Advanced Diesel Common Rail Systems for Future Emission Legislation

Dr.-Ing. Ulrich Dohle, Dr.-Ing. Steffen Kampmann, Dr.-Ing. Jürgen Hammer, Dr.-Ing. Thomas Wintrich, Dr.-Ing. Claus Hinrichsen (lecturer)
Robert Bosch GmbH, Stuttgart, Germany

ABSTRACT

With the future emission legislation challenging goals will be defined for Diesel engine manufacturers. Lowest emissions with highest engine performance, low noise level, benchmarking low fuel consumption and attractive costs are defining the targets of their development activities for future engines. A fuel injection system supporting these requirements will be a key factor.

BOSCH launched very early a fundamental study to investigate the requirements for future injection systems and their key characteristics e.g. mixture formation, maximum injection pressure, rate shape capability and multiple injection. Using several versatile prototype injection systems a comprehensive engine investigation was accomplished to determine the optimum system configuration for the above mentioned Diesel engine goals. Out of those overall system requirements, the evolution of Advanced Common Rail Technology could be defined.

Key-words: Future Emission Legislation, Concept Finding, Common Rail, Hydraulically Amplified Diesel Injector

INTRODUCTION

The modern Diesel engine still encounters a strong increase of its market share in all passenger car segments. Non-competitive low fuel consumption combined with high power density and sportive specific torque provide Diesel cars with an outstanding perceptible fun to drive factor.

On the other hand, the Diesel finds itself more and more faced with continuously burdening challenges which have to be overcome within the technical progress.

Figure 1: Diesel Progress for Passenger Cars
– Drivers and Challenges –

While the gasoline engine settles the benchmark for noise vibration harshness (NVH), the complexity of the overall Diesel system becomes higher and higher in spite of the tremendous desire to lower the overall system costs.

The biggest challenge in Diesel applications is the future emission legislation in mostly all markets over the world. To overcome this challenge an overall system optimisation of the fuel injection equipment, the engine and combustion process and the exhaust gas treatment is mandatory. Facing the task to realise a cost optimal solution fulfilling the future emission legislation, combustion noise comparable to gasoline engines, lowest fuel consumption and fun to drive on top, appears to be an insolvable task.

The big effort in exhaust gas treatment for heavy passenger car vehicles to fulfil future emission legislation leads to an unattractive low score for Diesel drive train systems. Out of that the engine out emissions have to be reduced due to an overall Diesel system optimisation. A promising approach is the air system, e.g. innovative boost pressure concepts in combination with high sophisticated cooled exhaust gas recirculation (EGR). Additionally the adaptation of the combustion process, for instance the optimisation of the piston bowl has shown a huge potential.

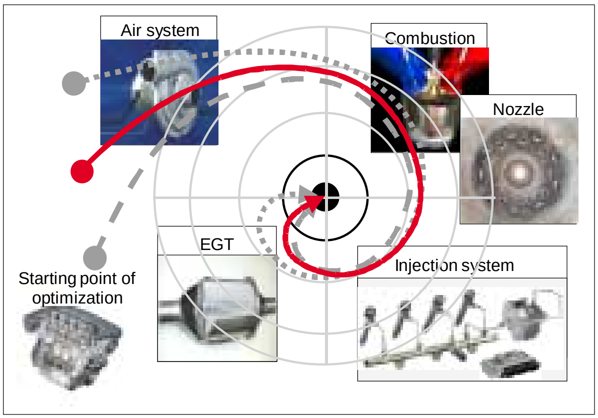

Figure 2: Diesel System Optimisation Areas

Last but not least the advanced fuel injection equipment plays a key role to achieve future Diesel goals. The examination of the overall system requirements and deriving out of them possible solutions will be discussed in the next chapter.

SYSTEM REQUIREMENTS FOR FUTURE FIE

The idea of overall system requirements evaluation is shown in figure 3. Based on the behaviour of well-known fuel injection equipment, the most important parameters to identify the required injection performance could be separated and evaluated. The next step leads to prototype injection systems which show all specific working behaviour corresponding to the initially mentioned parameters.

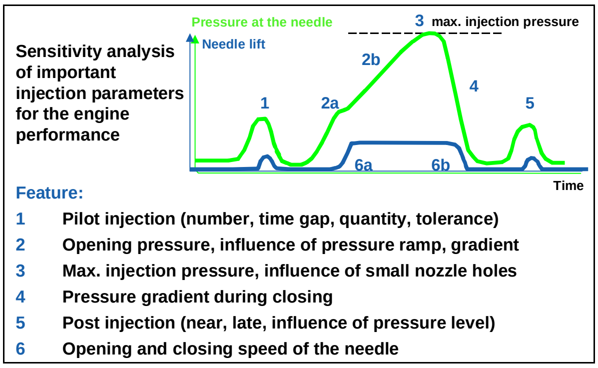

Figure 3: FIE Requirement Evaluation

The prototypes were designed as pressure – and stroke - controlled injection systems and hybrids out of them. Those prototypes were tested using an optimised Euro4 – combustion process for passenger cars and light duty applications. Those were calibrated for an equal power density by means of the absolute nozzle flow rate. Goal of the optimisation was the best trade-off in soot vs. NOx while fuel consumption was held as constant and noise targets could be reached.

Summarising the requirements on the desired advanced fuel injection equipment one will find again the well-known keywords of a standard Common Rail system like:

- fully flexible injection pressure
- maximum required injection pressure, dependant on the specific concept
- flexible timing of multiple injections and
- small and stable injection quantities to realise pilot and post injections.

Additionally the research leads to some new characteristics according to

- fast needle opening
- low injection rate during ignition delay, but
- max. allowed injections rate to increase the local air ratio
- strong increase of the injection rate after start of combustion
- high maximum injection rate
- fast rate decrease at the end of injection and also
- high needle closing velocity.

To solve this conflict the whole potential of modern fuel injection equipment has to be kept in mind and is basically needed. The investigations show, that a full flexible rate shape in the whole engine map leads to the required performance.

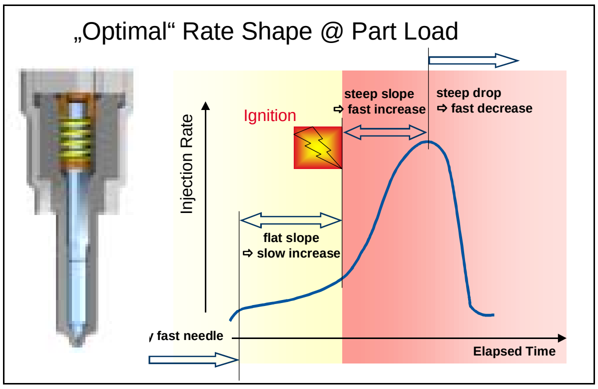

Figure 4: Optimal Rate Shape for PC-car engines

These findings on the demand for an optimum FIE behaviour led to the concept finding stage. Already at an early stage two possible main streams turned out to be promising: a further increase in rail pressure together with very small hydraulic nozzle flow rates based on the Piezo – Inline injection concept and an appropriate rate shaping out of hydraulic pressure modulation, the so-called Hydraulically Amplified Diesel Injection System (HADIS).

ADVANCED COMMON RAIL SYSTEMS

Figure 5 gives a brief overview on the product portfolio of BOSCH Common Rail Systems. Beside the already successful launched Common Rail generations CRS1, CRS2 and CRS3, it is planned to extend the available performance of fuel injection equipment to the OEM by extending the pressure level of the 3rd generation Piezo – Inline Common Rail up to 2.000 bar. Additionally, on the top - end of Common Rail, the synthesis of pressure controlled injection systems and Common Rail is done by providing the 4th generation of Common Rail with the highest pressure level of 2.500 bar and passive rate shaping.

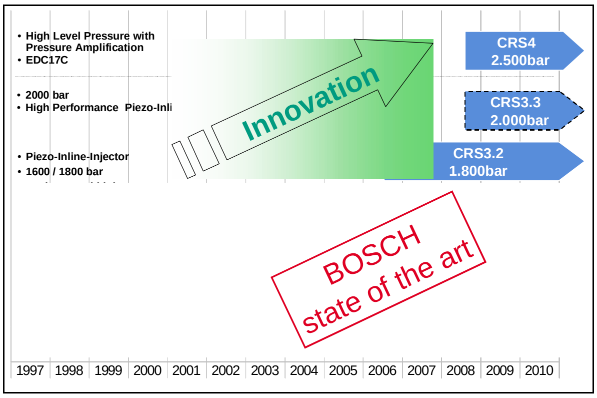

Figure 5: BOSCH – Common Rail Roadmap

By realising the Piezo - Inline - design in the 3rd generation of Common Rail, BOSCH did really maintain the ability of Piezo – actuating in a Diesel injection system.

Due to the fact, that a very stiff actuation chain, from energising the Piezo – stack down to the needle control, the near position of the stack to the control valve leads to the desired needle kinetics of the nozzle. This working principle will be extended to be driven by higher pressure levels, figure 6.

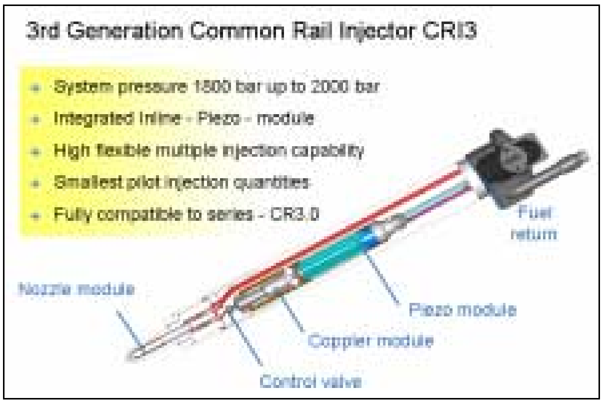

Figure 6: 3rd Gen. Common Rail Injector CRI3

To stay on very small injection quantities and fully flexible multiple injection events, the layout optimisation of injection dynamics with the higher pressure level is used. On the one hand at full load the injection rate could be moved to a nearly perfectly rectangular shape. This maintains a higher power output at rated point of the engine, while reducing the nozzle flow rate provides big steps in using the high pressure to realise an optimal spray formation.

Sake in pull – down the emissions and improving fuel consumption can be earned at the end of the engine calibration process. Finally the small flow rate leads to a reduced amount of prepared mix during ignition delay, therefore combustion pressure gradient flats down to give a smooth combustion noise frequency pattern.

From durability point of view the high stress parts of the injector and nozzle, naturally the whole system components, have to be qualified to the higher rail pressure level of 2.000 bar. Anyway, from engine mounting point of view it might be an important issue that compatibility to the series system, CRS3.0 with 1.600 bar, is fully given.

CRS4: HIGH PRESSURE CONCEPT - HADIS

The second concept investigated employs a further increase of the injection pressure utilising the Hydraulically Amplified Diesel Injection System (HADIS). An injection pressure in the nozzle hole area of 2.500 bar is realised. Figure 7 shows the hydraulically amplified injector CRI4 with its main topics.

Figure 7: 4th Gen. Common Rail Injector CRI4

Thus high specific power output can be achieved even with very low nozzle flow rates. The pressure amplifier is hydraulically driven with a geometrical transmission ratio of roughly 1:2 allowing a moderate high pressure level on the pump and rail side of up to 1.350 bar. This helps a lot in reducing the mechanical stress on the components, because only the nozzle module has to be designed for the highest pressure range. On the other hand the delivery rate of the high pressure pump has to be significantly increased to supply the necessary control quantity to drive the pressure amplifier.

The important parameters out of the requirement evaluation for advanced FIE are realised in the injection behaviour of the CRI4. Namely the ramp rate shape is characteristic for the CRI4 concept. At part load it enables to overcome the conflict between emission and noise and at full load the approach to the square shape provides the capability to inject the necessary fuel quantity to reach the specific power goal. The change of rate shape comes out of the specific hydraulic layout of the injector concept with only one electronic actuator and is called passive rate shaping.

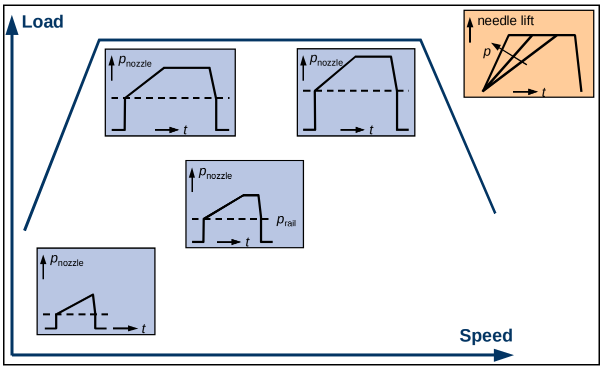

Figure 8: “Passive Rate Shaping”

These characteristics combined with a very high injection pressure leads to valuable benefits especially at high load conditions. Therefore the 4th generation Common Rail System suits optimal for LD and heavy passenger car applications in Europe and the US.

COMMON RAIL HIGH PRESSURE PUMP CP4

As already successfully launched for 1st and 2nd generation of BOSCH Common Rail systems the high pressure pump CP4 is also designed as a radial piston pump.

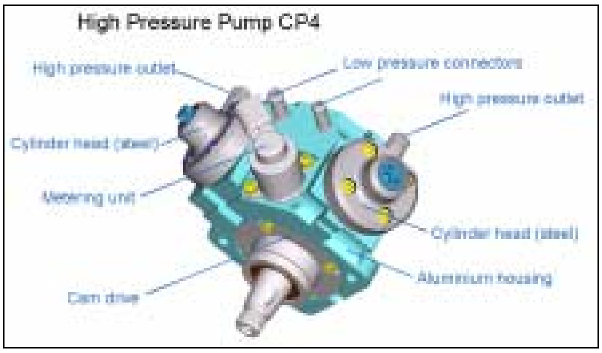

Figure 9: Common Rail High Pressure Pump CP4

Furthermore the intake suction control achieved by a metering unit was transferred to the high pressure pump CP4. Depending on the specific application there is the option of a mechanical or an electrical supply pump. Figure 9 shows the CP4 with their main design topics.

The CP4 - concept of a cam drive unit is completely different to the already launched Common Rail high pressure pumps of the whole world market. Derived from the successful distributor pump VP44, a double cam drives a roller tappet which moves the high pressure plungers to pressurise the fuel internally. The whole high pressure area is located in steel heads which also contain the high pressure element, suction and check valves. This avoids all internal high pressure lines, so the housing of the CP4 is designed to be made of aluminium. The pressurised fuel leaves the pump through two high pressure lines directly connected to the rail.

Summarising the CP4 key issues, one leads to

- Maximum high pressure up to 1.800 bar and high efficiency in the whole pump map, offering the potential for a further pressure increase.
- Reduced rail pressure ripples achieved by a high quality for the equal and synchronous delivery allowing improved metering accuracy of the injectors
- Flexible range of applicability in modern BOSCH Common Rail Systems with long term standardisation of the high pressure pump interface to the engine

The CP4 is engineered as a platform product offering different market oriented designs. The CP4 platform maintains the optimal scaling of a specific pump type to the required Common Rail system functionality for different applications. For example working with the 3rd generation Common Rail System one obtains the need of high pressure and less quantity using the Piezo – Inline injector system; vice versa in case of Common Rail 4th generation due to the bigger quantity amount of the CRI4 while driving the pressure amplifier at moderate pressure level.

POTENTIAL EVALUATION OF MODERN COMMON RAIL SYSTEMS

As discussed in the previous chapter the advanced FIE technology of future Common Rails Systems from BOSCH shows a clear beneficial performance increase of the foreseen FIE - generations. On the other hand due to the high technical value of the systems a certain additional effort is expected by means of an overall cost penalty. Under that challenge the discussion moves very fast to the question of optimisation in terms of benefit versus effort of the sub – systems of the whole Diesel drive train, namely FIE and exhaust gas treatment equipment. The question comes up for a strategy to find an optimal system configuration for each vehicle class in a specific market to reach the emission and performance goals within an overall cost minimum. Figure 10 illustrates that optimisation task in a very impressive way.

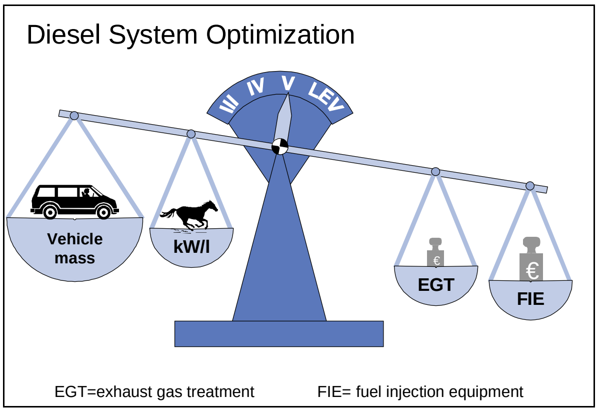

Figure 10: Overall Diesel System Optimisation

Here balance disturbances caused by the vehicle weight or the power output are compensated by the performance of the FIE and the exhaust gas treatment system in order to lower emissions. Still utilising a conventional combustion system, however, optimised for lowest raw emissions and based on the calculation of such a balance first answers can be given on the following two questions:

- What kind of efforts on the FIE and exhaust gas treatment side are necessary to meat the emission and performance goals for a specific vehicle application in Europe?

- Is there a way to reduce the effort on the exhaust gas treatment side generally employing a sophisticated FIE?

Utilising modern Diesel engines with the described Advanced Common Rail Systems from BOSCH leads to the answer of the asked questions for all markets and their today's and future emission legislation.

The first general finding is, that the better the FIE performance gets, the lower the effort on the exhaust gas treatment side remains. It depends on the assessment of the combustion specialist whether he assumes to achieve the future emission goals with the sophisticated solenoid driven injection system CRS2.2 or he might need to step into the Piezo technology of the 3rd generation of BOSCH Common Rail. This answer cannot be given in general and is a strong function of the specific power goal, the displacement of the engine and of course of the vehicle inertia mass.

Very powerful solutions are given with the 3rd and 4th generation of BOSCH - Common Rail Systems because their layout maintains a modern Diesel engine to reach power goals up to 70 kW/l. Simultaneously, these FIE play an important role by undershooting future emission limits in Europe, without any additional DeNOx - measure for compact class vehicles.

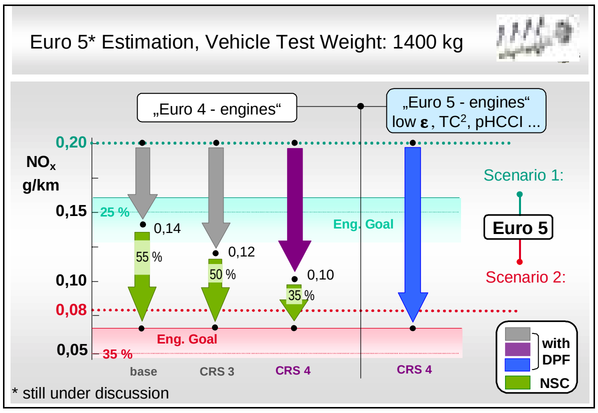

Figure 11: Estimation of FIE - Emission Potentials

CONCLUSIONS

Summarising the situation the biggest challenge in Diesel technology for the future is the fulfilment of continuously strengthened emission targets. BOSCH will continue support to meet the challenges by supplying advanced future FIE technology.

Derived from an overall system requirement evaluation to fulfil future performance targets of the Diesel the key requirements for future Common Rail systems were identified. The results from an engine based study using various prototypes of injection system concepts for advanced FIE, engine measures and exhaust gas treatment equipment lead to the path for technical solutions for future emission legislation. The required effort on the FIE and the exhaust gas treatment for passenger cars strongly depends on the inertia vehicle weight, the power output and the chosen engine displacement.

In terms of an overall optimisation it has to be stated, that the invest on the FIE has a big impact on the reduction of the exhaust gas treatment effort to get home with the project fulfilling future emission targets at a system cost minimum.