

2.4 Notch filter and dynamic offset compensation (DOC)

The functional principle of the movable heating rod implies vibration influences that BERU could already largely eliminate by a well-designed mechanical design. As the heating rod functions as the pressure transmission element, it must be prevented by suitable design measures that, above all, radial vibration excitations influence the measuring signal. The diaphragm and the strain gauges have therefore been designed largely symmetrical so that these radial components can reliably be compensated.

The combination of heating rod and extension tube is connected as mass to the measuring diaphragm. The measuring diaphragm itself is designed as a deformation element. As the geometry for these components is strictly defined, it is not possible to prevent any axial vibrations that are due to the design. The inherent modes are in a range of approximately six to ten kHz which is outside the sensor bandwidth

A programmable notch filter has been integrated into the ASIC in order to largely eliminate these axial natural frequencies from the sensor signal. Its filter frequency can be programmed in steps of less than 0.1 kHz in a bandwidth of six to 25 kHz - depending on the specific environmental requirements, **Figure 7**. Simultaneously, the digital filter produces a constant phase displacement that can be compensated in the ECU.

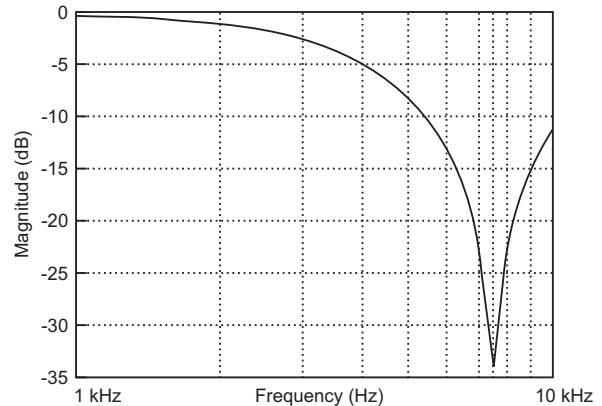


Figure 7: Bode diagram notch filter

In addition to this notch filter, an analog first-order low pass filter that efficiently suppresses high-frequency interferences has been integrated into the electronics.

Another efficient component in the filter chain is the dynamic offset compensation (DOC). Its function is to compensate any offset displacement caused by the thermal length change between plug body and heating rod. The DOC is a high pass filter that filters slow changes without influencing the dynamic pressure signal.

3. Measurement results of the pressure sensor glow plug

Figure 8 shows the specification that the PSG reaches based on the customer specifications. With a pressure range of between 0 and 200 bar, a burst pressure of 260 bar and a total cycle number of 500 million cycles, an accuracy of $\pm 2\%$ is guaranteed over the entire life.

Specification:

Pressure range:	0 - 200 bar
Test pressure:	220 bar
Burst pressure:	260 bar
Supply voltage:	3 V or 5 V ($\pm 5\%$)
Current load:	7 mA max.
Output signal:	11.5 to 91.5 % of V_s
Bandwidth:	0 to 5 kHz (-3dB)
Accuracy:	$\pm 2\%$
"Low clamp & high clamp":	6...9 % & 90...94 %
Error bands:	<4% or >96%

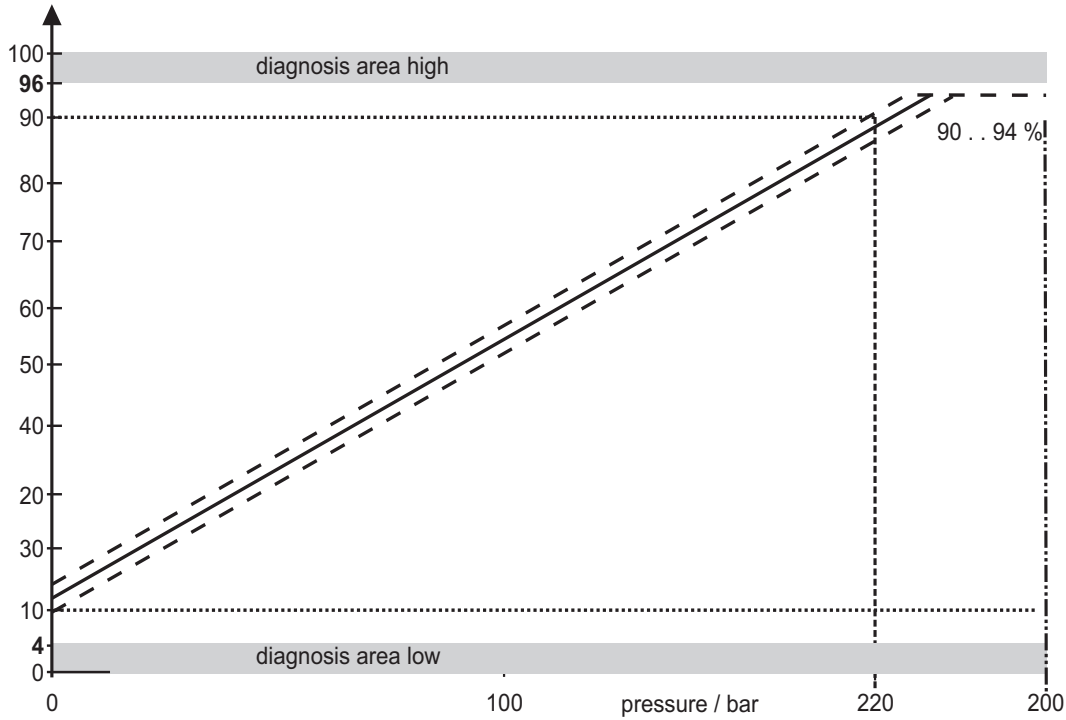


Figure 8: transfer cam

The requirement in this regard is an individual calibration of each PSG at the end of production, at different pressures and temperatures. The calibration parameters are stored in the ASIC of the PSG.

3.1 Dynamic measurement results

The easiest way to represent the determination of the dynamic behavior of the PSG is by means of a reference sensor (indicator engine). By way of example, **Figure 9** shows both pressure processes and the difference at a speed of $n = 1,400$ rpm and 35% load. The minor deviation of the PSG is visible, in which regard the pressure was recorded with a dissolution of $0.1 \text{ }^\circ\text{KW}$, a zero point correction was performed, and the constant phase delay of the notch filter was compensated.

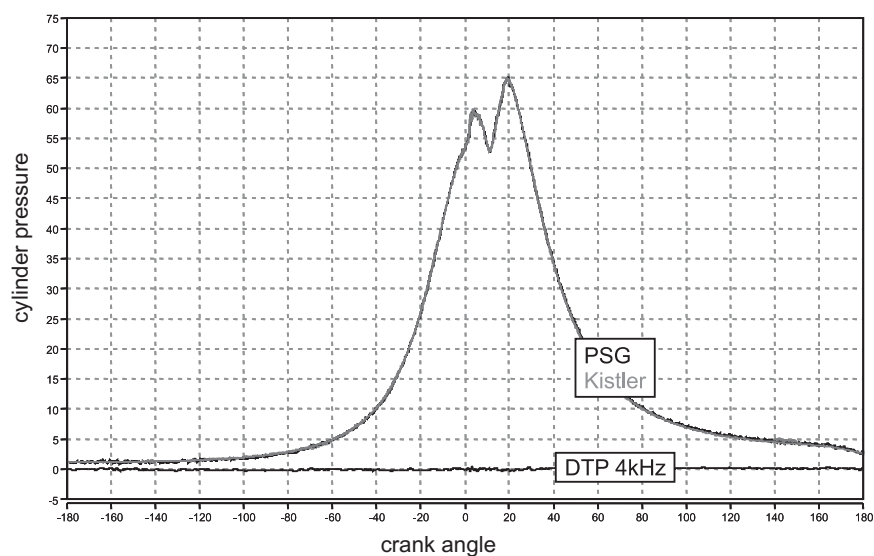
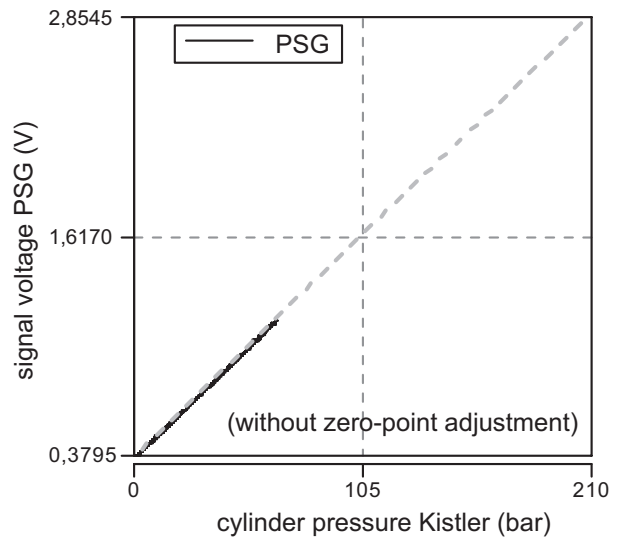


Figure 9: Pressure processes and difference of the pressure processes

When representing the pressure processes in a Lissajou figure, **Figure 10**, it is evident how the signal of the BERU pressure sensor glow plug corresponds to the reference sensor. In this representation, any possible hysteresis and vibrations of the system would also be visible.

Figure 10: Comparison of the pressure processes and difference of the pressure processes



The diagram in **Figure 11** shows the accuracy of the thermodynamic values 5 % rate (AQ 5) and the center of combustion mass (50 % rate = AQ 50), which were calculated based on the combustion pressure signals compared to the reference sensor. This sensitive evaluation also shows the high quality of the PSG signal.

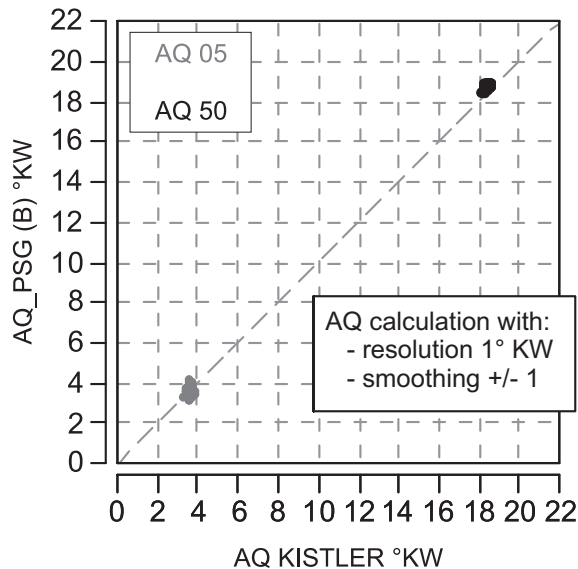


Figure 11: Comparison of the thermodynamic values of calculation and reference sensor.

4 Use in combustion development

With the possibility to measure the cylinder pressure process continuously during engine operation, new variants in combustion process development are conceivable. On the one hand, it is possible to bring standard combustion methods closer to their limits through more accurate recording of the actual condition. On the other hand, a cylinder pressure controlled combustion position control [5] is the key to

reliably controlling new combustion methods also in transient operation and at different environmental conditions. Together with AVL, BERU studied the PSG on the test bench and in the vehicle.

4.1 Potential of the cylinder pressure based combustion position control

In order to be able to utilize the potential of the diesel engine optimally, the measurement and control systems implemented in the engine electronics must reliably comply with the target values. In the currently used engine control strategies, the intake conditions and the injection parameters controlled by the specification of target values and recording of current actual values. However, there is no feedback on the combustion process itself. Thus, only system states outside the cylinder are recorded and the deviations from the required target states are minimized in the best possible manner using the available actuating elements.

From today's point of view, however, a process feedback is required for further developed conventional as well as new alternative combustion methods, in particular in transient engine operation. Two approaches for recording the state of the combustion are conceivable: Direct metrological process monitoring using cylinder pressure sensors, or a model-based combustion calculation integrating the actual intake conditions and injection parameters. A combination of the two approaches appears to become accepted. Due to the currently available computing capacities of the engine management systems, however, the sensor-based approach should initially be treated with higher priority.

4.2 Cylinder pressure based control of alternative combustion methods

Tests on a study engine quickly revealed that only a real control of the combustion, based on information on the combustion process directly from the cylinder, could render alternative diesel combustion [6] practicable in relevant medium pressure ranges. As a first step, suitable control variables were therefore determined from the cylinder pressure sensor signal in real time. The mass fraction burned 50% defining the center of combustion (AQ 50) as measure for the ignition delay on the one hand, as well as optionally the maximum pressure increase as measure for the EGR rate were identified as purposeful control variables.

For the cylinder-pressure based center of combustion calculation and control, the signal of the cylinder pressure sensor together with a standard crankshaft transmitter signal is provided to the "low level algorithms", **Figure 12**.

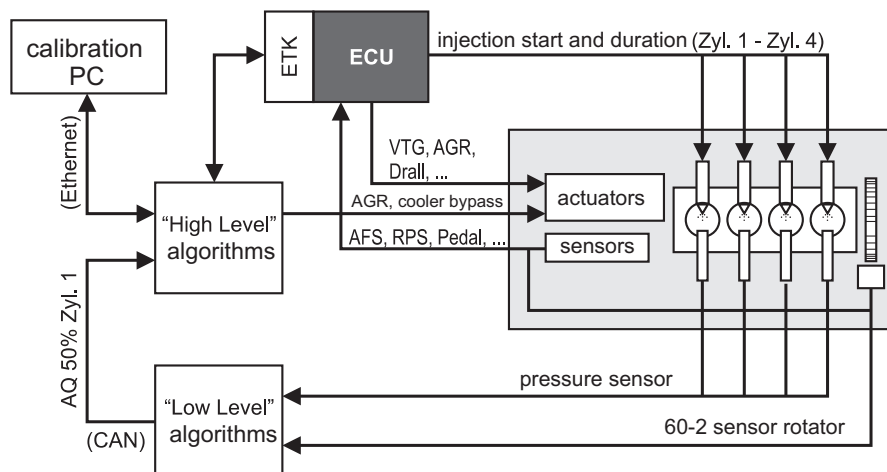


Figure 12: Representation of the used hard- and software system

Based on a 60-2 gear, the position of the 50 % mass conversion point (AQ 50), the indicated mean pressure, the value and the position of the maximum pressure increase, as well as the cylinder peak pressure, are determined. The results are available after every combustion and are transferred to the "high level algorithms". In the development control unit, a new time for the next injection is determined, using the algorithm of an adaptive controller strategy, from the difference between the target value for the position of the 50% mass conversion point (AQ 50) and the actual value determined by the CAN bus. The closed loop control can be based on one lead-cylinder therefore needing only one pressure sensing element or can be performed cylinder-selective in combination with one pressure sensing element per cylinder. For mass production need at least two sensor elements will be necessary for surveillance during lifetime and failure monitoring.

4.3 Emission results

Based on an EU4 exhaust gas standard, it was possible to achieve NO_x raw emissions lower than the discussed EU6 limit in demonstration vehicles by increasing homogenization also towards higher loads for AVL, **Figure 13**.

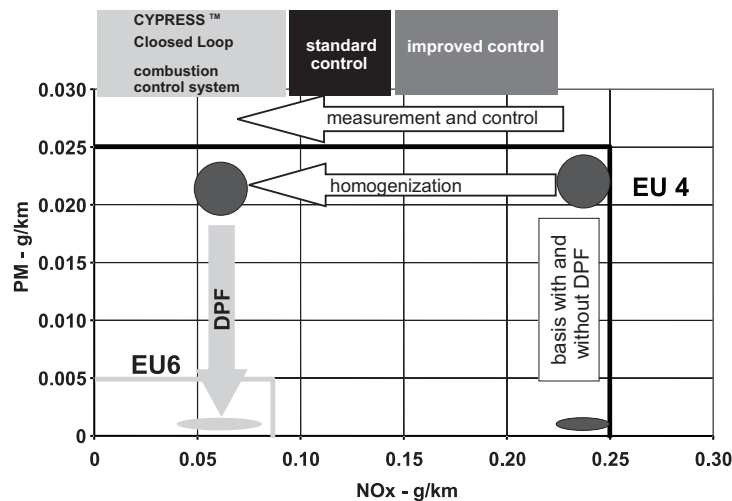


Figure 13: NEDC roller results with partially homogeneous combustion methods in connection with cylinder-pressure based combustion position control

Below a NO_x value of approx. 0.1 g/km, a cylinder-pressure controlled combustion position control is indispensable in the NEDC test to ensure attractive and stable drivability. In addition, suitable measures must be developed in order to be able to control the increased HC and CO emissions in future. The combustion and control strategies (AVL-CYPRESSTM) currently used in prototype vehicles are being developed further [7] in order to be able to represent as many advantages as possible also at series marginal conditions without having to make too many compromises as far as emissions are concerned.

4.4 Fuel quality

Another use of the PSG signals consists in the compensation of different ignition delays. In particular for US uses with a considerably varying cetane number, long-term stable emission control can be achieved. Fuels with a cetane number of 52 and 46 were used in the FTP75 cycle for unchanged calibration. In order to compensate the extended ignition delay for cetane number 46, an early adjustment of the injection start of approximately 4 °KW is required. This leads to the same position of the center of combustion by closed

loop control and results in no differences in fuel consumption and NO_x emissions in the FTP75 cycle.
Figure 14.

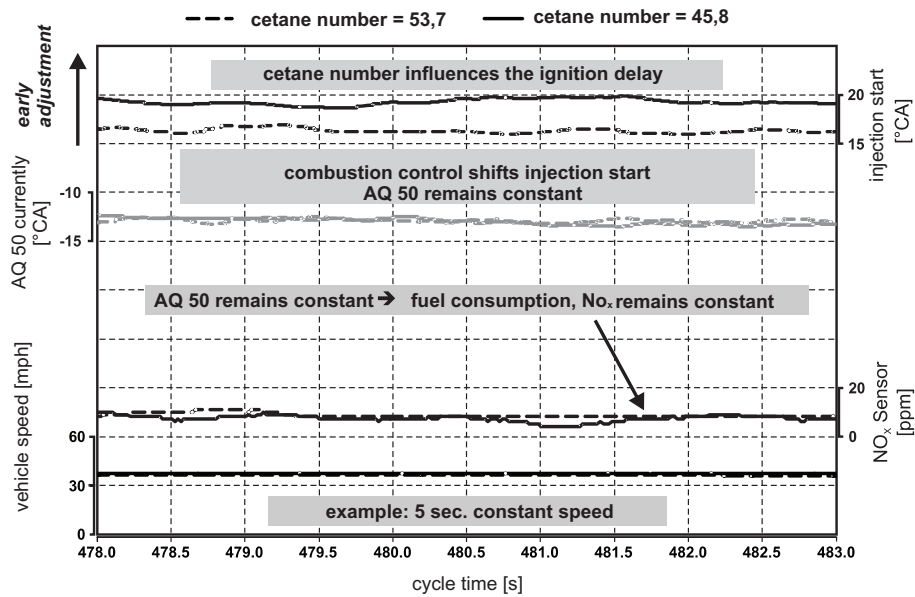


Figure 14: Compensation of different cetane numbers by cylinder-pressure controlled combustion position control

Outlook

AVL and BERU believe that by far not all the possibilities of cylinder pressure sensors have yet been exploited. With the further development of the control concepts, it will be possible to implement further advantages, such as for instance cold start and cold run optimization, closed loop torque control, as well as power increase by continuous peak pressure monitoring and improved emission stability over the life of the engine.

References

- [1] Breitbach, H., Enderle, C., Lindemann, B., Paule, M., Schommers, J., Stotz, M.: Weltweite Emissionsstrategie mit BLUETEC für Pkw-Diesel-Antriebe; 15. Aachener Kolloquium Fahrzeug- und Motorentechnik, Aachen, 2006
- [2] Bürgler, L., Cartus, T., Herzog, P., Neunteufl, K., Weißbäck, M.: Brennverfahren, Abgasnachbehandlung, Regelung – Kernelemente der motorischen HSDI Diesel Emissionsentwicklung, 13. Aachener Kolloquium Fahrzeug- und Motorentechnik, Aachen, 2004
- [3] Borgers, M., Haußner, M., Houben, H., Marto, A., Pechhold, F.: Drucksensor-Glühkerze (PSG) für Dieselmotoren. In: MTZ (65) 2004, No.11, P. 888-895
- [4] Endler, M., Houben, H., Schmitz, H.-G., Uhl, G.: Das elektronisch gesteuerte Glühsystem ISS für Dieselmotoren. In: MTZ (61) 2000, No.10, P. 668-676

[5] Breitegger, B., Hülser, H., Neunteufl, K., Unger, E.: Eine zylinderdruckbasierte Motorregelung für niedrigste Emissionen beim Dieselmotor. 5. Symposium Steuerungssysteme für den Antriebsstrang von Kraftfahrzeugen, Berlin, 2005

[6] Csato, J., Glensvig, M., Herzog, P., Sams, T., Weißbäck, M.: Alternative Brennverfahren - Ein Ansatz für den zukünftigen PKW-Dieselmotor. In: MTZ (64) 2003, No. 9, P. 718-727

[7] Bürgler, L., Glensvig, M., Neunteufl, K., Weißbäck, M.: Fahrzeugapplikation mit alternativer Dieselerbrennung. In: MTZ (66) 2005, No.11, P. 866-871