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The “green” injection for engines

Engine systems technology for stricter CO_2 and emissions targets

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Introduction

Notwithstanding the difficult economic climate that the automotive industry is currently experiencing worldwide, there is no letup in terms of the statutory requirements for the reduction of emissions and fuel consumption. On the contrary, the future exhaust gas standards such as Euro 6 (from 2014) and CO_2 legislation pose great challenges to both gasoline and diesel engines. Firstly the emission of combustion by-products such as nitrogen oxides (NO_x) and soot (particles) must be reduced further. Secondly, the emission of CO_2 – which, as an original product of the exothermal chemical reaction in the combustion chamber, has an impact on the climate – must be reduced, and that can only be achieved if fuel consumption continues to fall.

Whilst the classic automobile markets in Europe and USA/NAFTA are likely to see only a slow recovery, in Asia the demand for individual mobility is set to increase still further; most notably in China where, if anything, the level witnessed in 2007 is likely to be reached again in 2011. The greatest demand is in the A and B segments, that is to say those vehicles for which the vehicle manufacturer and supplier must weigh up issues relating to technological complexity and economic constraints. The growth rates are similarly high for South America, but at a lower absolute level. The upshot is that there is demand for years ahead (Figure 1).

In order to meet this level of demand successfully, further progress is necessary in engine system technology. Both diesel and gasoline engines offer potential in this respect. In the case of gasoline engines, it is primarily direct injection (DI) technology that will be used increasingly because it lowers consumption directly and also, in combination with turbo charging, enables an indirect reduction of engine displacement (downsizing) and thus further increases in efficiency. It means that gasoline engines can become economical on a par with their diesel counterparts. There is also potential for diesel engines. More targeted management of the combustion process and improved processing of the air-fuel mixture are smoothing the way for greater efficiency.

Moreover, both types of engine are becoming increasingly similar, and therefore both pose closely related challenges. For example, the issues of NO_x reduction and soot formation in DI gasoline engines are becoming increasingly relevant – which was not the case with a naturally aspirated engine. This is reflected likewise in the efforts being made to optimize the inner workings of the engine and to render the treatment of exhaust gas more efficient. The air path is also becoming increasingly similar in both engine types. The same applies to the trend towards greater variability in the valve gear (opening and closing times, valve overlap, valve lift). Because of this increasing level of similarity, the technical solutions for both types of engine are becoming more closely linked – right through to exchangeable software functions in engine management systems.

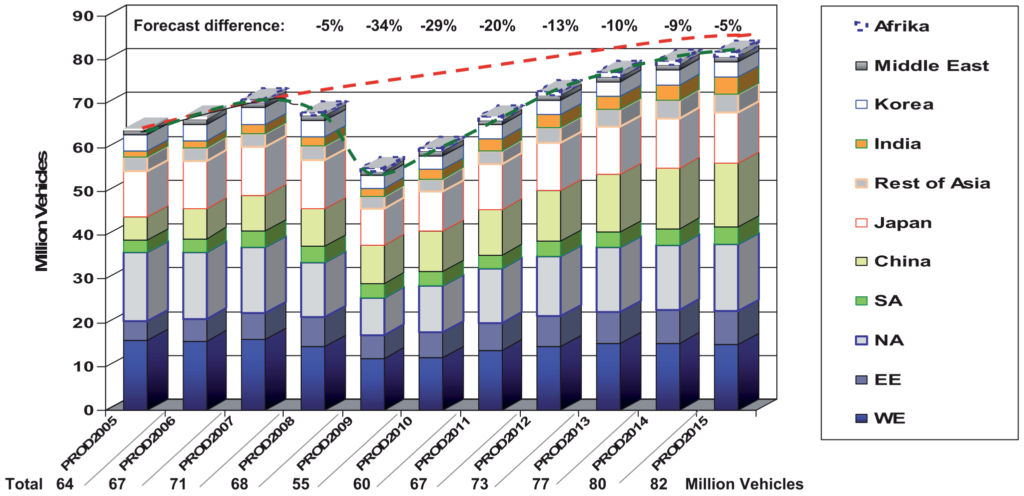

Figure 1 Future growth in passenger cars and light commercial vehicles will come mainly from Asia

There is also the fact that the underlying conditions for engine system technologies vary with the different markets and classes of vehicle. There are therefore no universal solutions. Instead, in future it will be the vehicle's weight class and the target market which, more than ever, will determine the technologies that will be employed in engines. In the emerging markets, for example, the demand will be for smaller engines with a low number of cylinders. Yet here, too, the requirements in respect of emissions are very high. The differences in legislation governing exhaust gases worldwide will narrow from 2014/2015 (for example with the introduction of Euro 5 in many markets). The converse argument is that only highly efficient system technology which utilizes the synergies from the mechatronic combination of software, electronics and hardware will have any sort of future.

Continental is prepared for these challenges and offers vehicle manufacturers solutions for all requirements by applying a system approach. From mechanical components through to electronic hardware and software, the technological solutions are tailored to all levels of the system and prepared with future requirements in mind.

System approach in engine technology

Because of the differing underlying conditions, Euro 6 system approaches for diesel and gasoline engines will vary from vehicle model to vehicle model. The question of what technology is to be used in a particular vehicle will be based more than ever on statutory and economic requirements. In the face of these defined goals and objectives, it is possible to specify for each individual vehicle which technology is the right one in a particular engine.

Diesel engine development

If we look, for example, at the total costs for a diesel engine together with the associated after-treatment system, the picture that emerges is one of various layers of complexity: in the case of small vehicles with a very narrowly restricted cost framework a pre-defined overall system approach with off-the-shelf components is required (EASY-U, see below) in order to fulfill price requirements. Medium to heavy vehicles require a flexible product line approach in order to be able to offer system solutions that comply with requirements (Figure 2).

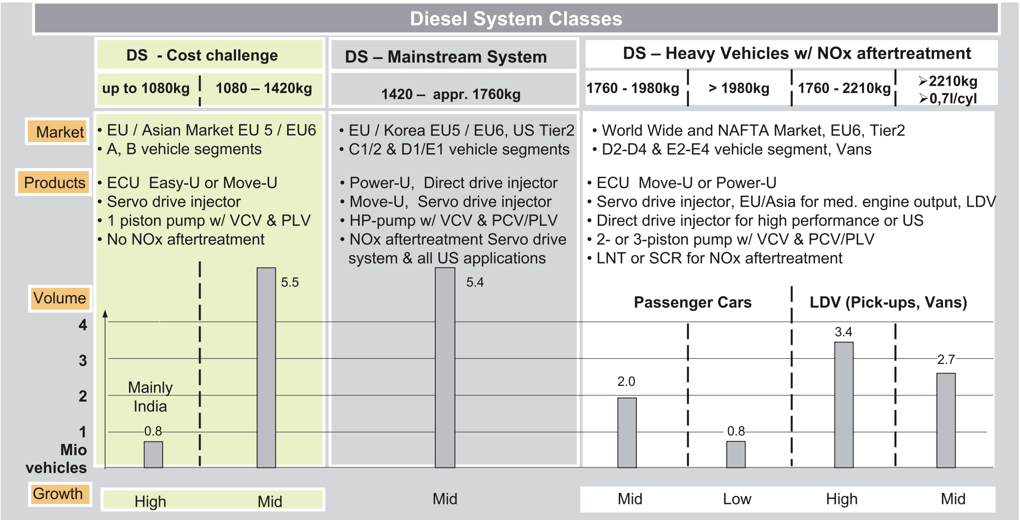

Figure 2 Technology options for diesel engines related to vehicle weight

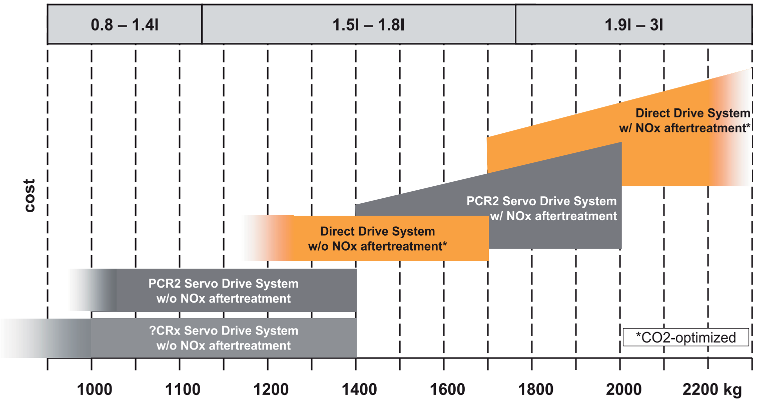

Figure 3 Influence of engine displacement and vehicle mass on engine system technology (PCR2 = current servo-driven piezo injector)

In the case of engines for medium to heavy vehicles (up to around 1.7 tons), the emissions specifications (and in some cases the CO_2 targets also) can optionally be achieved through increased use of internal engine optimization using higher-end injection systems or through simpler injection systems and more comprehensive exhaust after-treatment. Because of the direct interactions between both levels of the components and functions involved, there is scarcely any alternative to a system approach.

A comparison of the technology options available to diesel engines makes it very clear just how great the influence of the vehicle class, and therefore of the vehicle weight, is on the choice of technology to be employed. In the case of small and medium-sized vehicles in connection with suitable injection systems, it may be that it will be possible to comply with the emissions requirements of the Euro 6 standard without additional exhaust gas after-treatment, for example in the form of selective catalytic reduction (SCR) with urea. In the case of vehicles with a larger specific output and higher weight, on the other hand, a system for reducing nitrogen oxides (NO_x) in a conventional powertrain will be inevitable (Figure 3).

Key role of high-pressure injection

Preparation of the mixture in the combustion chamber will play a key role in the further optimization of diesel engines. Ever higher injection pressures, ever finer and ever more even atomization of the fuel, very accurately dosed fuel quantities and control strategies with multiple injection pulses (multiple injection) have made the diesel engine an extremely economical and efficient form of drive technology. And the development goes on. Injection pressures will also continue to increase, with 2000 bar and more is on the roadmap.

The piezo injectors for common rail systems developed by Continental, and which have now become firmly established in the market, represent a major step forward [1]. With their rapid switching capacity and high level of precision, these injection valves are suitable for demanding control systems in which the timing and quantity of the fuel delivery phase must be very accurate with high repeatability (so-called “shot-to-shot” accuracy). Moreover, piezo injectors allow a very large spread of the injection quantity, that is to say they can both meter very small quantities of fuel very accurately (economically in part load conditions) and as well dose large quantities of fuel (under full load). Their dynamics are so great that the transitions from one operating point to another can be very quick. With injectors of this type, highly mature low-emission, low-noise combustion strategies – for example with pre-, main and post-injection – can be realized (Figure 4).

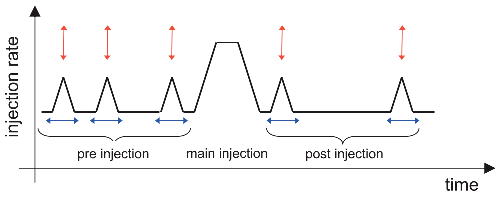

Figure 4 Chart/diagram with three pre-injections, one main injection and two post-injections

Continental has now developed a new generation of piezo injectors for injection pressures of between 2000 and 2200 bar (Figure 5). With these NG injection valves, a hydraulic boost is no longer required to achieve the desired movement of the nozzle needle. Because the actuator has a direct effect on the nozzle, the reaction – that is to say the injection – occurs more directly than with those of the hydraulically boosted generation – and without its hydraulic retroactions. As the NG injector has almost no leakage it is particularly efficient. The new generation of injectors also makes it possible – with up to nine injection pulses per cycle – to shape the adjusting characteristics of the injection process (so-called “rate shaping”). This enables what is known as a boot injection. A smaller, variable quantity of fuel directly before the main injection reduces, amongst other things, the injection noise by several decibels. The rate shaping can be set flexibly in broad ranges (Figure 6).

Figure 5 New-generation (NG) piezo injector with direct operation of the nozzle needle

Another new feature is the use of a multi-layer ceramic actuator in the piezo injector as a sensor. Because the electrical and mechanical behavior of the piezo ceramic are known, the actual position of the nozzle needle can be calculated if the electrical current of the actuator and the general conditions (temperature etc.) are also known. In this way it is possible to calculate for each individual cylinder how much fuel has actually been injected [2]. This is because even the precise piezo actuators are subject to minimal, production-specific tolerances from injector to injector, and they also exhibit a certain level of drift over the total operating period. Even these small tolerances are becoming relevant in the face of current emissions requirements. If, however, the actual position of the nozzle needle is known, it means that it is possible, for the first time, to establish a closed-loop control system in which the ACTUAL quantity of fuel can be adjusted to the TARGET quantity specified by the engine management system for each individual cylinder. This not only makes the combustion process cleaner, it also means that the individual cylinders work more evenly (cylinder balancing). The closed-loop control during injection also creates the basis for self-diagnostics as it will increasingly be required in North America (on-board diagnostics, OBD2/3).

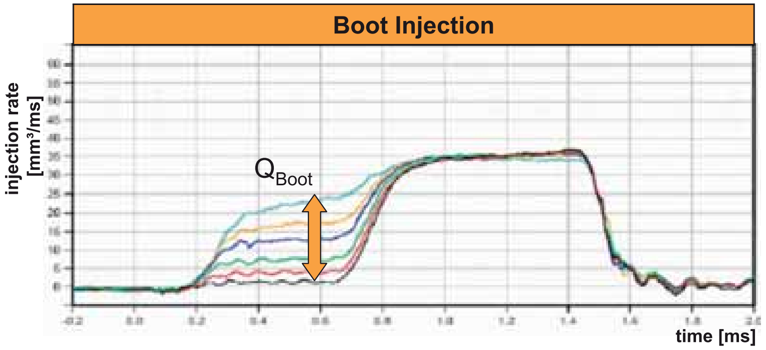

Figure 6 Diagram showing the boot injection variability directly before the main injection with varying quantity Q_{Boot}

In order to create the injection pressure for the injectors, Continental is at the same time increasing the efficiency of the diesel high-pressure pumps with a delivery pressure of initially up to 2000 bar. The new design sees the existing 2- and 3-piston pumps replaced by new generations of single-piston pumps designed for different delivery rates and forms of integration into the engine. From 2011 this will also include compression-proof versions for start-stop systems. In the medium term, piston pumps with up to 2500 bar delivery pressure will be available for Euro 6 applications. They are currently under development.

Gasoline engine development

Gasoline engines remain by some way the dominant form of drive mechanism used in passenger cars. At present, naturally aspirated engines with fuel injection into the inlet port (port injection) dominate the worldwide market (75 % of all gasoline engines employ this set-up). The gasoline engine is now on the verge of a renaissance that is linked mainly to direct injection (DI) technology. The future of multi-point port injection (MPI) in which the gasoline is injected into the inlet port just in front of the inlet valve (so-called external mixture formation) lies primarily in smaller engines, while for the medium class and above DI engines will come increasingly to the fore. In order to make as many gasoline engines as possible cleaner and more economical, technologies are required for both injection systems. The Continental system approach takes this into account (Figure 7) and comprises solutions for all segments and engine sizes.

Figure 8 XL3-type solenoid valve injector for multiple injection and stratified charge

In best-cost systems employing MPI technology, Deka 7 -type Continental injectors in connection with pre-configured engine management systems customized in terms of its range of functions (EASY-U: see below) enable applications through to Euro 6 with progressive on-board diagnostics (OBD2). Within this segment, gasoline engines are operated for the most part with a homogenous mixture in which the quantity of air is controlled in such a way that the fuel gets exactly the right quantity of oxygen for complete combustion (mixture ratio of air to gasoline 14.7:1; lambda = 1).

Even gasoline engines with direct injection will largely employ homogenous engine operation. Innovative injectors such as the Continental solenoid valve generation XL3 (Figure 8) are designed for medium and large engines which must also fulfill the requirements of Euro 6 and OBD2. As there is no wall wetting in the inlet port in a DI engine and the conditions for the mixture of air and fuel are particularly favorable (internal mixture formation), direct injection produces far fewer emissions than MPI. However, the injection pressures required are far higher than those on MPI systems. The new XL3 injectors, for example, are designed for pressure of up to 200 bar (Figure 8). Special actuating electronics enable improved injection of small quantities, but also the possibility of multiple injection in which a very small ignitable mixture cloud is created by two or three injection pulses following in quick succession.

The biggest reduction in fuel consumption is made possible in gasoline engines through lean operation (lambda >1) under part load. XL3 gasoline injectors are particularly suitable in this respect because their high dynamics and precision enable a stratified charge in an extended range at part load. This technology is difficult to master because the cloud of fuel spray involved must always be of the same form and depth of penetration – despite widely fluctuating pressure conditions – in order to ensure consistent ignition. Continental is currently working on the development of further generations of injectors for optimized stratified combustion or controlled auto ignition (CAI). These will also comply with coming legislation. Segmentation of the available technologies for gasoline engines is illustrated in Figure 9.

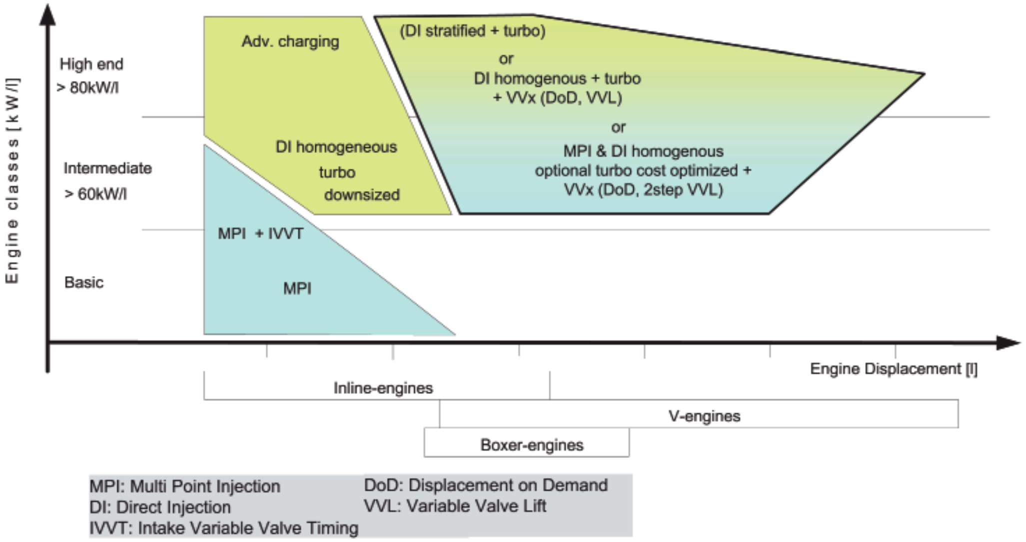

Figure 7 Areas of use for injection technology and valve control in gasoline engines

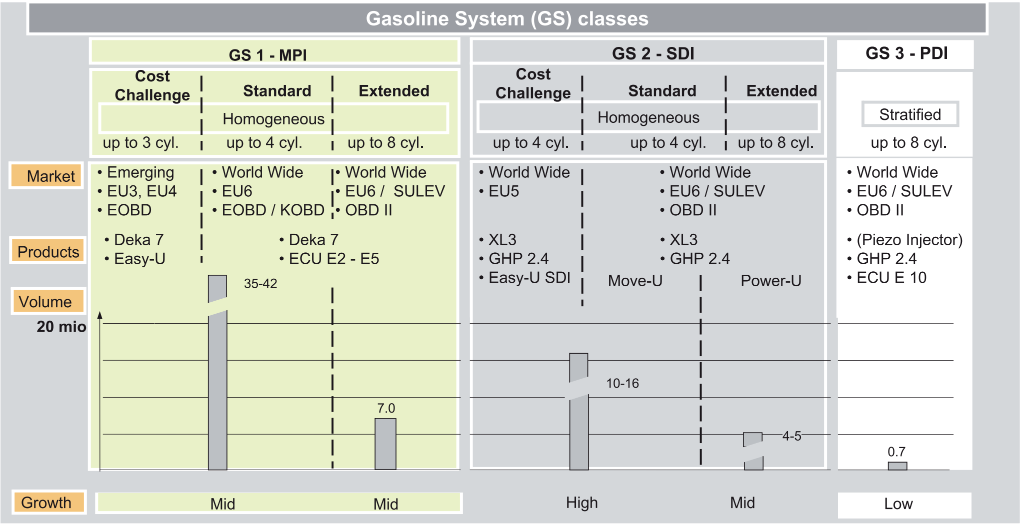

Figure 9 Segmentation of technology for gasoline engines

Gasoline engine optimization is rendered particularly challenging by the fact that, from 2015, under emissions standard Euro 6 not only will the quantity of soot have to be limited to 4.5 mg/km, but there will also be an upper limit for the number of soot particles permitted in exhaust gas. Particularly in the case of efficient DI engines it must be ensured at the development stage that there is a good balance between NO_x formation (combustion temperature too high) and the formation of soot particles (combustion temperature too low). Injectors are increasingly becoming a key component because they exert a significant influence on the quality of combustion.

An entirely new requirement for developers of gasoline engines is their use in range extender (RE) electric vehicles. In this drive concept, the gasoline engine is used exclusively to generate current for the purpose of charging the battery. The requirements for a gasoline engine used in an RE vehicle are quite different from those for a gasoline engine used in a conventional vehicle (Figure 10). Conti-

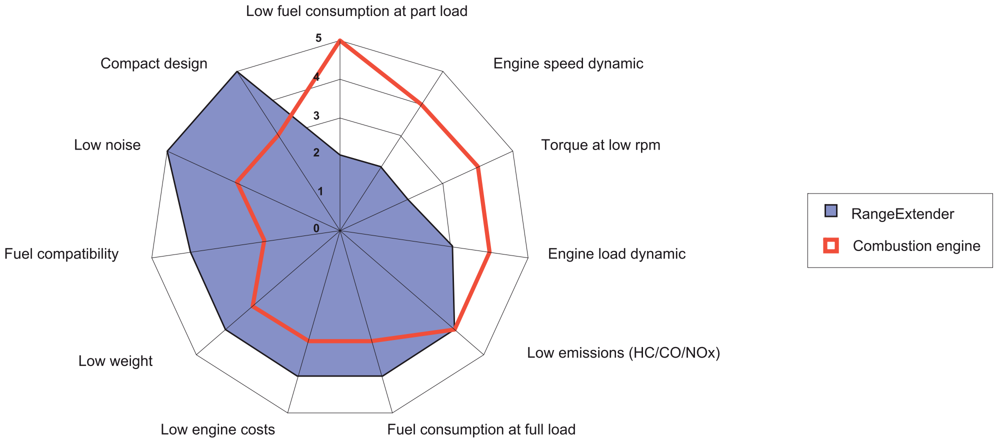

Figure 10 Differences in the requirements profile for engines for range extenders and conventional combustion engines

nental has recognized this challenge at an early stage, and is currently evaluating existing gasoline engine technologies in respect of their suitability for and relevance to RE vehicles.

Scalable engine management systems

The broad range of technology options for modern combustion engines is also reflected at engine management level: there is a considerable gap between a management system for an engine application in the basic segment and one for a high-end application which is difficult to bridge both technically and economically. For example, despite comparatively demanding peripheral equipment, for reasons of cost it must be possible to quickly apply a cost-effective preconfigured system for the OEM, while a high-end solution must be primarily open for the large number of technological options and the incorporation of software of the OEM or other suppliers.

This has been implemented by Continental at an early stage with its EMS2 engine management platform. In doing so, Continental has to a certain extent adopted the current AUTOSAR approach. The particular thing about EMS2 is the co-coordinated range of hardware and combinable, reusable software function packages (aggregates). The broadly recognized advantages of this open, scalable management system are sustained and expanded in the new EMS3 platform generation.

At the same time, Continental has used its platform experience to develop an engine management solution which can also be optimally applied to vehicles in the emerging markets. Designated EASY-U, this cost-effective solution comprises a portfolio of elements for a complete, scalable engine management system of modular design for gasoline engines with MPI and up to 4 cylinders (Figure 11). In addition to the EASY-U basic concept, Figure 11 shows the other product lines for flexible use (MOVE-U) and the open high-end range (Power-U).

For all applications above the basic segment, the new AUTOSAR-based engine management platform EMS3 provides a consistently open architecture with which Continental can either offer complete solutions from one source or incorporate components (software and hardware) from other manufacturers (Figure 12). The existing library of software units combines the security of validated and tested software with the cost effectiveness of a modular approach. With identical functions, the relevant software modules cater for diesel and gasoline engines in a common unit.

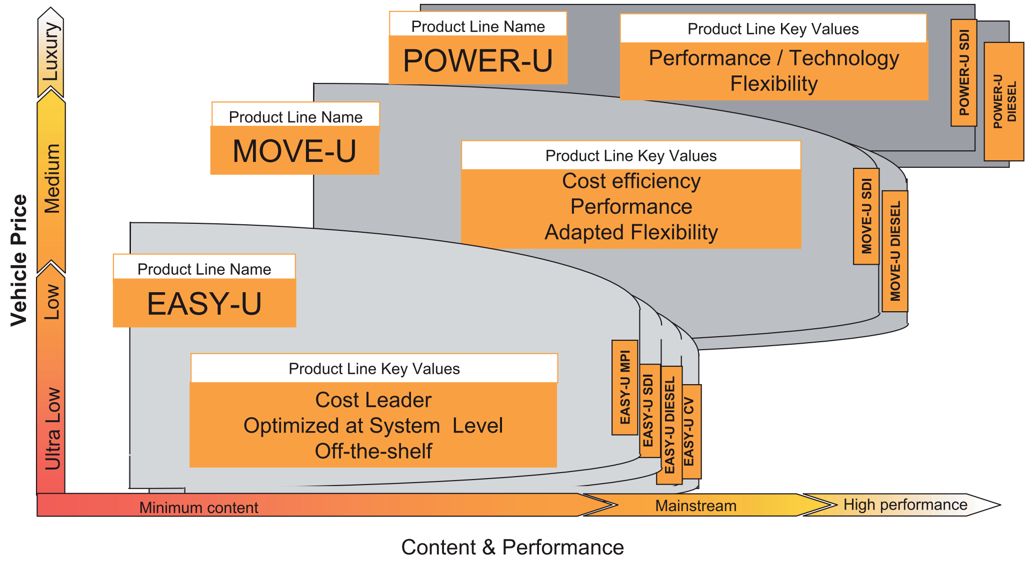

Figure 11 The product line strategy of Continental engine management systems

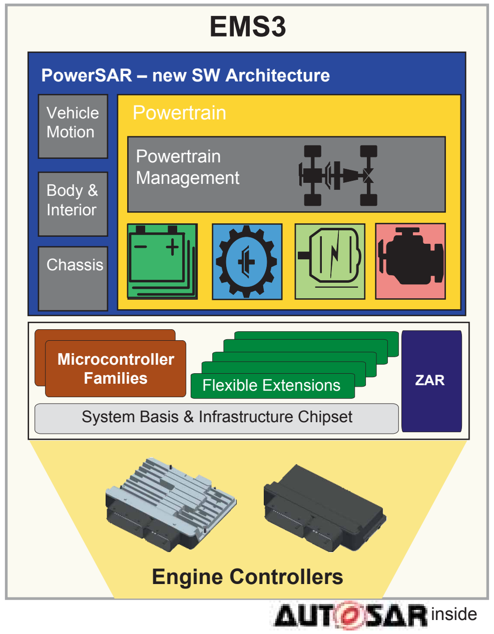

Figure 12 A complete scalable solution that is also open for integration: EMS3 with PowerSAR architecture (AUTOSAR for powertrain use)

The associated control unit platforms are also scalable, and reduce the development time for an engine management system despite the high level of functional complexity involved. In order to cater for management solutions of varying capability, the hardware comprises a microcontroller in highly integrated 90 nm Tricore or PowerPC technology in five graduated performance classes and an ECU housing concept optimized in terms of both size and weight.

Air path

In addition to the reliable mastery of injection technology, a more exact knowledge and control of the supply of fresh air will be required in future. The accuracy with which the inflow of fresh air is recorded and the mastery of the dynamics of the process have a considerable influence on emissions. Only if the air supply to the combustion chamber is known precisely can the injection be controlled so as to provide an optimum mixture. A deviation of ±1 % in the recording of the oxygen concentration can lead, for example, to a change of up to ±10 % in the volume of nitrogen oxide emitted.

For this reason, Continental has not wasted any time in developing model-based air path functions, and has brought flexible control of air quantity by means of variable valve control to mass production level. Such a control system combines several physical sub-models augmented by numerical methods for describing variable disturbances in the movement of air in the inlet manifold that are difficult to model.

The great advantage of such model-based control systems is the fact that they require dramatically less effort in terms of calibration (calculation of the individual data points for engine characteristic maps). The model-based control system in a test application, for example, replaced a total of 48 engine characteristic maps which would otherwise have to be parameterized for the variable valve control system of each vehicle model. By direct comparison, a model-based control system delivers outstanding accuracy. The precision of its projections is covered almost completely with the interpolation of the values in engine characteristic maps (Figure 13).

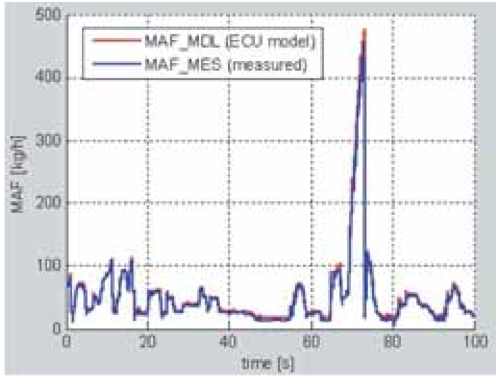

Figure 13 Correlation of air mass (MAF) based on sensor data/engine characteristic map (blue) and a model-based control system (red)

The fully variable valve adjustments of the future which will be able to flexibly control both opening times and valve lift on the inlet and outlet sides of the engine mean that emissions, consumption and driving dynamics can be optimized still further. The UniAir system produced by Schaeffler – which also

Figure 14 UniAir valve control system for fully variable control of engine ventilation

will be driven by Continental control units in the future – is an example of such a fully variable valve adjustment system (Figure 14).

Exhaust gas after-treatment – SCR

If inner-engine measures alone are not sufficient to comply with the future NO_x limits stipulated by the Euro 6 emissions standard, then the vehicle must be equipped with an exhaust gas after-treatment system. Corresponding systems for selective catalytic reduction (SCR) convert the nitrogen oxides into harmless nitrogen and water. They are based on the injection of an aqueous solution ("AdBlue") in the exhaust gas apparatus which contains urea.

Figure 15 SCR dosing unit for injecting reduction fluid containing urea into the exhaust system

In order to guarantee the successful reduction of nitrogen oxides, this injection process must be very accurate. In addition to exact volumetric admeasurements, it includes primarily an atomizing cone with evenly fine atomization of the reduction material. In addition, it must be ensured that the urea solution is also injected in liquid form at low temperatures. Because of their small cross-section, the pipes, in particular, must be protected against low ambient temperatures. To this end, Continental has developed dosing units (Figure 15), control algorithms (software), the SCR control unit and heated pipes with which major key components are available for SCR systems. Continental NO_x sensors provide a basis for calculating in each case the required supply of reduction fluid. Other components and know-how are provided courtesy of development partner Emitec, a 50 % subsidiary of Continental which also carries out system integration in its capacity as a system provider.

Outlook

Injection pressures will continue to increase in both diesel and gasoline engines because higher pressure makes improved treatment of the air-fuel mixture – and therefore even cleaner combustion – possible. Diesel injectors in particular – but increasingly also gasoline injectors – have today become a mechatronic cutting-edge technology which, because of the requirements in respect of accuracy, must be fitted in some cases in a clean room in order to exclude any possibility of impurities in the vicinity of the micrometer. On the control system side, the technical opportunities afforded by the injectors are converted into efficient and clean injection strategies, whereby an ever-increasing number of injection pulses are used to enable, in addition to preparation of the mixture, treatment of the exhaust gas and/or its regeneration. In future, even more powerful injectors will create a precondition for further developed combustion processes such as controlled auto ignition (CAI) for gasoline engines and homogenous charge compression ignition (HCCI) for diesel engines.

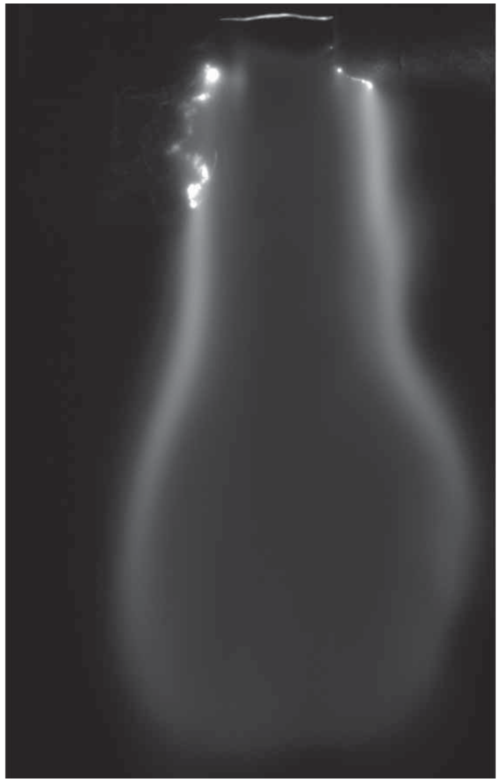

Figure 16 Ignition spark diffusion during the constant-current ignition process

Ignition plays a major role in the further optimization of the gasoline engine. Continental is currently developing, for example, a constant-current ignition process for turbocharged gasoline engines. When tested on the system prototype, the duration of combustion of the ignition spark was extended significantly by means of a continuously recharged spark (Figure 16). Despite the increased energy required for the ignition spark, this technology promises a much improved service life of the spark plug. At the same time, the region covered by the spark is increased and the shape of the spark can be defined by closed-loop control of the energy supply. This is a further opportunity for reliable ignition of, above all, lean or stratified mixtures (lambda >1), or for igniting misfires resulting from an over-rich mixture. This is achieved by greater depth of penetration into the combustion chamber and larger energy content.

Exhaust gas recirculation (EGR) will play a more important role in future. Firstly it reduces the temperature in the combustion chamber, and therefore restricts the build-up of nitrogen oxides, and secondly EGR can increase the exhaust gas volumetric flow at low engine speeds and therefore support earlier turbocharger response. Continental is conducting research in this field to identify the optimum means of returning exhaust gas into the combustion chamber.

Literature

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