Euro 4 and Beyond – Role of Diesel Fuel Injection Systems

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ABSTRACT

The Euro 4 emission norms can be achieved by the well-known 2nd and 3rd generation Common Rail Systems of BOSCH. The beyond Euro 4 emission legislation is a challenging goal for diesel engine manufacturers. Lowest emissions with highest engine performance, namely high specific power output, petrol like noise levels, benchmarking low fuel consumption and attractive costs are the targets for development activities of the future engines. Key for the success will be sophisticated fuel injection system which supports all the above mentioned targets.

Therefore, BOSCH did launch very early a fundamental project defining the requirements for future injection systems with regard to mixture preparation, maximum injection pressure, rate shaping capability and multiple injections. Using several versatile prototype injection systems a comprehensive engine investigation was accomplished to optimise the system configuration to meet the above targets of diesel engines. Applying the criteria of performance, manufacturing robustness, lifetime durability and costs, the variety has been reduced to a hydraulically amplified diesel injection system, which works with hydraulically amplified injectors. This concept together with a potential evaluation for two different Euro 5 scenarios is given in this paper.

INTRODUCTION

The high-speed direct injection diesel engine has gained world-wide acceptance. It is especially successful in Western Europe where the market share of new registered vehicles exceeds 52%. It is predicted that the market share of diesel passenger cars will double by 2014 in the rest of the world. This is due to the well-known advantages such as fun to drive, excellent fuel economy and good noise behaviour. As seen in Fig.1 the specific torque increased by a factor of 3 and specific power by a factor of more than 4 over the last 6 decades. In parallel the fuel efficiency improved by 50% and power increased from 33 kW to 171 kW.

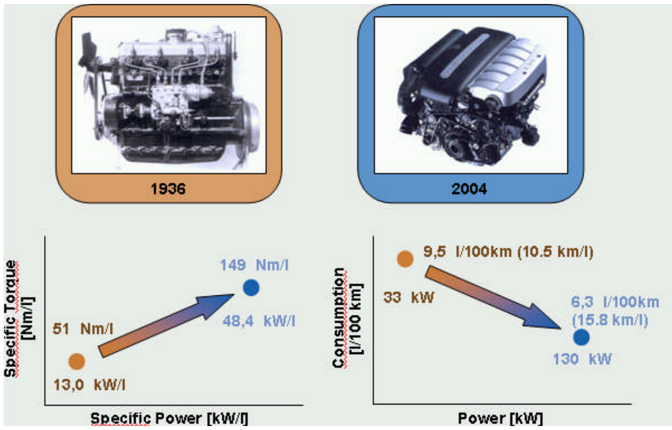

Figure 1: Change of diesel engine characteristics

On the other hand, the diesel engine faces more and more continuously burdening challenges which are overcome using latest injection technology. While the petrol engines set the benchmark for Noise Vibration Harshness (NHV), the complexity of the overall diesel system becomes higher and higher in spite of the tremendous efforts to lower the overall system cost.

In the truck segment of the diesel world the targets namely fun to drive, NHV are not the main drivers as compared to the passenger car segment. The main driver is the absolute low fuel consumption which plays a vital role for commercial vehicle fleet owners, as the fuel consumption covers the major part of the overall maintenance of the commercial vehicle fleet. Furthermore noting the fact that a modern diesel engine still represents the most robust drive train for commercial vehicles, the still rising challenge on life expectancy requirements of the diesel system, e.g. the fuel injection equipment, is ongoing.

Meeting the future emission legislation for the passenger car and truck diesel applications of the world market is a big challenge. To meet this challenge an overall system optimisation like fuel injection equipment, the engine, the combustion process and the exhaust gas treatment is mandatory. Facing the task to realise a cost optimal solution fulfilling the future emission legislation, petrol like comfort, lowest fuel consumption and fun to drive on top, sounds like an impossible task.

Heavy passenger car vehicles require a big effort in exhaust gas treatment to fulfil future emission legislation leading to an unattractive low score for diesel drive train systems. Emissions out of the engine have to be reduced by 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. Additionally the adaption of the combustion process, for instance the optimisation of the piston bowl has shown a huge potential.

Last but not least the advance fuel injection equipment plays a key role to achieve future diesel goals. The basic question to develop the future fuel injection equipment is the overall system requirements, which will be discussed in chapter 3 of this paper. Next we will focus on the status of the Euro 4 compliant vehicles.

2. COMMON RAIL SYSTEMS FOR EURO 4

In 1997 BOSCH introduced the first Common Rail System for diesel engines [1]. The start of production of the Common Rail System 2nd generation was in 2000 [2], where the maximum system pressure was increased to 1600 bar. A high pressure pump with quantity control, improved injectors with multiple injections was introduced. An overview of the Common Rail System 2nd generation is given in Fig. 2. Via the tank and the filter fuel is supplied by the gear pump to the quantity-controlled high pressure pump CP3. The suction throttle at the high pressure pump divides the fuel flow into two parts: one supplies the pump elements and the other serves for cooling the pump and lubricating the bearings. The high pressure pump compresses the fuel up to 1600 bar into the common rail. The rail pressure sensor registers the actual pressure. The rail pressure is controlled via the metering unit integrated into the high pressure pump. The pressure limiter valve opens in case of any overpressure in the system due to any malfunction. The solenoid actuated injectors are energised depending on the set point of the electronic control unit. Start and duration of the injection as well as the number of injections can be chosen arbitrarily.

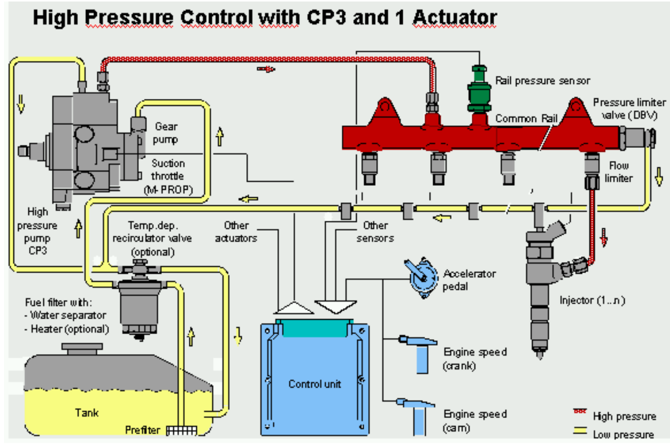

Figure 2: System overview Common Rail System 2nd generation

In 2004 the 3rd generation Common Rail System is introduced into the market. The system overview is given in Fig. 3. The major changes are new software functions like quantity balance control, pressure wave correction, lambda control and the totally new in-line piezo injector. By integrating of the piezo actuator into the injector body a technology jump was achieved. The innovative in-line concept allows high nozzle needle velocities up to 1.3 m/s. The excellent performance of the piezo injector results in higher flexibility of the engine design. The quantity controlled high pressure pump is a compact high performance unit. With this injection system Euro 4 emissions can be achieved with vehicles of more than 2000 kg demonstrating the excellent performance of the BOSCH 3rd generation Common Rail System. In a next step the injection pressure of the 3rd generation Common Rail System will be increased to 1800 bar in 2006 and 2000 bar in 2008.

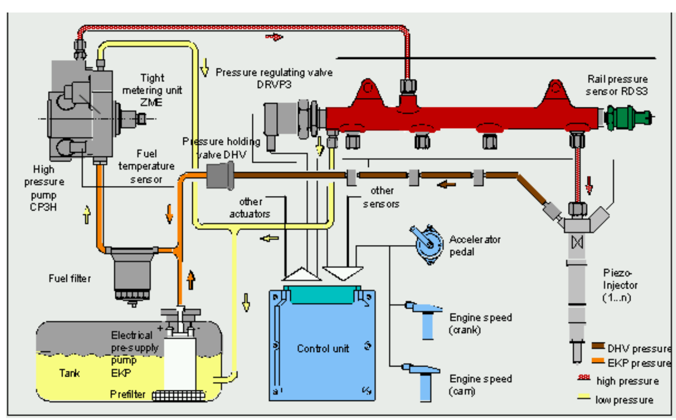

Figure 3: System overview Common Rail System 3rd generation

Type approval data of passenger cars from July 2004 meeting min. Euro 3 are given in Fig. 4. A lot of vehicles achieved already Euro 4 norms with the BOSCH injection systems like the distributor pumps VP44 and VP30, Unit Injector System and Common Rail System. Due to the introduction of particulate filter in these vehicles, lowest particulate emissions could be achieved. Euro 4 emission levels are achieved with 2nd generation Common Rail System except in one case, which are a 3.0 ltr engine of 171 kW and a weight of 2040 kg. Without any particulate filter or DeNOx device the Euro 4 norms are fulfilled with a substantial engineering margin.

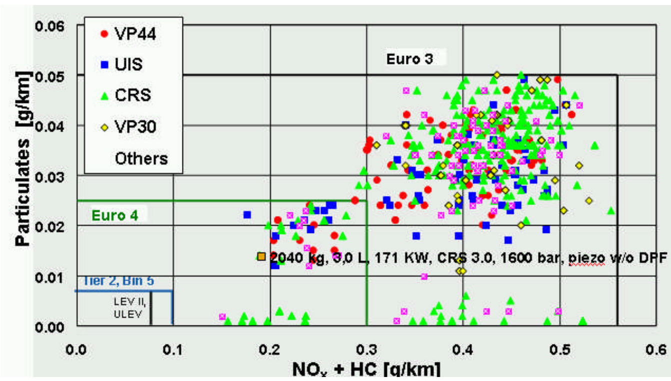

Figure 4: Type approval data for passenger car diesel meeting min. Euro 3

The ultra-low emission levels of LEVII/ULEV require even more sophisticated injection systems and in parallel improvements in the air system, exhaust gas treatment and the combustion process like for e.g. homogeneous combustion. The next step of the injection system for Euro 5 and the tight US-norms are given in the next chapters.

3. Overall System Requirements FOR Future Common Rail Systems

The idea of overall system requirements evaluation is shown in Fig.5. Based on the well-known behaviour fuel injection equipment, the most important parameters influencing the required injection performance could be evaluated and separated. The next step leads to prototype injection systems which show all specific working behaviour corresponding to the initially mentioned parameters (as mentioned under ABSTRACT).

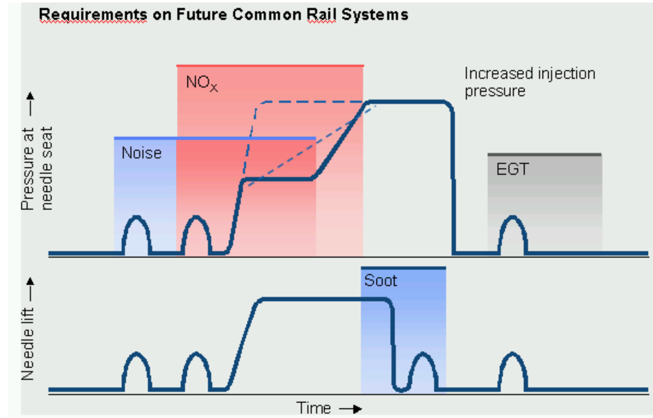

Figure 5: Requirements on future Common Rail Systems

The prototypes are designed as pressure- and stroke-controlled injection systems and hybrids out of them. These prototypes are tested using an optimised Euro4 combustion process for passenger cars and light duty applications. These are calibrated for an equal power density due to the absolute nozzle flow rate. Goal of the optimisation is the best trade of in Soot vs. NOx while fuel consumption is held constant and noise targets could be reached. A summary of important results out of the overall system requirements gives Fig. 6.

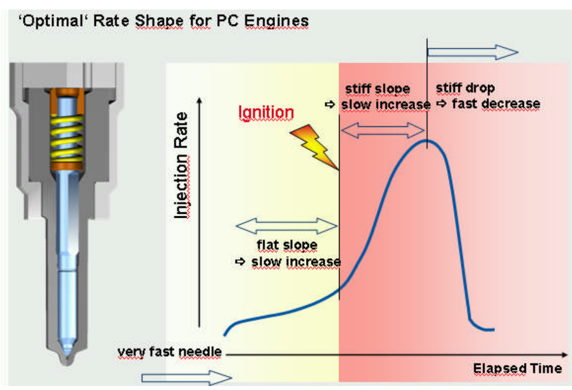

Figure 6: Optimal rate shape for passenger car engines

The baseline to find out prototype performances came out of the 1st generation Common Rail Systems and unit injector system applications. Emission output performance is in the range between Euro 3 and Euro 4. Looking at the best values reached with prototype fuel injection system one can obtain specific NOx raw emissions lower than 2 g/kg while keeping the relation of NOx to soot at 10:1. For a vehicle in the compact class segment the 2 g/kg NOx corresponds to a target emission value calculated per distance of 0,08 g/km.

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, depending on the specific concept
- flexible timing of multiple injections
- 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
- max. allowed injection rate to increase the local air ratio,
- strong increase of the injection rate after start of combustion,
- high maximum injection rate
- steep decrease at the end of injection and also
- high needle closing velocity.

On the truck side the overall system requirement evaluation was done in the same way. On one hand the biggest driver on diesel technology for trucks is to pull down the fuel consumption while on the other the stringent emission legislations, like Euro 5 and US07 and long term US10 have to be met. To solve this conflict, 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.

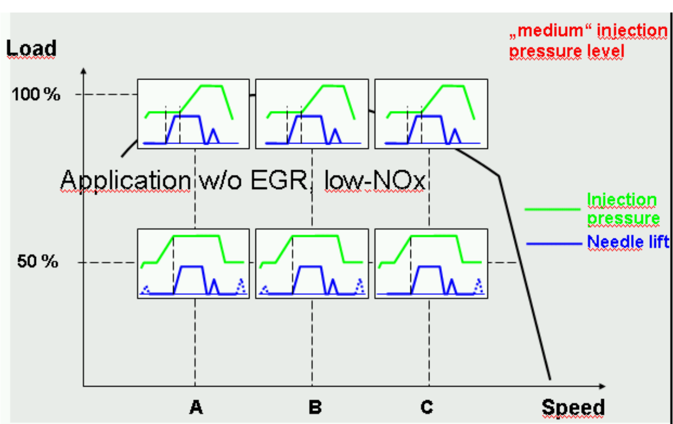

Figure 7: Truck Requirements on Injection Rate Shape and Pressure

Figure 7 shows the optimal rate shape for each area of the engine map maintaining a combustion process without exhaust gas recirculation (EGR). For mean settled part load the so-called ramp shaped injection rate gives the best trade-off in NOx versus consumption, in spite of the full load area where a boot shape gives additional benefits in the whole engine map area. Reason for that could be the optimised injection quantity amount in the ignition delay phase which causes lowest NOx emissions at a given air-mass fuel ratio.

Introducing EGR, the situation changes in almost all speed – load points, wherein the injection system has to be driven in the square rate shape mode. One can explain that the EGR reduces NOx at engine out, so the spray momentum brings down the soot output. This seems to be true generally outside the lowest speed area, where also the boot shape gives still a benefit because of the big time constant and high temperatures supporting NOx – generation as a combustion product, Fig. 8.

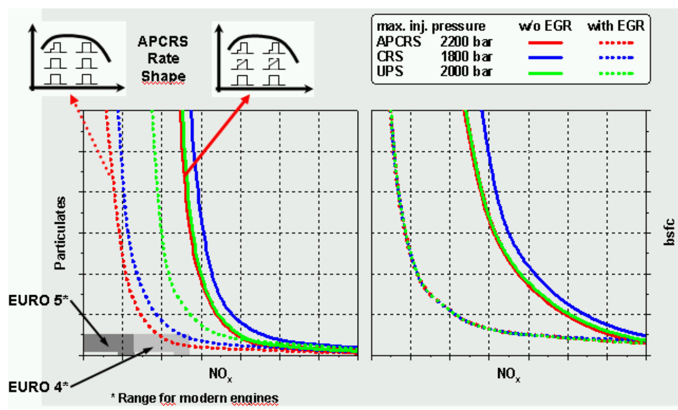

Figure 8: Comparison of different fuel injection systems for trucks

In short words, the full flexible Common Rail system beats all counter players like Unit Injector systems and conventional Common Rail systems and hence for truck applications seems to be favourite system.

4. ROAD MAP PLANNING OF FUTURE COMMON RAIL SYSTEMS

With the strategic planning of future Common Rail system generations, the world market leader BOSCH provides the desired diesel fuel injection equipment in time for the world wide market. Using this technology the OEMs are able to reach future requirements on their diesel drive trains.

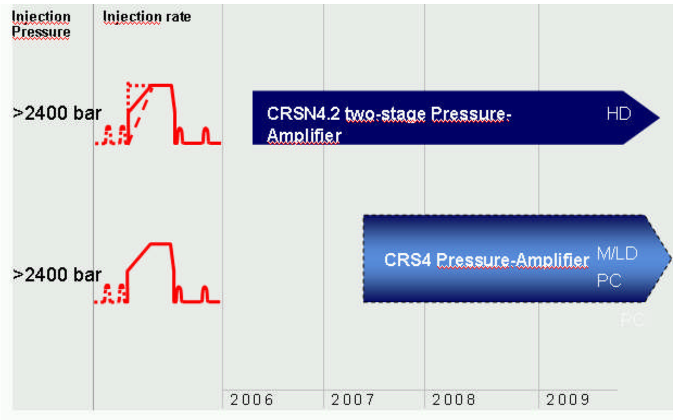

Figure 9: Generation Planning Common Rail

In 2006 the most flexible common rail system is introduced for heavy duty vehicle applications (Fig. 9), which provides also injection pressures higher than 2400 bar. The road map (Fig. 9) shows in 2007 the start of the 4th Generation Common Rail System for passenger cars introducing a pressure amplified fuel injection system with highest injection pressures.

5. CRS4 – COMMON RAIL 4th GENERATION FOR PASSENGER CARS AND LIGHT DUTY TRUCKS

The so-called Hydraulically Amplified Diesel Injection System (HADIS) works with hydraulically amplified injectors. These amplifiers realise injection pressures of more than 2400 bar in the nozzle hole area due to which high specific power output can be achieved despite very low nozzle flow rates. The amplifiers are hydraulically driven with geometrical transmission ratio of more than 1:2 by means of a moderate high pressure level on the pump and rail side, up to 1350 bar. This helps a lot in terms of reducing 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 deliver the necessary control quantity to drive the amplifiers. The cross section view of the hydraulically amplified injector (HADI) highlights the main modules, Fig 10.

The guiding parameters out of the requirement evaluation of advance fuel injection systems are realised in the injection behaviour of HADI, namely the ramp rate shape for part load to overcome the conflict between emission and noise, the square shape at full load which provides the ability to inject the necessary fuel quantity for a given injection duration at maximum pressure to reach a certain specific power goal. The change of rate shape comes out of the specific hydraulic layout of the injector concept with only one electronic actuator. That's why it's called *passive* rate shaping. This characteristic combined with a very high injection pressure leads to valuable benefits especially at high load. Therefore the HADI system is optimal for LD and heavy passenger car applications in Europe and US.

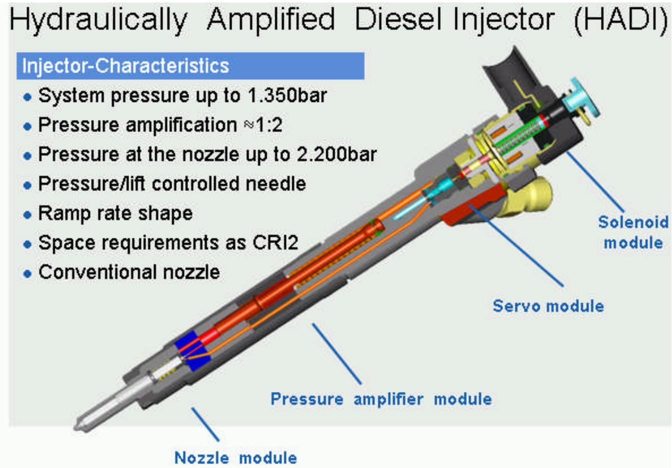

Figure 10: Hydraulically Amplified Diesel Injector (HADI)

After successful launching of 1st and 2nd generation of BOSCH Common Rail systems, the high pressure pump CP4 is also designed as a radial piston pump with inner cam drive. Further the intake suction control with the metering unit is transferred to the high pressure pump CP4. Depending on the specific application one can choose a mechanical pre-supply pump or an electrical lift pump as a pre-feeding concept. Fig. 11 shows the cross section of the CP4 with their main design topics.

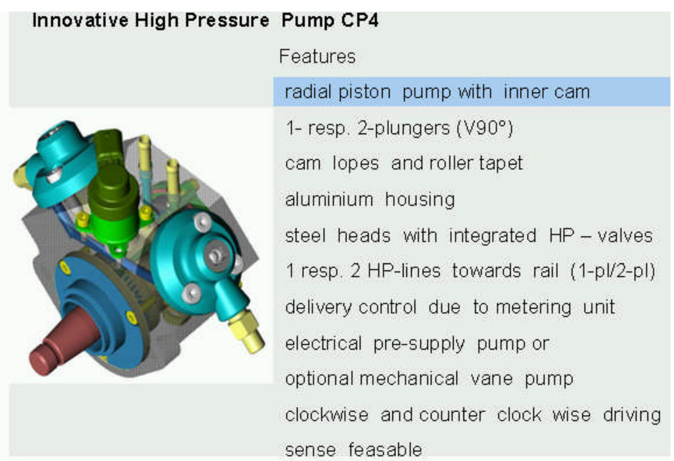

Figure 11: Common rail high pressure pump CP4

CP4-concept of a cam drive unit is completely different to the already launched Common Rail high pressure pumps of the world-wide market. Derivative of the well-known 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 internal high pressures in lines and hence the housing of the CP4 is designed to be made out of aluminium. The pressurised fuel leaves the pump through two high pressure lines directly connected to the rail.

The key topics are

- Maximum high pressure up to 1800 bar with high efficiency in the whole pump map Potential (pressure, delivery rate) can be used for emission and power targets of present and future engine concepts.

- Reduced rail pressure undulations due to a high quality of equal and synchronous delivery which leads to the reduced metering tolerances of the injection.

- Flexible range of applicability in modern BOSCH Common Rail Systems with long term standardization 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 fits for all different applications with regard to functionality of common rail system. For example, working with 4th generation common rail system one can achieve the requirement of high pressure and less quantity using vario injector system instead of HADI which otherwise deliver higher quantity at moderate pressure level.

6. CRSN4: Common Rail System for HD Commercial Vehicles

The industrialization of the full flexible Common Rail Injection concept to cater the requirement of HD-engines is worked out by BOSCH engineers leading to the so-called "2-step pressure amplified Common Rail System". The system is designed as two-stage pressure generation using an amplifier piston integrated in the injector for amplifying the rail pressure of about 1000 bar to injection pressures of about 2400 bar. A total cross section of the 4th Gen. Common Rail Injector for trucks including the key features is shown in Fig. 12.

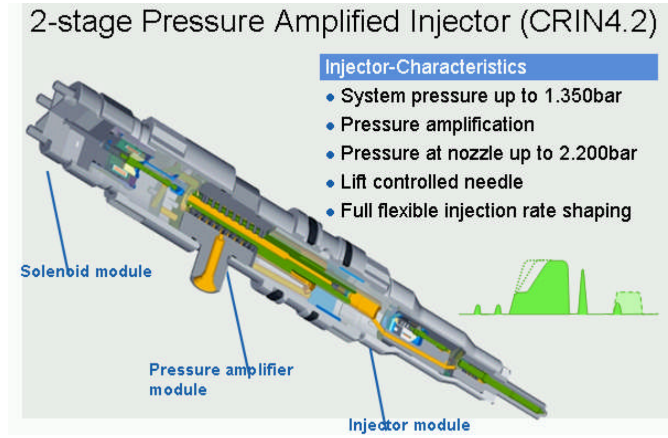

Figure 12: Cross Section and Topics of CRSN4

By integration of a 2nd solenoid valve in the fuel injector this 2-stage pressure concept allows to vary the timing of the amplifier activation. Thus the injection rate after needle opening can be varied between the profiles 'boot', 'ramp' and square', use the electronic device which controls the timing of the two solenoid valves.

The hydraulic layout of the pressure amplified system is similar to the standard Common Rail System but for rail pressure and amplifier piston modules wherein rail pressure is at high medium level. The injectors contain amplifier modules to generate high injection pressure determined by a stepped piston. The amplifier is activated by a second solenoid valve in the injector. Without activating this solenoid the injection system acts as a standard Common Rail System because of the bypass path with check valve. Varying energising time of both solenoid valves flexible pressure shapes from boot and ramp to square shape can be generated.

An additional outstanding benefit of the 2-stage pressure concept is that the highest pressure is limited to the small nozzle area where the max. pressure is needed. The rail and the high pressure pump with the external fuel line connections to rail and injectors remain at moderate pressure levels in the range of 1000bar. This feature of the system concept is the key for significant pressure increase of higher than 2400bar for future applications.

7. Potential Evaluation of Modern Common Rail Systems For Passenger Cars in Europe

As discussed in chapter 4 the advanced fuel injection technology of future Common Rail Systems from BOSCH show a clear beneficial performance increase. On the other hand due to the high technical value of the system the additional burden in terms of overall cost of the system is expected. This challenge takes the discussion very fast to the question of optimisation in terms of benefit versus effort of the sub – systems of the whole diesel drive train, namely fuel injection system and exhaust gas treatment equipment. This necessitate the application of right strategy that deals with the optimal system configuration for each vehicle class in a specific market to achieve the emission and performance goals within the min. overall cost.

Fig.13 illustrates that optimisation task in a very impressive way.

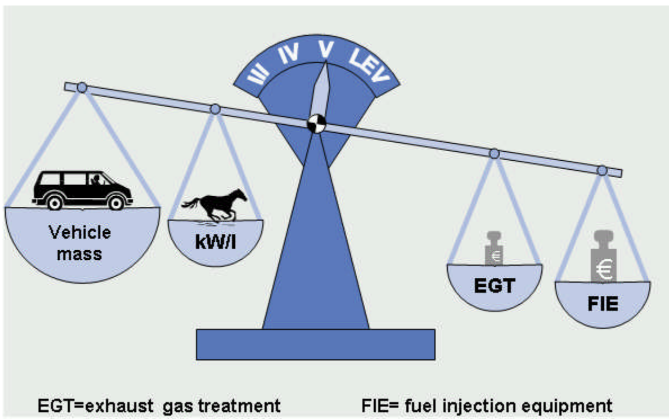

Figure 13: Overall optimisation of the diesel system

Due to the disturbance of the balance between vehicle weight and power output to engine emissions, the performance of the fuel injection system and exhaust gas treatment system improves the balance by lowering the emissions. Still providing a conventional combustion system optimised for lowest raw emissions based on the calculation of such a balance, one can give first answers to the following two questions: what kind of efforts are required on the fuel injection and exhaust gas treatment systems front to hit the emission and performance goals for a specific vehicle application in Europe? Generally is there a way because of a high sophisticated fuel injection system to reduce the efforts on the exhaust gas treatment side?

Before we try to give some quantitative answers for two specific vehicle segments as an example, the following scenarios to be discussed which are dealing with Europe's future emission legislation (Fig. 14).

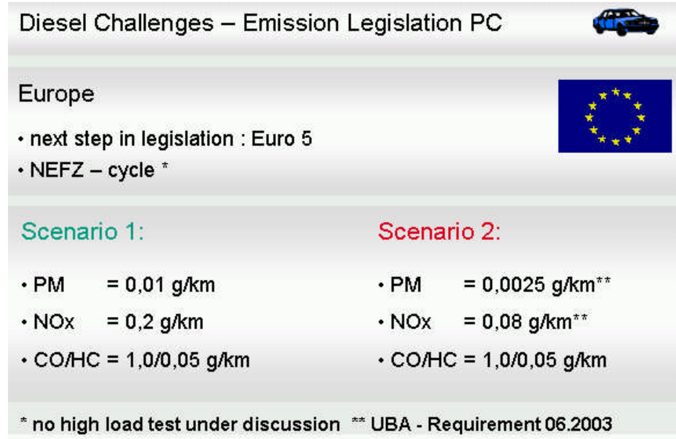

Figure 14: Scenarios for Euro 5

Scenario 1 expects no change in the defined driving cycle MNEDC in the next years and the next step in emission legislation to succeed Euro 4 will not be implemented before year 2010.

Scenario 2 takes into account the proposal of the German federal environmental agency. Extremely low particulate values are required, which can't be measured within the needed accuracy up to now. Furthermore the technology for vehicles to fulfil those emission limits is still a big challenge, also for petrol direct injection engines. On top of that the required NOx-limit of 0.08 g/km would cause the introduction of a NOx-storage catalyst, also for low vehicle weight applications. This would pose a big challenge to the price sensitive diesel market segment, as an uncompetitive technology due to the very high add on cost.

Keeping in mind the self-commitment of the ACEA to undershoot the CO_2-emissions of the overall passenger car vehicle fleet value of 140 g/km in the year 2008 will only become reality by keeping a certain diesel market share. Out of these aspects it is expected that somewhat similar to the more realistic „Scenario 1“ will be fixed as the next emission legislation step beyond Euro 4.

Trying now to give some answers to the questions mentioned above for a passenger car compact class vehicle, we use the data given as an estimation out of prototype engine results fired also with early prototype fuel injection devices.

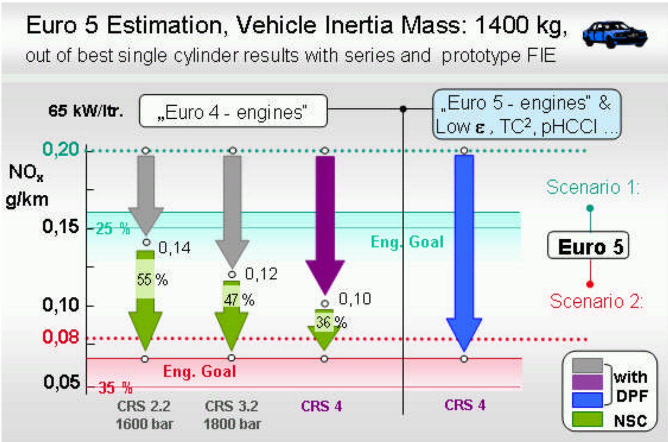

Figure 15: Estimation of fuel injection systems - Emission potentials for compact class vehicles

Fig. 15 summarises the results of a performance assessment of several diesel system bundles consisting of advanced fuel injection system and exhaust gas treatment systems. The ordinate gives an idea about the NOx – reduction potential using these bundles combined with the modern, conventional optimised Common Rail diesel engine. To mirror the results of those diesel systems on the emission goals, one finds the discussed emission limits for the next step beyond Euro 4 including some safety margin, the so–called engineering goal.

In general one can expect, the better the fuel injection system performance is, the minimal the effort on the exhaust gas treatment side. It depends on the assessment of the combustion specialist if he attempts to hit the future emission goals with the sophisticated solenoid driven injection system CRS2.2 or with 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 swept volume of the engine and of course of the vehicle inertia mass. A very powerful solution is provided by the 4th generation of BOSCH Common Rail as pointed out in Fig. 15, show a power goal of > 65 kW/l can be reached simultaneously by undershooting the NOx limits of Euro 5 scenario 1 without any additional effort on exhaust gas treatment side besides the particulate trap.

Have a look at Fig. 16 where the assumption is made for cars with an inertia weight of 1800 kg one considers the advantage of the pressure amplified Common Rail System HADIS. Using the same engine swept volume at 1800 kg vehicle, the HADI clearly points out its advantage for higher partial load point operation. Also for that application the 4th generation Common Rail System falls clearly into the settled engineering goal of scenario 1 without any DeNOx measure.

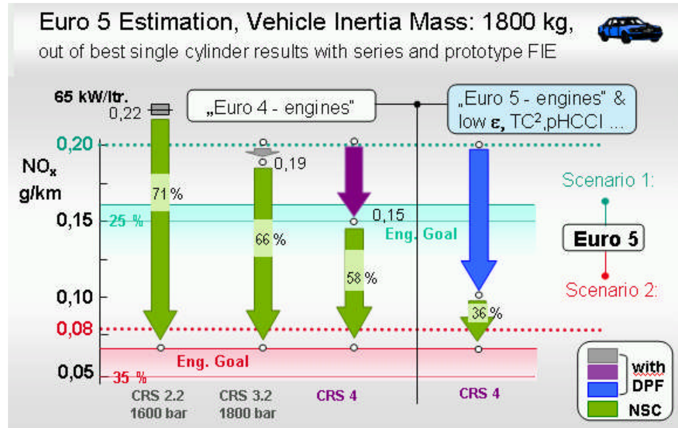

Figure 16: Estimation of fuel injection systems - Emission potentials for upper compact class vehicles

CONCLUSIONS

Euro 4 emission norms can be achieved with the BOSCH 2nd generation Common Rail System. High performance engines with specific power of more than 55 kW/ltr and high vehicle weight require the 3rd generation Common Rail System.

The biggest challenge in diesel technology for the future is the fulfilment of continuously challenging emission targets. BOSCH will continue to support in overcoming these threats while maintaining advance fuel injection technology.

Out of an overall system requirement evaluation of truck and passenger car diesel engines to hit future performance goals of diesel the guiding key issues for future Common Rail systems are identified.

The industrialisation of the key issues lead to the so-called 4th Generation Common Rails systems of BOSCH which is described as a hydraulically amplified injection system for passenger cars and light duty vehicles and the fully flexible 2-stage pressure amplified Common Rail system for heavy duty trucks.

First results out of an engine based estimation using bundles of diesel systems built up with 4th generation Common Rail System, engine improvements and exhaust gas treatment equipment lead to technical solutions to reach future emission legislations.

The effort on the fuel injection system and the exhaust gas treatment for passenger car vehicles is a strong function of the inertial vehicle weight, the power output and the chosen engine displacement.

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

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