Helmut Tschöke *Hrsg.*

9. Tagung Diesel- und Benzindirekteinspritzung 2014

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9. Tagung 2014
Diesel- und Benzindirekteinspritzung

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VORWORT

Die Kraftstoffdirekteinspritzung ist beim Dieselmotor längst Stand der Technik und entwickelt sich beim Ottomotor mehr und mehr zum Standard. Ihre Funktion und optimale Anpassung an den Motor ist Voraussetzung zur Erfüllung zukünftiger Anforderungen hinsichtlich Kraftstoffverbrauch, CO_2-, Schadstoff- und Geräuschemission sowie dem Betriebsverhalten. In Zusammenhang mit der intensiven Entwicklung von Downsizing-Konzepten und den zukünftigen Emissionsstandards ergeben sich sowohl für den Otto- als auch für den Dieselmotor neue Herausforderungen an die Gemischbildung und damit an die Einspritztechnik.

Beim Ottomotor stehen dabei die Verbrennungsstabilität, die Erreichung der Grenzwerte für die Partikelanzahl und der CO_2-Ausstoß, beim Dieselmotor die Schadstoffemissionsreduzierung im Vordergrund. Die Weiterentwicklung der Brennverfahren erfordert Maßnahmen an der Einspritztechnik selbst, den Einspritzstrategien sowie der Applikation. Die Auslegung der Injektoren ist nicht zuletzt aus Kostengründen Gegenstand von Forschung und Entwicklung.

Beim Diesel- und besonders beim Ottomotor wird an der weiteren Steigerung der Einspritzdrücke und Verbesserung des dynamischen Verhaltens bei Mehrfacheinspritzung gearbeitet. Hinzu kommen zusätzliche Herausforderungen bezüglich Qualität und Lebensdauer sowie durch die Anwendung alternativer Kraftstoffe, z. B. Gaskraftstoffe.

Die dargestellten Ergebnisse aus experimentellen und theoretischen Untersuchungen wurden am 3. und 4. Dezember 2014 auf der Fachtagung Diesel- und Benzindirekteinspritzung, die zum neunten Mal in Berlin stattfand, präsentiert.

Wie bei den vergangenen Tagungen haben auch diesmal wieder kompetente Vertreter der Motoren- und Zulieferindustrie, Wissenschaft, Engineering-Dienstleister und interessierte Teilnehmer Fragen um die Einspritztechnik auf der zweitägigen Tagung intensiv diskutiert. Erstmals begleitete und unterstützte die IAV GmbH diese Veranstaltung, hierfür herzlichen Dank.

Der Herausgeber dankt allen Autoren, Mitautoren, Moderatoren und den beteiligten Unternehmen für ihre exzellenten Beiträge, die eine solche Tagung und damit dieses Buch erst erfolgreich machen.

Der Dank gilt auch Herrn Dr. C. Andreae und Frau J. Lupczyk vom Haus der Technik Essen für die Tagungsorganisation und konstruktive Zusammenarbeit und Frau E. Lange von Springer Vieweg für die Unterstützung bei der Veröffentlichung der Beiträge in digitaler Form und als Buch.

Dezember 2014 Helmut Tschöke

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Bosch Diesel Fuel Injection System – with modularity from entry up to High-End Segment

Michael Raff, Jürgen Hammer, Dirk Naber, Dietmar Zeh

1 Summary

The modern Common-Rail Diesel engine is no more a European phenomena and the worldwide prognosis shows growth not only in India and China but also in US market. In these markets the Diesel engines will be used in different vehicle segments and under different boundary conditions.

In India the Diesel engine is becoming increasingly popular due to the need of low operating cost while in China there is not only an ever increasing demand for light commercial vehicles but also for Passenger Cars. These two markets need robust and cost attractive Diesel Injection Systems, which should also be capable to fulfill the new emission norms like BS5 (Bharath Stage 5) or CN5 (China 5).

Indian and Chinese OEM's want to profit by the increasing number of Diesel vehicles in these markets. But nevertheless, European OEMs are also trying to sell their entry and standard segment vehicles in these emerging markets. To reduce the varieties, the engines are often used in Europe as well as in all other regions of the world. Due to this, the requirements on a Fuel Injection System are increasing tremendously. The fuel injection equipment should fulfill the severe requirements to meet emission legislation and CO_2 standards of EU and also be robust for worldwide usage as well.

The requirements for the European High-End Segment are not only to consume less fuel with the same power output – but to have the same noise and comfort level like a comparable DI-Gasoline-engine. For these demands highest injection pressure up to 3000bar as well as full flexible multiple injection are required.

BOSCH as a full line Diesel injection system supplier is able to fulfill these different and challenging requirements for all vehicle segments worldwide with a tailored and modular System approach.

2 Worldwide Diesel market and the requirements for the Fuel Injection Systems

The worldwide combined average growth rate of passenger cars and light vehicles is increasing in the upcoming years. The Gasoline PFI engine will stay the most common propulsion due to its very attractive cost-benefit ratio. With the new direct injection technology the gasoline engines are now reaching especially in the entry segment very good consumption levels. This makes it more and more difficult for the Diesel engine to keep its worldwide market share of actual 22%.

The major Diesel market is still and will be also in future Western Europe. Here the Diesel share will stay stable until 2020 but the number of Diesel vehicle in total will

still grow. In the US market Diesel engines are expected to be sold in the Light Duty Truck (LDT) and Sports Utility Vehicle (SUV) segment and this will increase the Diesel share by 10% but based on a low level. The biggest growth of Diesel is expected in the emerging countries like China and in India. In China the off road and light commercial vehicle sector but also the passenger car segment will sustain the Diesel share. In total the growth of total number of Diesel vehicles will increase by 2.1% until 2020.

Both engine types – Diesel and Gasoline – will be more and more equipped with electrification measures and this means also new requirements for the fuel injection system.

All markets have two main drivers for new requirements (see Fig.1):

- Legislation: emission, new testing cycles and CO_2 targets (hybridization)
- Market/end user: power output, fuel consumption as well as vehicle cost, noise (NVH) and robustness

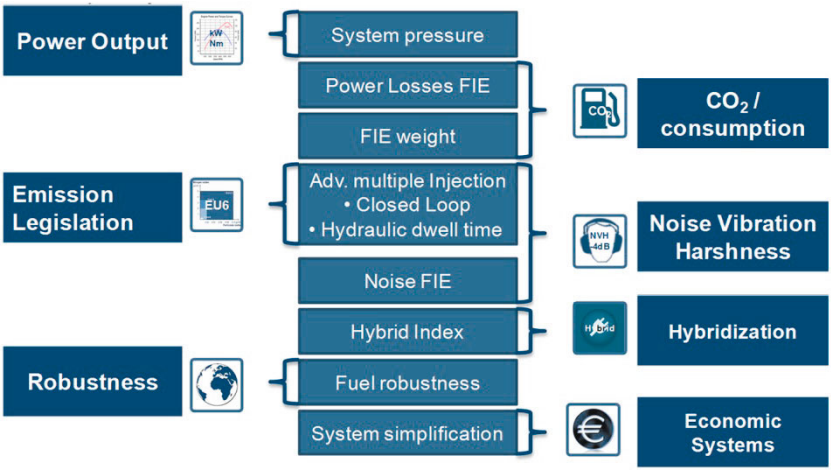


Fig. 1: Key requirements from Market and for FIE

In the following subchapters the specific requirements for Diesel engines are described more in detail for the emerging markets like China and India as well as for the European market.

2.1 Emerging Markets – China and India

Traditionally India and China are following European emission legislation and driving cycles, but with a time lag. For this reason injection strategy requirements are already known and proven in field from former European projects.

The major challenges for Fuel Injection Systems in Indian and Chinese market are especially in the rural areas the critical fuel quality and on the other hand the necessity to provide low price fuel injection equipment.

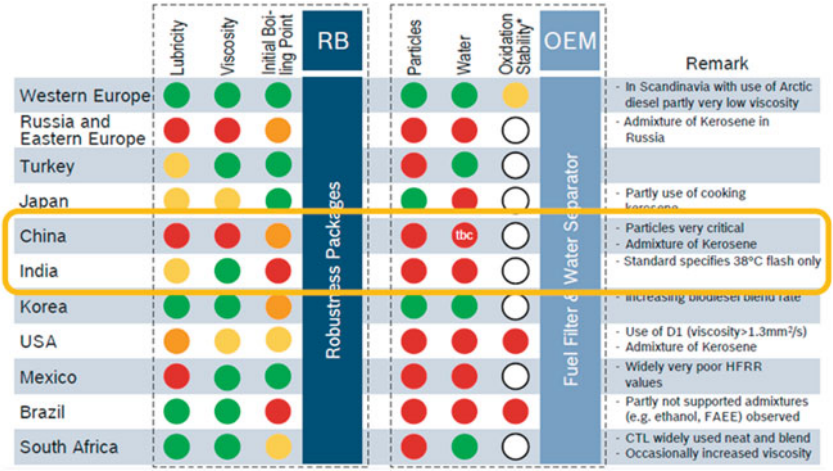


Fig. 2: Overview Fuel Quality and Measures

Fig. 2 shows the different fuel properties of the various Diesel markets. These properties must be divided into two parts:

- Lubricity, viscosity and Initial Boiling point must be assured by fuel injection system supplier (robustness packages for fuel injection components)
- Particle and water content as well as oxidation stability have to be checked by OEM (layout fuel filter and low pressure circuit of fuel injection system)

In India the Initial Boiling Point of the fuel at the gas station is much lower than for EN590. Due to this fact, the cavitation risk inside the injector and in the drive train of the fuel lubricated pumps is increased. In China lubricity and viscosity of the fuel as well as particles and water content inside the fuel are critical for CR systems in terms of wear and corrosion. These properties are impairing the wear robustness of the CR components.

In field the fuels are not according to the specification of these countries. This fact makes it very challenging to design fuel injection components which are robust against every fuel characteristic without increasing the component costs and losing the technical capabilities to reach legislation needs.

The major segment in these countries is low price vehicles. To reach the price target for FIE, proven technologies have to be used as well as complexity reduction of the fuel injection system have to be developed.

2.2 Requirements for Standard and High End segment in Europe

In Europe the primary focus for the OEMs is to fulfill new emission legislation. The new test procedure WLTP[1] (Worldwide harmonized Light Vehicle Test Procedures) for CO_2 and emissions expected to replace the NEDC (New European Driving Cycle) in the next years.

This test will be more dynamic and consist in higher load areas than the NEDC. In addition the so-called Real Drive Emission (RDE) standard will be introduced to widen the area beyond the test procedure making sure that in all real possible drive conditions the emission output stays limited. Due to the fact that Diesel Particle Filter technology is standard from Euro5 the particulate issue on the Diesel side is already solved. The next step in term of exhaust gas treatment will be for the NO_x emissions and with the new test procedures the $DeNO_x$-Trap or SCR exhaust gas treatment will become a standard for the Diesel applications in Europe and the US.

All these legislation requirements implicate for the Diesel combustion system the following main key technologies:

- well de-throttled air path with powerful intercooler [4]
- High efficient low and high pressure EGR path [4]
- Advanced turbo air charging [4]
- Best in class fuel injection equipment [2, 5]
- Fuel/air mixture preparation optimized combustion chamber

From injection technology point of view the main requirements can be obtained by focusing on these market requirements:

- full flexible injection pressure
- maximum pressure depending on combustion, air and EGR
- system and rated power target
- full flexible multiple injection capability

1 Not yet defined

- application specific number of injections, dwell time,
- minimum quantity and tolerances
- nozzle technology with robust compromise coking vs. hole
- efficiency, optimized sac hole volume

These so-called CR standard requirements [2] have to be specifically quantified for each application and extended depending on segment.

Secondly OEMs would like to match the comfort level of Diesel vehicle to a Gasoline DI. This is an outcome of several workshops with the OEMs [7]: the absolute combustion noise decrease.

This demand makes it necessary to have the maximum degree of freedom in terms of injection pattern to improve the cylinder pressure increase and with that the combustion noise of the Diesel engines. This smooth and low gradient behavior as a function of the crank angle can be realized by calibrating two pilot injection very close to the Main Injection (Digital Rate Shaping = DRS). In addition, the heat release can be controlled and this enables a noise reduction of 2dB and using higher rail pressure by keeping soot equivalent.

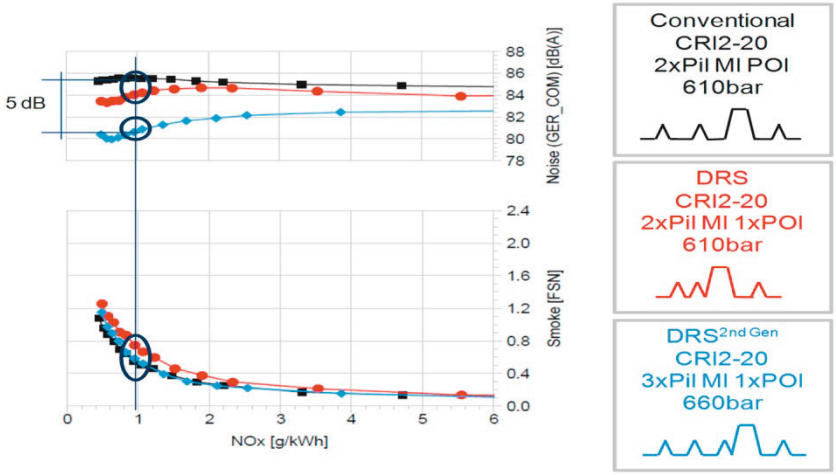


Fig. 3: Conventional strategy, DRS, DRS 2nd Gen – engine results

A further improvement of the combustion noise can be realized by a digital emulated ramp shape – so called DRS 2nd Gen. In addition to the two pilot and one main injection a third pilot injection is calibrated and this injection pattern can limit the heat re-

lease to a certain level by still keeping the soot on a base level. The noise improvement compared to a conventional injection strategy is approximately 5dB – of course depending on the load point (see also Fig. 3).

3 Modular Diesel Fuel Injection System Solutions

All these different market requirements pose a challenge for the Diesel Injection System. BOSCH has developed as a full-line supplier a modular System approach to satisfy all the demands of the market. In the next subchapters two system examples are shown, which can fulfill the specific demands of the different markets.

3.1 System solutions for China and India

In emerging countries BOSCH offers a modular system concept based on its 1st generation of CRS with fuel and oil lubricated pumps (integrated into the engine or with separate pump housing) to have a robust and cost attractive system proposal (see Fig. 4)

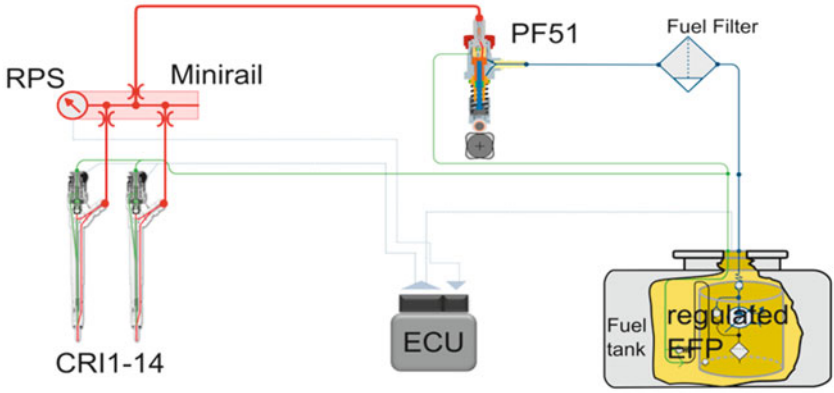


Fig. 4: CRS1-14 for 2-cylinder-engine with Minirail (+RPS), PF51 (oil lubricated pump) and a rail pressure regulation by Electrical Feed Pump (EFP)

The CRS1-14 is a 1450bar CRS especially designed for the entry segment (2 to 4-cylinder engines). To reduce the complexity of the system and also the total system costs the rail pressure control by an additional fuel metering unit was replaced and the function was transferred to the Electrical Feed Pump (EFP) in the fuel tank. The regulation of the rail pressure is of course not as fast as with an additional metering unit,

but is sufficient to reach actual Bharat Stage 4 and 5. The oil lubrication of the PF51-pump makes the Common Rail Pump more independent to the fuel quality in the market.

The CRI1-14 is based on the very robust CRI2-26 which is already in series since 2003 (solenoid injector with ball valve). Few design simplifications to reduce production cost without losing the good injection metering have been realized. But also for higher pressures the valve ball design is now extended up to 1800bar to serve especially in China the Light Duty vehicle market.

3.2 System solution for Standard and High End segment in Europe

The challenge for the European car manufacturer are the wide spread of requirements from Fuel robustness – to ensure the possibility to sell the vehicles also in the emerging markets – to combustion noise level of a gasoline engine with low fuel consumption.

To meet these targets BOSCH uses the modular system concept to improve the characteristics of the FIE components. Coming from the CRS1 (see also Fig. 4) to comply with EU emission legislation the changes on CRS2 are on the pump an improved Oil-Fuel-separation and on the injector an improved multiple injection capability (see Fig. 5)

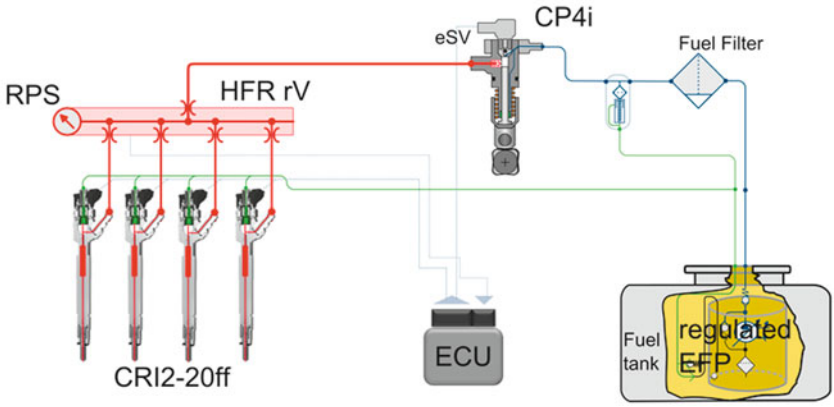
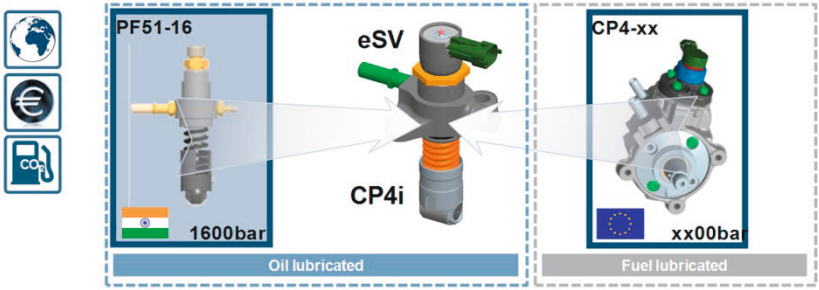


Fig. 5: CRS2-20 for 4- to 6-cylinder-engines with Hot Forged Rail (+RPS), CP4i (oil lubricated pump integrated into the engine) and rail pressure regulation by eSV

For the high pressure pump these improvements are high pressure capability, efficiency, rail pressure regulation quality and also medium separation (Oil-in-Fuel = OiF and

Fuel-in-Oil = FiO). With the experience of oil-lubricated pumps (like PF51) in India and the knowledge of high efficiency pumps like the CP4 a new high pressure pump – able to fulfill European as well as fuel critical market requirements – was developed: the CP4i. To reach the high pressure capability and the good efficiency the cylinder head of the CP4 2nd Generation with an electrical Suction Valve (eSV) is used for the CP4i. With the eSV not only the efficiency of the pump can be improved but also in combination with a Pressure Control Valve (PCV) on the rail the rail pressure regulation quality will be more precise than with a regulated EFP or the standard Metering Unit. The drive part is a mixture of PF51 and CP4 parts. The most difficult for an oil lubricated pump for Europe is the separation of Oil and Fuel. For this reason Bosch is developing a new sealing to push the OiF and FiO below 1,0ml per million pump strokes, to prevent soot accumulation in the Diesel Particle Filter (DPF) and oil dilution. This new integrated High Pressure Pump can be installed directly in the engine and driven by the camshaft or balancer shaft, but BOSCH offers also this oil lubricated pump with an integrated housing. An additional benefit of the oil lubricated pumps is the reduced fuel quantity demand of the high pressure pump and with that a reduced electrical effort for the Electrical Feed Pump in the fuel tank.



- integrated fuel metering (eSV)
- advanced fluid separation (≤ 1ml / 1Mio plunger lifts)
- high frequency/speed capability (i=1)
- highest hydraulic efficiency (> 95%)
- backflow free
- innovative hp pump based on deep series experience (CP4, PF51, HDP5)
- high degree of system integration
- CRS simplification
- modular approach (optional w/ hsg.)
- WWU capability
- ISS-capability (standard: 360k starts)

Fig. 6: CP4i (oil lubricated pump integrated into the engine) with electrical suction valve (eSV)

Not only the pump but also the Injector needs enhanced functionalities in regard of pressure, multiple injection and short injection separations by keeping the same robustness as the CRI1-xx used in India or China. For this purpose BOSCH enhances the CRI2 (solenoid injector with pressure balanced valve) and CRI3 (piezo injector) family.

The CRI2 is already in series with pressures up to 2000bar and the 2200bar version will go into series this year. But for the upcoming power and emission targets the 2500bar will be necessary and is under development. For reduction of the injector backflow quantities and therewith the fuel temperature in the backflow pipes a minimization of the relevant guidance and diameter dimensions will be introduced. Of course this minimization is also improving the injector efficiency. For an advanced injection pattern – injection separation – and to realize the DRS 2nd Generation the fuel metering of the CRI2 will be controlled by a Closed Loop Control by using a needle closing sensor integrated into the injector head.

For the high end segment the pressure demand is going up to 3000bar. This will be released with the CRI3 family. This year the 2500bar version is going into series and the development of the 2700bar as well as the 3000bar is started. Especially for the 3000bar version new materials and manufacturing processes have to be developed and are very challenging (see Fig. 7.).

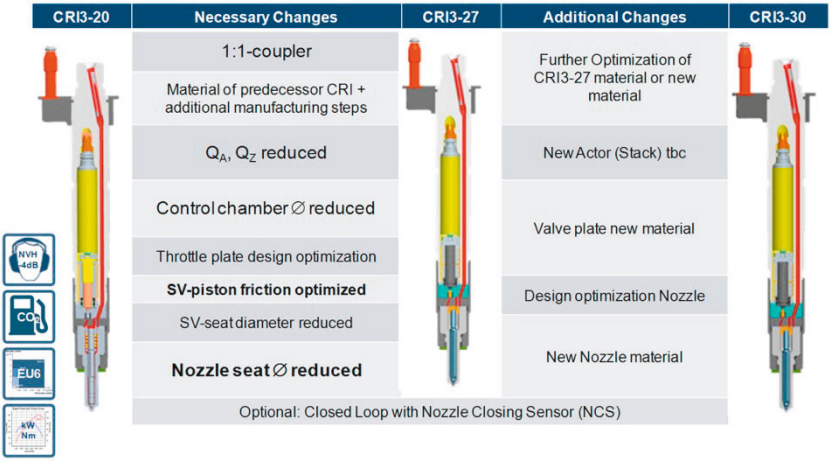


Fig. 7: Evolutionary concept of 2700 and 3000bar injector based on robust CRI3-20

Like for the CRI2 a minimization of the guidance and diameter are necessary to improve the injector efficiency and to keep the fuel backflow temperatures in a manageable level.

The CRI3 is already capable to perform DRS 2nd Generation patterns, but to increase the degree of freedom for the high end segment applications a closed loop function with an additional sensor will be available. With this function the end of injection as well as the switchover point can be detected. With these two points the Software is able to calculate the complete injection rate and can separate the quantity changes into drift by wear or by coking of the nozzle.

With all these modular components the Fuel Injection System can be adapted to the market, segment and customer requirements and enables the worldwide fulliner strategy of BOSCH:

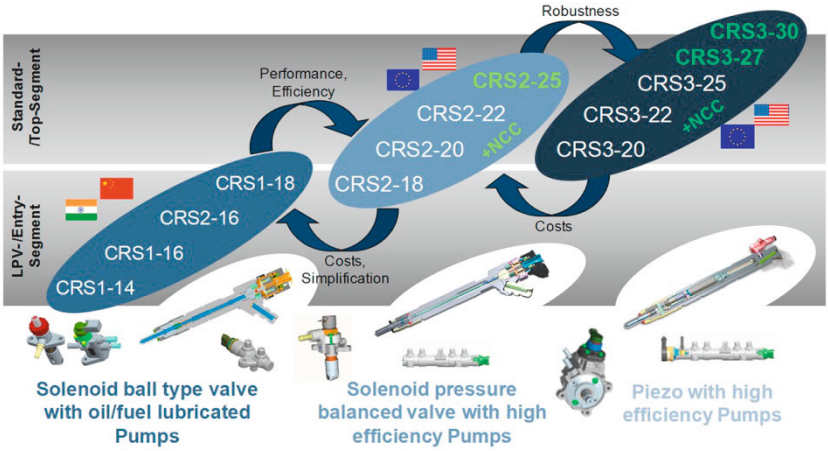


Fig. 8: BOSCH Common Rail System Modular Strategy

1st Gen CRS1 fulfills the emerging market requirements of cost and robustness. In addition the 2nd Gen CRS2 fulfills the developed market requirements of noise and emissions. Furthermore the 3rd Gen CRS3 fulfills the premium market segment requirements of highest power and comfort.

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