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Injection rate control strategy with Bosch Smart CR Injector for optimized injection performance

Engine Component Developments - Fuel Injection & Gas Admission

Thibault Henrion, Robert Bosch, Powertrain Solutions, Large Engines

Florian Moesenbichler, Robert Bosch, Powertrain Solutions, Large Engines
Christoph Redtenbacher, LEC GmbH
Maximilian Malin, LEC GmbH
Martin Bernhaupt, Robert Bosch Powertrain Solutions, Large Engines
Robert Wrede, Robert Bosch, Powertrain Solutions, Large Engines
Jens-Olaf Stein, Robert Bosch, Powertrain Solutions, Large Engines

ABSTRACT

Motivation & Target

Latest emission regulations for large engines were reached through introduction of common rail injection technology. Upcoming CO2 reduction targets require the implementation of advanced and new technologies in the large engine business. Engine efficiency improvement is one of these paths. It must be accompanied by accurate emission control measures in order to fulfil future more stringent targets.

Engine efficiency and emissions are affected by the deviation of injector function from its nominal condition. We differentiate between two origins for this variation:

- Manufacturing processes results in part to part functional deviation. This spread is considered in the engine design by setting a safety margin to engineering targets. This safety margin steers engine efficiency to lower levels.

- Wear condition results in injector functional change. Among others, change in nozzle flow, deposit formation or wear on nozzle seat will modify injection function over time. This leads to suboptimal combustion parameters, efficiency losses up to several percent, and emission degradation. Typically start of injection shift will influence CO2, NOx and PM emission whereas injection duration changes are effecting CO2 and PM emissions.

Injector individual closed loop control allows a significant reduction of these deviations over lifetime. Nozzle needle control chamber volume pressure contains high quality information upon the needle movement and thus allows more accurate injection correction than other known concepts. This signal is therefore used in the Bosch large engine Smart Injector platform.

Content

This paper shows an innovative method, using injector internal pressure sensor, for controlling cylinder individual injection and reaching optimal combustion and efficiency.

First, engine testing results demonstrate how wear behavior effects specific consumption. It shows how injector function must be corrected in order to reach optimal engine performances.

After revealing the concept of the Bosch Smart Injector, an insights into the unique sensor signal interpretation is given: basic injection timing characteristics describing start/end of needle opening and closing phases are correlated to the sensor signal. Further, injector basic physical parameters are defined for characterization of manufacturing deviation and functional drift due to wear. Using large amount of injector test data, correlations between sensor signal and physical parameters are established with different methods:

- Conventional approach: using multidimensional linear interpolation

- Artificial Intelligence (AI): using different type of neural networks

Finally, the implementation of these methods into the engine control unit is described. The combination of both (conventional and AI) leads to an excellent accuracy of the compensation model. Compared to already available concepts, the present injector control process uses a novel precise model for quantity and injection rate prediction, that delivers accurate information on start of injection, injection duration and injection rate shape. The change in injection rate is thus identified and corrective actions on timing are taken, to minimize the detourition of fuel consumption and emissions due to injector wear. This new control strategy will reduce operative expenditures through lower fuel consumption, increase engine availability and contribute to stable and low emissions in field.

1 INTRODUCTION

The environmental challenges of our time require effective action in curbing emission-generating processes all over the world. Technologies supporting this change are already being developed in many different fields. However, this process takes time and requires new technologies as well as the optimization of existing technologies. In the large engine segment, the internal combustion engine will remain on the market alongside new technologies (e.g., fuel cells, batteries, hybrid systems) beyond 2050. Therefore, further improvements in efficiency are necessary.

Diesel engines may be optimized significantly by aligning diesel injection timing and quantity for each cylinder and by ensuring injection precision over the whole lifetime of the injection equipment. Traditionally, improvements were achieved by increasing the robustness and reliability of components and by optimizing design and manufacturing. However, the active correction of injection quantity by predicting the wear on the injection equipment over its lifetime was not possible.

So far, legislation has allowed emission verification via deterioration factor testing. This method is used to prove that engine emissions remain within the required limits over the lifetime of the engine. For example, the target for engines used in power generation sets beyond 560 kW is set at 8,000 hours [1]. If emission targets need to be ensured during field operation over the entire lifetime, the monitoring of every emission relevant component in the engine would be necessary, and the use of closed loop injection equipment essential.

Many different concepts for improving the performance of diesel engines have already been introduced, e.g., common rail systems with high pressure levels over 2000 bar. To gain more accuracy in fuel injection, however, it is beneficial to know how the nozzle needle actually moves inside the injector. The exact detection of the needle opening and closing time is required in order to achieve improvements regarding injection accuracy and stability.

Three main approaches to detecting the needle movement inside the diesel injector are already known: analysis of the drop in rail pressure during injection [2], evaluation of the electrical contact between the nozzle needle and the nozzle seat [3] and measurement of the hydraulic control pressure inside the injector [4].

BOSCH has developed a new smart injection system for large engines. The so-called Needle Closing Control (NCC) system is based on common rail technology with solenoid valve injectors, which enables closed-loop control of the injection duration. Using a piezo sensor in the injector and a new software architecture, the system measures and controls the exact duration of the individual fuel injection events with a resolution of a few millionths of a second. As a result, fuel dosing and processing, which are essential for combustion, remain stable over the entire lifetime of the engine. [4]

This new injection system technology was initially developed for the passenger car engine segment. In the next innovation step, BOSCH uses this experience and adapts it for the large engine market. This measure has the great potential to reduce the emissions and fuel consumption of large diesel engines and therefore makes a significant contribution to addressing our climate challenges.

This paper gives an overview of the main wear mechanisms of diesel injectors and shows how the NCC technology helps to compensate for the wear effects. Furthermore, it discusses measurement results from tests on a single-cylinder engine (SCE) and a multicylinder engine (MCE) performed at the LEC, indicating the potential of this technology to decrease fuel consumption and emissions.

2 POTENTIAL OF NCC TECHNOLOGY FOR LARGE ENGINES

The first step in the NCC technology development process was to determine the potential for improvement in terms of engine fuel consumption and emissions with a closed-loop controlled injector. This section describes the applied approach.

2.1 Effects of injector wear mechanisms on engine operation

The relevant injection parameters with regard to fuel consumption and emissions are:

- injection timing with the start of injection (SOI) and end of injection (EOI),
- injection rate shape (see the example of an injection rate shape in Figure 7), i.e., the maximum flow through the nozzle, as well as its rising and falling edges, and
- nozzle spray characteristics such as penetration depth and jet breakup.

Due to manufacturing tolerances, new injectors show part-to-part scatter of these three parameters. This scatter even increases and deviates from the nominal value over lifetime due to wear mechanisms occurring under operating conditions. Figure 1 shows the predominant wear mechanism on the injection nozzle: cavitation erosion. Besides the nozzle, further injector components such as the orifice plate and the solenoid valve contribute to injector functional drift due to wear.

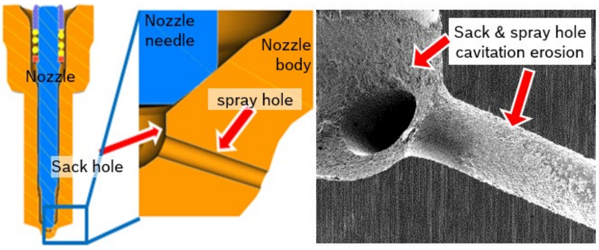

Figure 1: Typical sack and spray hole cavitation wear in a common rail injector nozzle

Reaching optimal engine efficiency requires a cylinder-specific equalization of the injection quantity and the cylinder peak pressure. This helps achieve a constant output with each cylinder and a uniform load. The scatter described above and changes in injection behavior work counter to this equalization, resulting in suboptimal combustion conditions and drawbacks in emissions and fuel consumption.

With the NCC technology correction functions, the parameters start of current (SOC) and duration of current of each injector can be adjusted cylinder-individually. In this way, the injection timing parameters can be equalized, as can the quantities via highly sophisticated algorithms. Nozzle spray characteristics or injection rate maximum flow or slopes cannot be directly corrected.

2.2 Methodology for determining the potential of smart diesel injector technology

2.2.1 Basic approach

When evaluating the NCC technology for large engines, a distinction must be made between its theoretical potential and its actual benefit on a real engine. The following section describes how these values differ and how they are determined.

Basically, an operating point can be corrected with NCC technology only by adjusting the parameters start of injection and injection duration. Assuming that the injection duration control is used for load balancing, the start of injection remains to compensate for injector wear and aging effects on fuel consumption and emissions.

The three schematic brake-specific fuel consumption (BSFC)/brake-specific nitrogen oxides (BSNOx) trade-off curves in Figure 2 provide an example of the behavior of new and worn injectors in an engine. The black curve corresponds to a new injector, the red one to a worn injector with a minimum nozzle flow characteristic and the blue one to a worn injector with a maximum nozzle flow characteristic. It can be seen that at the same start of injection, the BSFC and the BSNOx achieved with the worn injectors differ from the respective values achieved with the new injector. By adjusting the start of injection with the worn injectors, either the same BSFC or the same BSNOx can be met. Only in the exceptional case, when the new and the aged injector would result in a congruent BSFC/BSNOx trade-off curve, it would be possible to fully compensate for both values at the same time. As a result, in the theoretical case, a correction can only be performed by targeting either the same fuel consumption or the same emission level.

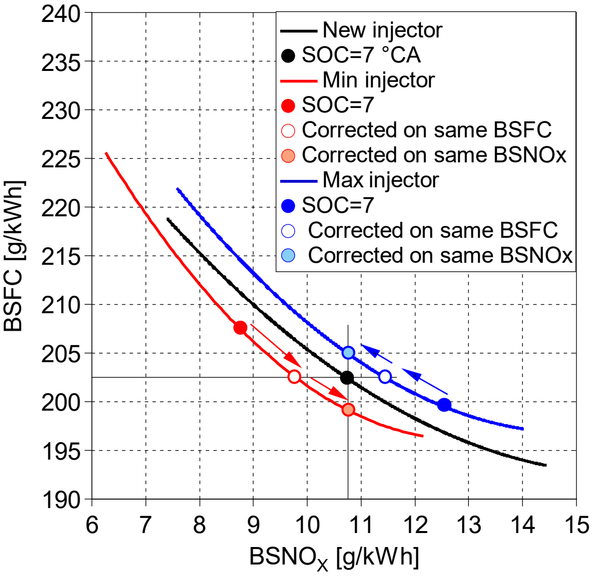

Figure 2: Possibilities for operating point correction

In this paper, the theoretical potential of the NCC technology with an injector at a given operating point is based on the correction of the start of injection so that exactly the BSNOx level as with a new reference injector is reached. In the case of a trade-off curve to the left of the reference trade-off curve, the theoretical potential gives the maximum BSFC benefit within the BSNOx level of the reference point. In the case of a trade-off curve to the right of the reference curve, the theoretical potential gives the achieved BSNOx benefit. The theoretical potential can be determined specifically for a single cylinder on an SCE as well as provided as an averaged result over all cylinders on an MCE. In both cases, the measurements are performed without applying a correction algorithm.

The actual benefit of the NCC technology is derived by comparing the results of an engine operating point measured once with a new reference injector without any correction algorithm and once with an aged injector where the correction algorithm is applied. Even with the use of sophisticated correction algorithms, the theoretical potential can generally not be exactly realized. Since boundary conditions constantly vary during engine operation and complex interactions of various types of wear occur, the correction value required to achieve the same BSNOx cannot be predicted exactly. Like the theoretical potential, the actual benefit can be determined specifically for one cylinder or for the entire engine.

To determine the theoretical potential and the actual benefit of the newly developed NCC technology for large engines, a multistage approach combining different experimental methods was developed as shown in the flow chart in Figure 3.

In step 1, artificially aged diesel injectors were produced on an injector endurance test rig at BOSCH. Several injectors were operated on this test rig at defined boundary conditions over a long period of time until the desired wear patterns (e.g., cavitation erosion, nozzle flow change, spray asymmetry) were generated. In addition, limit samples at the edge of the tolerance range were manufactured. Thus, all relevant types of wear could be represented individually as well as in combination with each other.

In step 2, the aged injectors were measured on an injector test rig at BOSCH, where the newly developed engine control unit (ECU) algorithms for wear detection and operating point correction were tested and evaluated. These results were compared to those achieved with new injectors.

In step 3, new and aged injectors were operated on the SCE at the LEC. The corresponding BSFC/BSNOx trade-off curves were determined by performing injection timing variations at defined operating points. This allowed an evaluation of the theoretical potential of applying NCC technology depending on the wear mechanism. The SCE test bed is described in more detail in section 2.2.2.

In step 4, the technology was tested on the system test rig at BOSCH as a complete common rail system with twelve injectors, a common rail pump, a cable harness and control unit. This setup was used to identify the influence of multiple injectors on hydraulic performance and electrical signal quality. Furthermore, calibration data was validated.

In the final step 5, the NCC technology was evaluated at defined operating points on the MCE (see description in section 2.2.3) at the LEC. It was first equipped with new injectors alone and then with aged injectors of different wear types. In the configuration with the aged injectors, the measurements were performed once with and once without the correction algorithms. The theoretical potential and the actual benefit of applying the new technology on an MCE were determined by comparing all three measurement results.

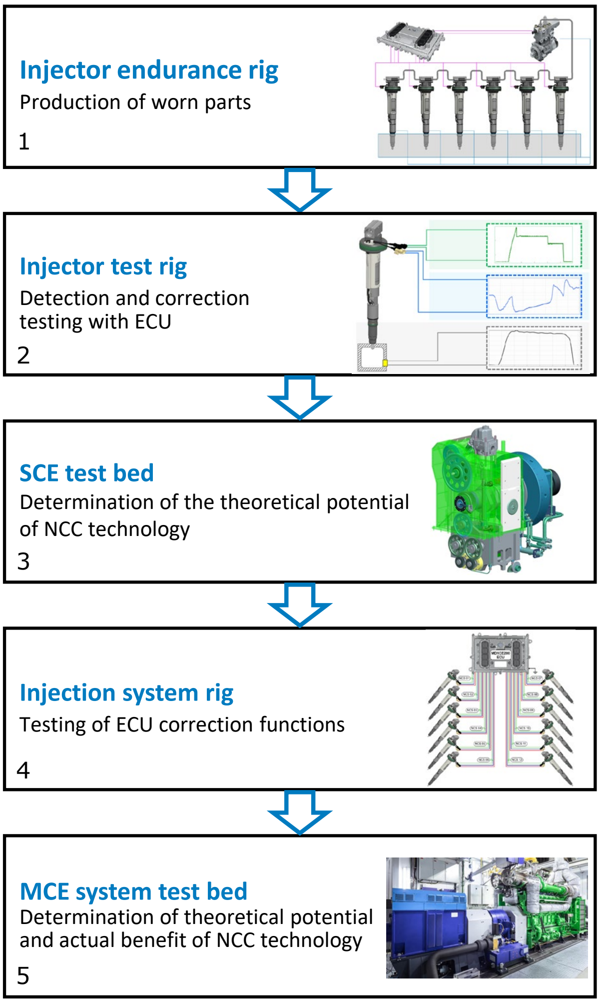

Figure 3: Methodology for determining the theoretical potential and the actual benefit of NCC technology

2.2.2 Single-cylinder engine testing

The theoretical potential of applying NCC technology was evaluated on a high-speed four-stroke SCE with a displacement of 6.24 dm³ and a nominal speed of 1500 rpm. All necessary engine operating media, i.e., cooling water, lubrication oil, diesel fuel and charge air were conditioned to ensure well defined and reproducible operating conditions. Instead of a turbocharger, the charge air was supplied by a screw-type compressor upstream of the engine. A valve flap in the exhaust system was used to adjust the back pressure in the exhaust manifold. The engine was equipped with a diesel engine power unit configuration which was optimized for lowest emissions in combination with a selective catalytic reduction exhaust aftertreatment system. An engine-independent common rail system provided rail pressures up to 2200 bar. A BOSCH MD1CE200 (ECU) was used for injector control and sensor signal processing. The test bed was equipped with the latest crank angle-based and time-based measurement systems to measure all values required to evaluate the NCC technology performance in detail.

2.2.3 Multicylinder engine testing

The final evaluation of the NCC technology was carried out on a 12-cylinder V60° 2 MW diesel engine with a nominal speed of 1500 rpm using the same type of power unit as in the SCE investigations. The engine was equipped with a one-stage turbocharger and a waste gate for excess air ratio control. For MCE control, a BOSCH MD1CE200 ECU with integrated NCC algorithm was used. Similar to the SCE, the MCE was equipped with an engine-independent common rail system with a high-pressure pump powered by an external electrical motor. Like the SCE test bed, the MCE test bed was equipped with the latest crank angle-based and time-based measurement systems. For detailed evaluation of the NCC technology, crank angle-based measurements were conducted on all twelve cylinders (e.g., cylinder pressure, NCC sensor signal, injector current signal).

2.2.4 Investigated engine operating points/test cycle

For both the SCE and the MCE investigations, the engine operating points were defined according to the ISO 8178 C1 test cycle.

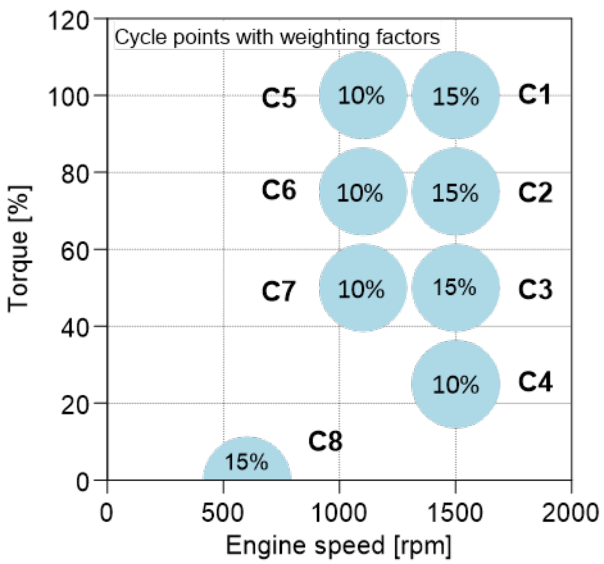

Figure 4: C1 Test Cycle

ISO 8178 [5] is an international standard to determine exhaust emissions of internal combustion engines of non-road engine applications. In this standard, the C1 cycle is referred to as the Non-Road Steady Cycle. This cycle includes eight different cycle points from full load to idle operation (C1 to C8) at three different engine speeds (rated, intermediate, low/idle) and two different weighting factors (10%, 15%). There was a conscious deviation from ISO 8178 at the C4 load point, where the measurements were made at 25% load instead of 10% load. The operating points are shown in Figure 4.

2.3 Evaluation of the theoretical potential based on SCE investigations

Figure 5 presents an example of results of the SCE investigations in which the BSFC/BSNOx trade-off curves of new injectors are compared at the C1 cycle point. Three of the injectors were nominal mean injectors (Nom-injector) and one injector had a minimum injection rate characteristic, however within the new part tolerance (Min-injector).

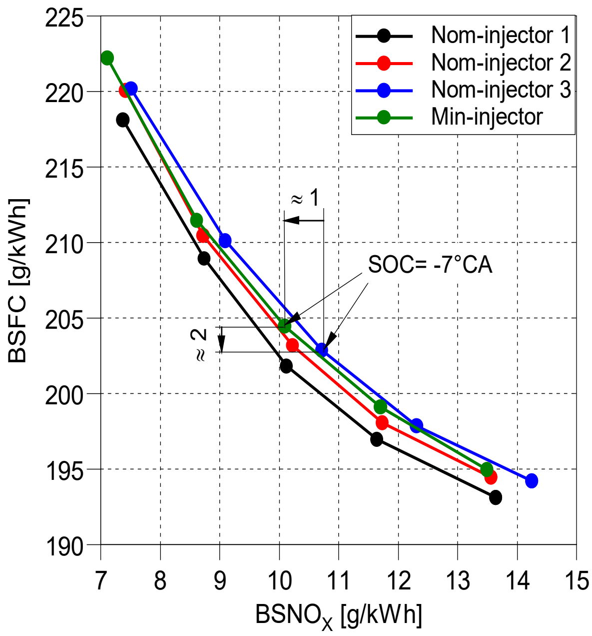

Figure 5: BSFC/BSNOx trade-off curves of new injectors

In the case of engine operation without a correction function, the start of current is the same with all injectors (e.g., SOC = -7°CA). Under this boundary condition, the Min-injector results in increased fuel consumption. Compared to the Nom-injector represented by the blue curve, the drawback is ≈ 2 g/kWh but at slightly lower BSNOx emissions of ≈ 1 g/kWh. By advancing the start of injection with the Min-injector, the BSFC of the Nom-injector could be reached with almost same BSNOx emissions. However, the three Nom-injectors show scattering in the same range as the deviation of the Min-injector. In summary, there is only a limited potential for improving the fuel consumption of an engine with new injectors.

Figure 6 shows a similar plot for the C1 cycle point with a Nom-injector and two selected aged injectors representing conditions at the end of injector lifetime.

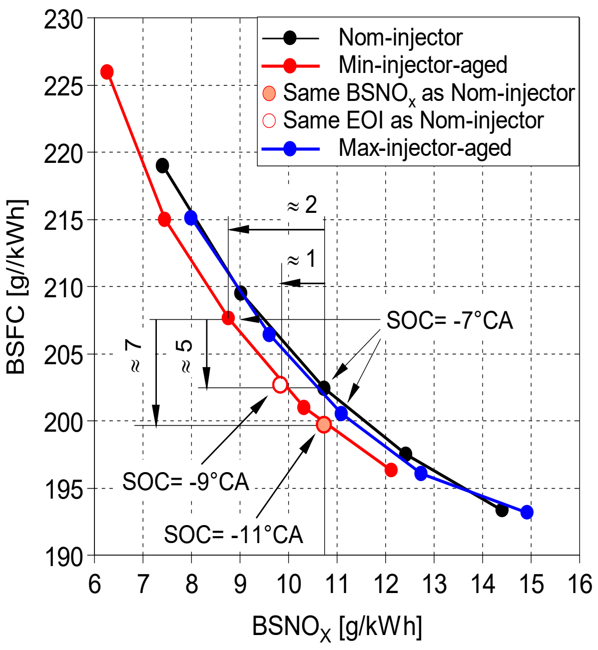

Figure 6: BSFC/BSNOx trade-off curves of aged injectors compared to a new nominal injector

One injector was aged in the direction of increased injection quantity (Max-injector-aged). Its trade-off curve is almost congruent to that of the Nom-injector. Thus, a correction to the same BSNOx would result in almost the same fuel consumption.

The other injector was aged in the direction of reduced injection quantity (Min-injector-aged). Compared to the Nom-injector, its BSNOx level is ≈ 2 g/kWh lower at the same start of current (SOC = -7 °CA), but its fuel consumption increases by ≈ 5 g/kWh. The explanation for this behavior is twofold: an increased injection delay due to wear at the solenoid valve, which results in a later start of injection and a longer required injection duration (to keep the engine load constant) due to a reduction in flow rate caused by cavitation erosion. Based on the measurement results, different correction strategies can be derived: By advancing the injection with the Min-injector-aged to SOC = -11 °CA, the BSNOx level of the new injector can be reached. This results in a theoretical BSFC potential of ≈ 7 g/kWh. A somewhat more conservative approach would be to shift the injection to the same end of injection corresponding to SOC = -9 °CA. In this case, the BSFC potential is ≈ 5 g/kWh.

Note that for high load points, the exploitation of the BSFC potential may be restricted by the peak cylinder pressure limit of an engine. Furthermore, the particulate matter emissions must also be taken into account.

3 BOSCH LARGE ENGINE NCC CONCEPT

3.1 Diesel injector design and function

The large engine NCC technology detects nozzle needle movements thanks to a piezo sensor integrated into the solenoid valve of the common rail injector (see Figure 7). At the heart of the closed-loop control system, this needle closing sensor detects the main characteristics of the injection process [4]. The nozzle movements are actuated hydraulically over a control volume where pressure is changed in order to trigger needle opening and needle closing. The integrated piezo sensor measures the pressure of this volume, which acts on a membrane. The resulting force is measured by a very stiff sensing system (sensor and adjustment bolt) supporting the intermediate wall so that the membrane is not subject to deformation [6].

The sensor signal is proportional to the pressure trace of the control volume. Based on the control volume pressure curve shown in Figure 7, optimized ECU algorithms are able to detect the following features:

- **Needle opening start** (NOS) and the start of injection that directly follows
- **Needle opening end** (NOE) when the needle reaches its top end position
- **Needle closing start** (NCS) when the needle moves from the top end position or reverses its movement in case it starts to close before it reaches the top end position (so-called ballistic operation)
- **Needle closing end** (NCE) and the end of injection that directly follows

Thanks to the two wires used for signal transfer, this innovative sensing principle allows a clear signal with little influence by parasitic noise or other hydraulic and mechanical loads.

Another advantage of the design is the clear maxima and minima of the control volume pressure trace that correlate with nozzle needle movement. Large pressure change amplitudes lead to high signal amplitudes and result in robust and accurate timing detection.

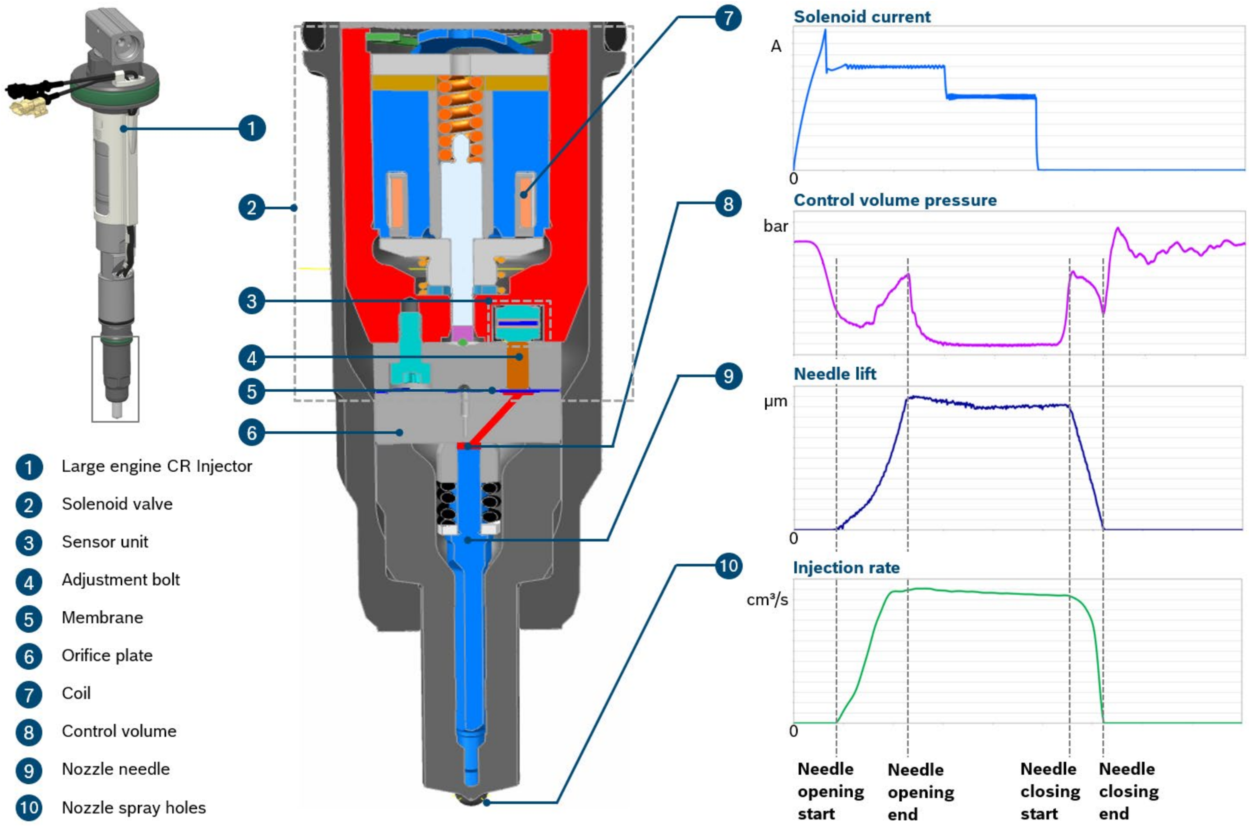

Figure 7: NCC technology functional principle and design

3.2 Engine control system

The BOSCH ECU MD1CE200 is a fully fledged engine control unit. New functions (see Figure 8) relevant to the NCC technology have been implemented in order to fulfill the requirements for closed loop operation.

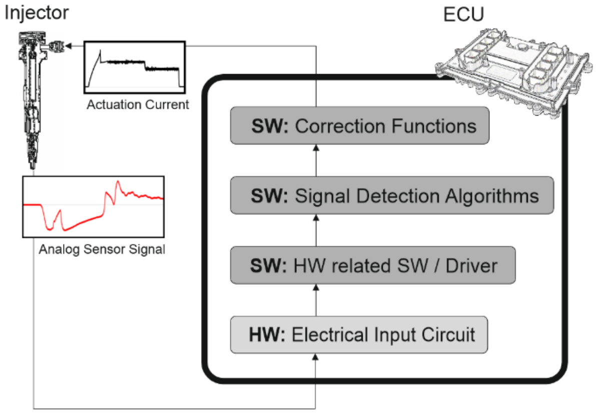

Figure 8: ECU function disciplines

The electrical input circuit is designed for optimal charge amplification of a piezo sensor and has suitable filter characteristics. The hardware-related software controls all components, e.g., analog-to-digital converter, multiplexer and RAM, which are required for digitizing the analog sensor signals.

The ECU design allows the recording of every injection type per working cycle and high-resolution sampling down to three microseconds. Specially designed signal detection algorithms analyze the digitized sensor signal and extract the points in time relevant to needle movement. They have been specially designed and validated for robust detection over the complete operating range of the engine and efficiently cancel out potential signal noise. Correction functions use the detected points in time of each individual cylinder to calculate the necessary adjustment in injector control (injection start and injection duration) and achieve the desired optimal injection.

Due to the wide variety of different control systems on the large engine market, alternative control concepts were developed that do not employ a BOSCH ECU for the entire engine control system. In Figure 9, option 1 is a software as a product (SaaP) concept compatible with any alternative hardware. Option 2 – software sharing (SWS) – is a third-party software that can be implemented on BOSCH hardware. In option 3, the injector is only driven by BOSCH hardware, which communicates in turn with the hardware that drives the engine. This option is appropriate for retrofitting existing engines with NCC technology.

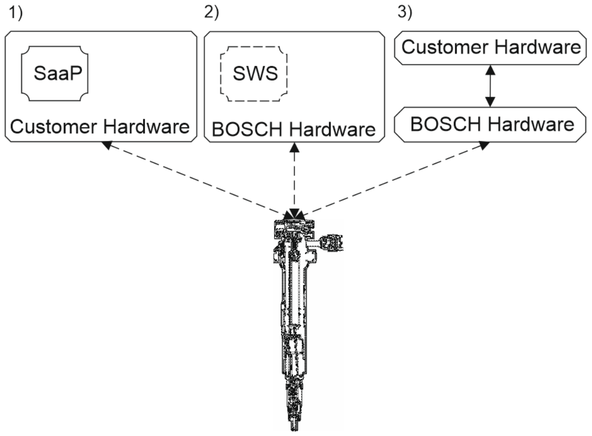

Figure 9: ECU hardware/software options

3.3 Sensor signal interpretation and utilization

As described in 3.1, optimized ECU algorithms are able to detect four timing points based on the control chamber pressure curve of the sensor signal. These algorithms were developed specifically for large engine NCC technology.

The large engine common rail injector can operate in two different operating modes: 1) the non-ballistic or linear mode with contact between the needle and the upper stop (detection of four timing points, see Figure 10), and 2) the ballistic mode with no contact between the needle and the upper stop and instead a needle turn point (detection of three timing points, see Figure 11).

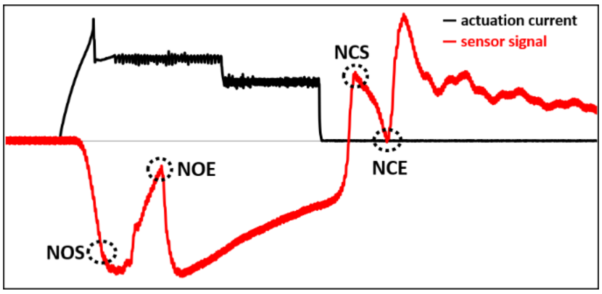

Figure 10: Control chamber pressure – linear mode

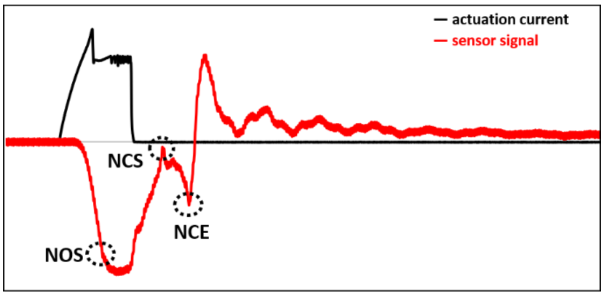

Figure 11: Control chamber pressure – ballistic mode

Detecting the exact timing of the transition from ballistic to non-ballistic operation mode is especially challenging.

Furthermore, the detection of the timing needs to be independent of sensor signal amplitude since this injector-specific amplitude varies due to the actual rail pressure as well as manufacturing tolerances and the effects of aging on the sensor cell. Thus, detection algorithms normalize the sensor signal with the detected amplitude.

Sensor signal evaluation requires the examination of the entire operating range from high rail pressure and long actuation times to low rail pressures (idle, start-up) and short actuation times. Any needle movement can be reliably detected, even when it is minimal, and it is possible to detect whether the nozzle needle has opened at all.

3.4 Injector deviation from nominal behavior

In a conventional common rail system without closed-loop control, the electric valve energizing times required for dosing are stored in a so-called energizing time map that describes a reference injector and is dependent on the rail pressure. However, unavoidable injector tolerances and lifetime drift lead to varying injection durations for the individual samples despite identical electric energizing times. This results in deviations in the injection quantity compared to the reference injector set. A very good correlation between the hydraulic injection duration and the injection quantity is seen with servo injectors that run in ballistic operation mode of the nozzle needle (see upper right diagram in Figure 12).

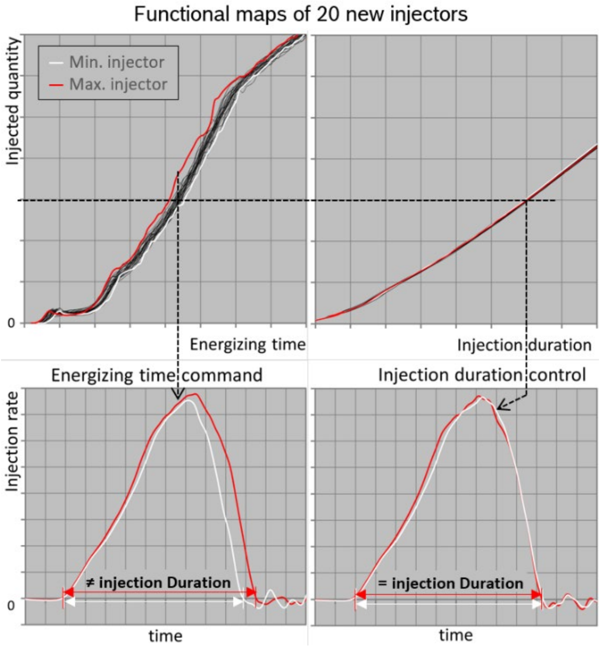

Figure 12: Improvement in new part deviation with injection duration control

As a result, the hydraulic injection duration is the lead parameter of the NCC system instead of the electric energizing time. The hydraulic injection duration is stored in an additional characteristic map for the reference injector set [4]. Figure 12 shows how injection duration-controlled injectors deliver fuel with an up to 75% better quantity accuracy in the ballistic operation mode. This correction can be easily achieved thanks to the detected timing information.

It appears that in operation outside the ballistic mode, a remaining quantity deviation increases with the injection duration. This is due to variation in the nozzle flow between the injectors. This behavior is also identified as one of the main reasons for injector quantity deviation over lifetime as shown in Figure 13. Therefore, additional corrections are required in order to control injection quantity at a nominal level over lifetime.

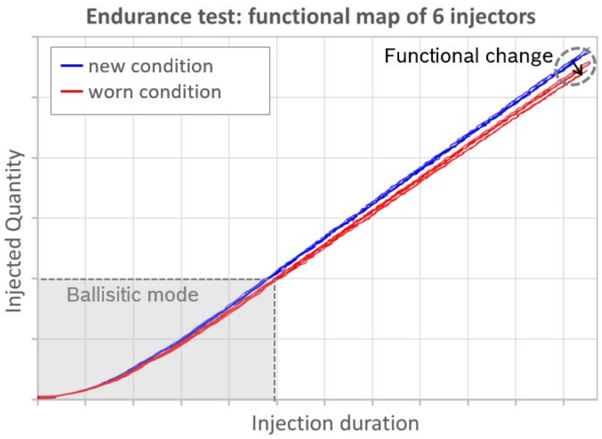

Figure 13: Functional change after operation

3.5 Injector drift and wear identification

Large engine CR injector behavior analysis has shown that injection duration control is insufficient for maintaining nominal behavior over lifetime. Especially nozzle flow change due to wear affects the injection rate maximum, thus changing the injected quantity even when injection duration remains constant (see Figure 13). Nozzle flow change cannot be detected directly with the sensor signal as it is not calibrated with absolute pressure. However, investigations show good correlations between some sensor timing values and nozzle flow change.

Therefore, an extensive study has been conducted in order to systematically quantify correlations between injector wear parameters and sensor timing values. Hydraulic simulation as well as injector testing were performed. The following wear parameters of the injector parts have been considered:

- **Nozzle wear**: flow change, needle lift change and sealing diameter change
- **Orifice plate wear**: inlet and outlet orifice flow change
- **Solenoid valve wear**: sealing diameter change, seat leakage

As a result, the established correlations show that nozzle flow drift induces changes in NOE time as well as NCE time. It has no influence on NOS and NCS time. On the other hand, needle lift wear affects the same parameters as nozzle flow, yet it influences NCE in the opposite way: When a needle lift increase yields a later NCE, a nozzle flow increase yields an earlier NCE.

Besides the influence of injector internal behavior changes over lifetime, the effects of the following external system parameters on timing were considered:

- **Injection pattern**: dwell time between pilot and main injection, main injection current duration
- **Cylinder back pressure**
- **Fuel viscosity**
- **System pressure at injector inlet**

The correlation between wear behavior, system parameter and sensor timing was quantified in order to identify which timing value is the most suitable for identifying wear parameters over lifetime. The timing values correlate with several wear and system parameters at the same time. Thus for an accurate wear estimate, it is essential to choose a timing characteristic that highly correlates with the identified wear parameter and does not correlate or only slightly correlates with other parameters.

Wear identification with singular correlations

Based on this analysis, needle closing time was chosen as the best parameter for identifying nozzle flow change. This parameter is least influenced by external and wear parameters except for nozzle needle lift change. It is thus necessary to identify both wear parameters (nozzle flow change and nozzle needle lift change). This identification requires information from different pressure levels. The timing information “closing time” is used according to Equation 1:

$$\Delta t_{closing}^{p_{sys}} = f1^{p_{sys}}(\Delta Lift) + f2^{p_{sys}}(\Delta Q_{nozzle})$$

Equation 1

Where $\Delta t_{closing}$ is the closing time change and where f1 and f2 are system pressure (p_{sys}) dependent functions of needle lift change (ΔLift) and nozzle flow change (ΔQ_{nozzle}). These functions are calibrated with injector test rig limit sample testing.

During engine operation, wear parameters are constantly monitored and learned by the control system. The nozzle flow change is used as an input for the quantity correction function.

Wear identification with artificial intelligence

To improve wear identification accuracy, further identification methods that employ artificial intelligence (AI) were developed. Artificial neural networks (ANNs), the part of AI which can be called bionics, were used. Since ANNs learn explicitly, some restrictions apply to their use. These include the fact that trained networks can interpolate well but cannot extrapolate well or at all. Therefore, it is important to train the network with the full range of influencing factors. A set of injector measurements with different wear behavior was used for training. The objective of the ANN is to predict the nozzle flow change based on the sensor signal. To this end, different ANNs (multilayer perceptron - MLP, decision tree, convolutional neural network - CNN and long short-term memory - LSTM) were tested to find the best balance of accuracy, computational effort, computational time, etc. Both the timing signal points and the complete sensor signal were investigated as input parameters.

Validation results

Both of the above-described methods for wear identification (singular correlations and artificial intelligence) were validated with injector measurement data. Limit sample parts with variations in nozzle flow, nozzle needle lift and orifice plate flow were measured in 81 different combinations. They represent the complete variation between new and end of life injection functional behavior. The results show that depending on the identification method, the average uncertainty on nozzle flow can be reduced as follows:

- about 50% with the singular correlations method of Equation 1
- about 80% with the MLP neural network using the detected timing value of the sensor
- about 90% with the CNN using the complete sensor signal as an input. However, the computational demand on this type of network is challenging for an ECU.

These results are very promising and are subject to additional investigations under real wear conditions. To further improve accuracy and identify outliers, it is planned to implement a plausibility check in which the prediction of the ANN is compared with the prediction of the singular correlations.

3.6 Injection correction and diagnosis function

With knowledge of nozzle needle movement timing and nozzle flow deviation, several correction functions that modify injection start and duration of every cylinder individually can be designed. Depending on the engine application, different correction strategies are possible. Figure 14 provides an example of a correction method based on the injection rate. The injection rate of a worn injector with a change in nozzle flow (ΔQ_{max}) and timing is shown before and after correction by the NCC technology. The target was to align the timing and quantity of the worn part to the reference injector.

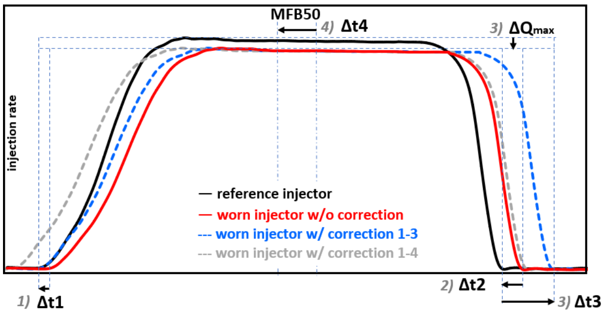

Figure 14: Correction strategy example

The different steps of the control strategy are shown in the diagram. First, the injection start is governed to the same angle as the reference injector with timing change Δ**t1**. Next, the end of injection is governed to the same end of injection as the reference injector with the timing change Δ**t2** in intermediate step 2). Then in step 3), the detected nozzle flow deviation $\Delta \mathbf{Q}_{\mathbf{max}}$ is translated by means of a correction map into an injection duration correction Δ**t3**. This aims to equalize the injected quantity to the reference. The last step 4) with Δ**t4** consists in shifting the injection begin in order to keep the combustion center (50% mass fraction burned (MFB50)) aligned. This last correction has proven to be beneficial for maintaining optimal combustion parameters.

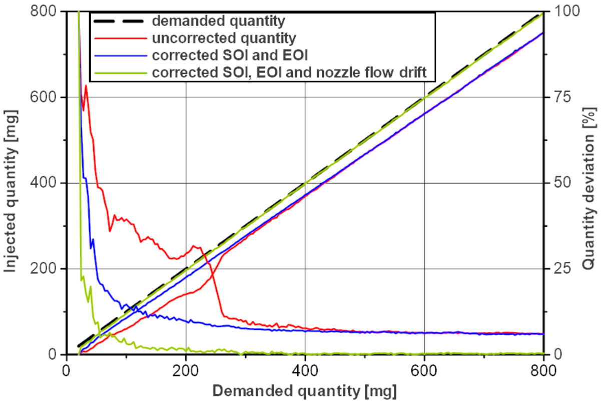

Figure 15: Potential of injection quantity correction

Figure 15 displays the results of corrections on injection quantity for a quantity demand sweep. The diagram compares the demanded quantity (dashed black line) to the injected quantity measured on a test bench. The second y-axis visualizes the deviation between the measured injection quantity and the demanded quantity in percent. The red lines show the behavior of a worn injector at the end of life. The blue lines illustrate the effect of aligning start of injection and end of injection to the nominal injector timing. The remaining error is strongly related to nozzle flow drift. Accurate identification of the nozzle flow change yields an optimal correction result as shown by the green lines.

The NCC system helps to achieve stable injection timing and quantities over lifetime. Complex injection patterns can be implemented in a robust manner. Thanks to permanent sensor-based monitoring of the injection process, NCC can become an ideal component of connected engine diagnosis concepts. Even in the event of sensor failure, the system functionality available with the sophisticated pre-control path and the adjustment values that are frozen as soon as an error occurs is more comprehensive than what a conventional, uncontrolled system offers. [4]

4 CONCEPT VALIDATION ON THE MULTICYLINDER ENGINE

As described in chapter 2.2.1, the final step in the multistage approach was to test new and worn injectors on the MCE at engine operating points of the ISO 8178 C1 test cycle.

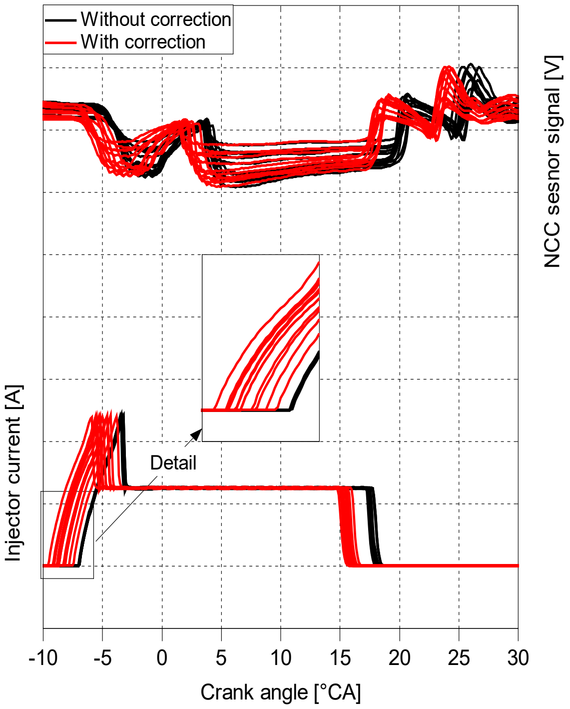

Figure 16: Smart injector operation with and without correction

Figure 16 shows the smart injector signals and the energizing signals for each of the twelve worn injectors over the cylinder-specific crank angle. The position at 0 °CA represents top dead center in the high-pressure phase of the cylinder cycle. The results are based on an average of 120 cycles in each case. The black lines present engine operation without applying the correction function and the red lines present engine operation with an activated correction function at the C1 cycle point. It can be seen that start of energizing with no correction is the same for all twelve cylinders. Due to the different operation behavior of each worn injector, the needle closing timings deviate significantly from each other despite the equal energizing signals.

The impact of the correction function on the energizing signals can also be seen clearly. By activating the correction function, each injector starts to optimize the start and end of energizing time to compensate for its wear behavior. As a result, the energizing start times in particular differ significantly from each other. At the present operating point, the start and the end of the energizing timings are advanced. This is a result of the minimum flow characteristic of all worn injectors that requires an advancement in the start of injection to compensate for the wear effects.

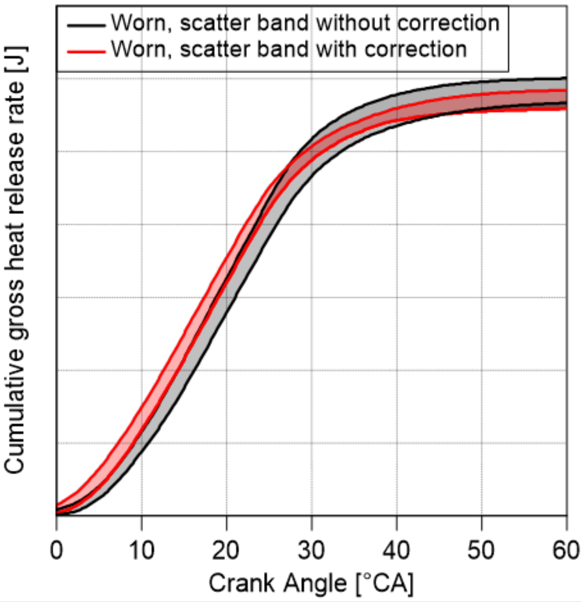

Figure 17: Scatter bands of the cumulative gross heat release rates

The effects on the combustion process at the C1 cycle point is shown in Figure 17. The scatter bands of the cumulative gross heat release rates of all twelve cylinders are compared once without and once with an activated correction function. The latter results in advanced combustion phasing. Furthermore, the spread of the scatter band is reduced considerably, indicating reduced scattering of the indicated mean effective pressure between the individual cylinders.

Figure 18 shows how the correction function affects the BSFC at the C1 cycle point. Measurement results from an engine setting with new injectors and no correction serve as the baseline (New baseline). Using worn injectors with no correction (Worn baseline) results in increased BSFC of 2.3 g/kWh. By activating the correction function (Worn corrected), the BSFC can be reduced to the baseline level. A further BSFC reduction of 2.1 g/kWh would be possible if the theoretical potential were fully exploited by further advancing the start of injection so that the BSNOx level of the baseline configuration is reached (Worn theoretical potential).

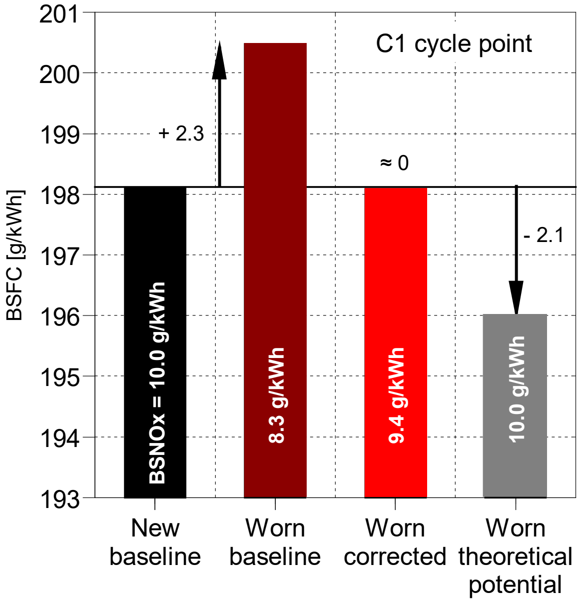

Figure 18: Influence on BSFC at the C1 operating point

The influence of the NCC technology on BSFC was evaluated over the entire ISO 8178 C1 test cycle. Figure 19 provides the results for the individual cycle points. The red values present the BSFC drawback when the engine is operated with worn injectors with no correction compared to with new injectors. The green values show the actual BSFC benefit when the worn injectors are operated with an activated correction algorithm related to the worn baseline case. It can be concluded that the correction function has a positive effect on the BSFC over the entire cycle. When interpreting the results, it should be remembered that in the present investigations, the NCC calibration was optimized for the C1 cycle point and that the same settings were used for the entire test cycle. Even better results can be expected with cycle point-specific optimization of the algorithm.

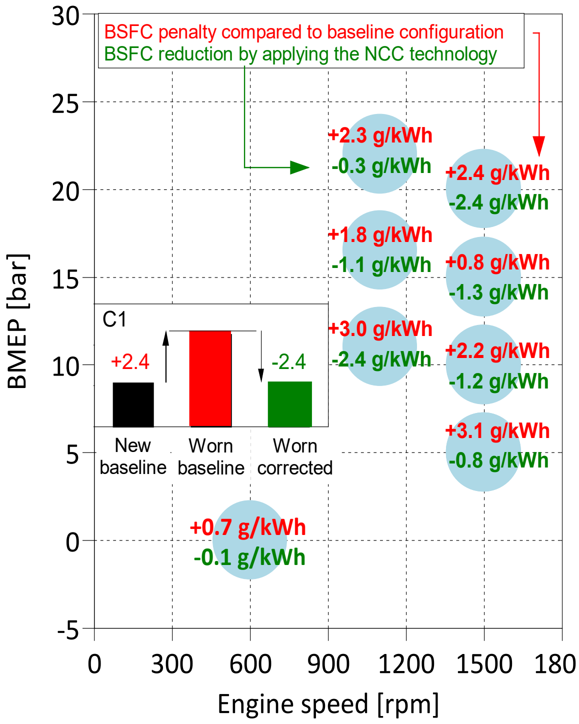

Figure 19: BSFC results for the individual cycle points

Finally, Figure 20 shows the BSFC cycle results calculated according to ISO 8178 for the different injector settings. The setting with worn injectors and no correction results in a BSFC increase of 2.3 g/kWh over the new injector setting. The actual benefit of the applied corrections can be calculated by comparing the "worn baseline" case with the "worn corrected" case: A BSFC reduction of 1.6 g/kWh was achieved with the activated NCC technology.

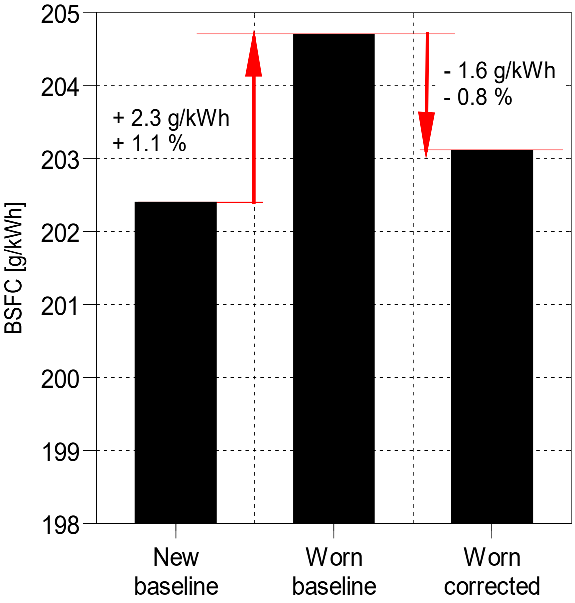

Figure 20: BSFC results for the overall cycle

5 NCC TECHNOLOGY BENEFITS

The investigations described above have uncovered a whole range of potentials that can be exploited by engine manufacturers and engine end users to reduce emissions and increase availability. The effectively usable potential is strongly related to the type of engine and application. The benefits can be summarized as follows:

1. Significant fuel consumption benefit over engine lifetime
2. BSNOx emission control over lifetime due to cylinder specific SOI adjustment
3. Stable multiple injection patterns over lifetime, e.g., stable post injection contributes to stable particle emission over lifetime
4. Extended possibilities for injector diagnosis leading to predictive maintenance and thus a reduction in engine downtime and engine damage
5. Extended injector lifetime due to compensated injector drift; potential for an extended service interval and improved CO_2 footprint due to longer equipment lifetime
6. Optimization of engineering targets (e.g., NOx, BSFC) due to optimal corrected injection over lifetime; potential for a further fuel consumption benefit in new condition

6 SUMMARY AND OUTLOOK

This paper describes how NCC technology, the new innovative closed-loop injector control technology from BOSCH, is implemented and validated on a large engine injector and system.

The technology's main feature is a piezo sensor that records the actuation pressure of the nozzle needle over a thin wall-supported membrane. The collected signal is interpreted by robust detection algorithms that reliably deliver information on needle opening and closing movements over the complete engine operating range.

Based on BOSCH passenger car NCC technology know-how, correction functions were integrated into the BOSCH MD1CE200 large engine ECU and validated on a full-scale large engine at the LEC test rig in Graz, Austria.

The investigations with new and worn injector sets were successful and showed the potential of the technology to improve fuel consumption over lifetime and to achieve emission stability. The implemented corrections can reduce the part-to-part timing and quantity scatter of new injectors. Furthermore, the combustion results show a significant potential for improved control of emissions with injectors at the end of their lifetime. The technology enables the engine to make up for the combustion efficiency drawback caused by injector wear.

Besides this operative benefit, the new control strategy allows much better monitoring of the engine condition. Its advantages will help engine manufacturers to meet future requirements that require proof of emissions stability over lifetime, thereby contributing to a solution to the global climate crisis.

The development phase also revealed challenging aspects, like the timing detection stability and scatter over lifetime and the accurate identification of injector wear parameters. Especially the nozzle flow change turned out to be very demanding. New concepts for further improving injection quantity control were brought to light. In fact, efforts to further reduce injection quantity error led to the development of an injection rate model. This model aims to use information from sensors to estimate the injection quantity for each injection.

The quantity prediction model developed during this research is based on the detected timing values and a measured injection rate for a nominal injector. It is innovative compared to known injection rate modeling methods that use a trapezoid to model the injection rate [7].

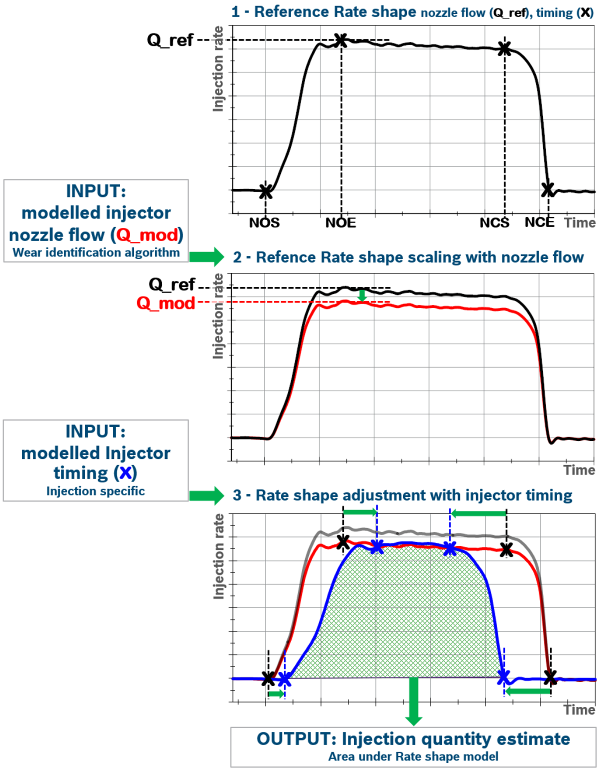

Figure 21: Model-based Injection quantity estimate

As shown in Figure 21, the reference injection rate is first adapted with the injector individual nozzle flow information calculated by the wear identification method presented in section 3.5. Then the injection rising edge (needle opening phase), decreasing edge (needle closing phase) and duration are modified according to the differences between the timing values of the reference and of the modeled injection point of the individual injector. After these transformations, the injection rate integral yields the injected quantity estimate.

This concept can be seen as an online injector individual injection analyzer as it is able to deliver a rate shape for each injection. Its benefits are still under assessment, e.g., rising edge-dependant correction maps could be implemented in order to further optimize the combustion parameters.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AI: Artificial Intelligence
ANN: Artificial Neural Network
BMEP: Brake Mean Effective Pressure
BSNOx: Brake-specific Nitrogen Oxides
BSFC: Brake-specific Fuel Consumption
CA: Crank Angle
CNN: Convolutional Neural Network
CR: Common Rail
ECU: Engine Control Unit
EOI: End of Injection
HW: Hardware
LEC: Large Engines Competence Center
LSTM: Long Short-term Memory
MCE: Multicylinder Engine
MFB50: 50% Mass Fraction Burned
MLP: Multilayer Perceptron
NCC: Needle Closing Control
NOS: Needle Opening Start
NOE: Needle Opening End
NCS: Needle Closing Start
NCE: Needle Closing End
SaaP: Software as a Product
SCE: Single-cylinder Engine
SOC: Start of Current
SOI: Start of Injection
SW: Software
SWS: Software Sharing

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